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New approaches to how bilingualism shapes cognition and the brain across the lifespan: Beyond the false dichotomy of advantage versus no advantage

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Editorial: New approaches to how bilingualism shapes cognition and the brain across the lifespan: Beyond the false dichotomy of advantage versus no advantage

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Editorial on the Research Topic
New approaches to how bilingualism shapes cognition and the brain across the lifespan: Beyond the false dichotomy of advantage versus no advantage

For much of the 20th century, bilingualism was thought to result in cognitive disadvantages. In recent decades, however, research findings have suggested that experience with multiple languages may yield cognitive benefits and even counteract age-related cognitive decline, possibly delaying the manifestation of symptoms of dementia. Subsequently, conflicting evidence has emerged, and this has led to questions regarding the robustness and generalizability of these claims. A heated debate has raged for more than a decade (Antoniou, 2019), with certain research groups consistently finding support for a bilingual advantage, and others consistently finding none. The field has reached a stalemate, which has stifled research opportunities and the advancement of knowledge. In organizing the present Research Topic, we sought contributions describing new approaches needed to advance our field. These contributions help move the field beyond the traditional framing of bilingualism as a binary variable and toward approaches that capture the dynamic nature of effects relating to bilingualism and cognition.

New conceptualizations

One way of moving beyond traditional framing is to explore new conceptualizations of bilingualism, itself, and the relationship between bilingualism and cognition.

In her opinion piece, Bialystok likens the bilingual advantage debate to COVID-19 debates concerning which public health measures and mandates should (or should not) be implemented. She quotes virologist, Ian Mackay, who applied Reason's (1990) Swiss cheese model to COVID-19 risk mitigation by proposing that individual measures are imperfect (containing holes like a slice of Swiss cheese) and that only a multi-layered approach has sufficient redundancy built in to successfully offer protection from the risks at hand (similar to stacking slices of Swiss cheese so that the holes become covered). By adopting this metaphor, Bialystok is proposing that our field should move beyond simple conceptions concerning the relationship between bilingualism and cognition. Through this lens, bilingualism offers a layer of cognitive protection, but one which is porous rather than absolute. Bialystok's framing serves as a reminder that we, as a field, need to move beyond the "all or nothing" framing that has featured throughout the bilingual advantage debate over the past two decades.

The contribution from Sanches de Oliveira and Bullock Oliveira argues that the question of whether there are bilingual advantages in cognition is ill-formed and unanswerable. Bilingualism is a problematic category, according to the authors, because bilingualism and monolingualism are on a continuum rather than discrete, and languages and dialects are likewise on a continuum; what is more, a person's language proficiency is variable and skill- and context-specific, and full proficiency in any language is not even attainable, as one cannot have full proficiency in the vocabulary jargon of every possible activity. Cognition (and by extension cognitive advantages) are similarly problematic concepts, Sanches de Oliveira and Bullock Oliveira claim, partly because such concepts fail to account for the context-specific and thus variable nature of cognitive functioning.

Wagner et al. explore the questions of what it means to be bilingual, and what people consider to be a language. In doing so, they address the concern that many studies rely on participants' judgments of whether they themselves belong in the bilingual group or monolingual group. This self-assignment can be problematic because participants might vary considerably in what they believe constitutes a bilingual and even a language. In a survey of 528 participants, Wagner et al. observe a range of responses from participants when judging whether fictional speakers qualified as bilingual and fictional linguistic systems qualified as a language. Participants' definitions of bilingualism depended on several factors, including continued use of a language after immigrating and the presence of a writing system. Participants' definitions of a language depended on the presence of a writing system, similarity to other languages, and geographic breadth. Wagner et al. conclude that the variable and potentially inaccurate conceptions of bilingualism and language could contribute to some of the variable findings in the literature.

Chung-Fat-Yim et al. discuss the nuanced nature of attention, dividing this multi-faceted concept into sustained attention, selective attention, alternating attention, divided attention, and disengagement of attention. For each component of attention, the authors review relevant models from the psychology and neuroscience literature, as well as empirical research that has examined bilingualism's potential positive effects.

Voits et al. discuss the commonalities and complementarities between the bilingualism and cognitive aging literatures. Bilingualism tends to be reduced to a dichotomous trait, which misrepresents its status as a complex experience; other times it is overlooked as a contributory factor all together. These authors discuss why bilingualism is not recognized as a contributor to cognitive reserve. They also helpfully suggest how bilingualism can be better integrated into aging research in future work. A model of aging is needed that encompasses the contributions of lifestyle factors, one of which is likely to be bilingual experience.

New measures

Another way of moving beyond the stalemate debate surrounding bilingual benefits is to create new tasks, measures, and analyses.

Wu and Struys examine the influence of language dominance on bilingual word recognition. Uyghur-Chinese bilinguals completed lexical decision tasks administered in the L1 and L2, as well as a flanker task. Although bilinguals differed in their language dominance, all reported that they preferred reading in Chinese, their L2. Consequently, better performance was observed in their L2 than L1 on the lexical decision tasks. Further, those who had acquired their L2 earlier and had higher across-modality dominance in the L2 tended to recognize L2 words faster. The findings suggest that language dominance may be operationalized as a continuous or a categorical variable, and in doing so may exhibit effects not only for lexical recognition but also indirectly impacting domain-general contributions to recognition.

van den Berg et al. also investigate how individual bilingual experiences affect executive control by studying two samples of bilinguals (in university and non-university contexts). In doing so, they calculated a measure of language entropy through a language background questionnaire, which they used as a continuous predictor of the participants' performance in a color-shape switching task. Apart from collecting Reaction Times, pupil size was also measured as an objective index of set shifting abilities that are required for this task. The authors report that, while typical switching costs in RTs were not affected by entropy in either of their samples, entropy did predict a switching cost in a non-university context when pupil dilation was studied. van den Berg et al. conclude that social diversity in bilinguals' experiences may indeed be linked to their executive control abilities, but this may depend on the exact social context and may be detectable in measures that are more sensitive than RT, such as pupil size.

Similarly, Freeman et al. focus on how quantified individual bilingual experiences affect performance in a non-linguistic task tapping executive control. Specifically, a sample of 146 Spanish-English heritage bilinguals were tested in a Stroop arrows task, from which the Stroop, facilitation and inhibition effects were calculated. Measures of individual experiences were used as predictors of these effects, including participants' sociolinguistic context (categorical), a composite continuous variable indexing L2 proficiency and exposure, as well as L2 age of acquisition, L2 proficiency and a measure of non-verbal cognitive reasoning, all continuous factors. The authors report a rich pattern of findings which converged in that increased bilingual experiences and cognitive skills led to increased abilities of focusing on relevant stimuli while ignoring irrelevant ones. These findings were also modulated by the sociolinguistic environment of the individuals, suggesting that any effects of bilingualism on cognition should be viewed in relation to the contexts that bilinguals find themselves in.

Grant et al.'s contribution follows on the same path of avoiding a binary monolingual-bilingual comparison and employing a seldom-used but meaningful and sensitive neural measure. Specifically, participants listened to speech-in-noise in their L1 and L2; the continuous independent variable of L2 age of acquisition and the dependent variable of EEG-measured alpha power were used. Findings indicate an increased alpha power when listening in the L2 and when the participant had an older L2 age of acquisition.

In a similar vein, Marin-Marin et al. turn their attention to the effects of bilingualism on brain structure, by using a measure of bilingual experiences as a predictor of regional gray matter volume in a group of Catalan-Spanish bilinguals that were immersed in a bilingual environment. They report non-linear volumetric fluctuations in a series of cortical and subcortical regions that have been linked to speech processing and language control. The authors argue that their pattern of results are corroborative of theoretical suggestions for dynamic, non-linear effects of bilingualism on the adult brain.

Finally, Dash et al. attempt to advance modeling bilingualism as a continuous variable. They show that a multifactorial approach to different dimensions of bilingual study may lead to a better understanding of the role of bilingualism on cognitive performance. Rather than reducing variability or treating it as problematic, these authors argue that variability needs to be embraced in bilingual profiles if we are to generalize the results of individual studies to the wider literature.

Future directions

Taken together, the articles within this Research Topic provide suggestions concerning how our field might move beyond the entrenched positions that have characterized the bilingual advantage debate for more than a decade. We are excited by the ambitious and rigorous studies that will emerge in coming years to advance understanding of how experience with multiple languages interacts with other variables to affect cognition, the structure and function of the brain, and aging. There remains a need for detailed theoretical models that generate testable predictions in order for us to understand what types of bilingual experiences are more (or less) likely to show plasticity effects in a given domain. To achieve this, it is necessary to pay attention to how bilingualism is conceptualized and to methodological nuances in experimental designs, such as differences in tasks used and in the components of cognition they measure. By focusing on these aspects, we believe that this Research Topic offers a window into how knowledge can advance within our field, specifically concerning how bilingualism affects cognition and the brain.

Author contributions

MA, CP, and SRS contributed equally to the writing of this editorial article. All authors contributed to the article and approved the submitted version.

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References

Antoniou, M. (2019). The advantages of bilingualism debate. *Annu. Rev. Linguist.* 5, 395–415. doi: 10.1146/annurev-linguistics-011718-011820

Reason, J. (1990). *Human Error*. Cambridge, UK: Cambridge University Press.

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OPINION
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Bilingualism as a Slice of Swiss Cheese

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INTRODUCTION

As the Covid-19 pandemic ravaged the global population, an intense discussion began about how best to contain the spread of the deadly virus. Debates ensued about whether masks should be mandated, borders closed, crowds controlled, businesses shuttered, and so on. The assumption in these debates was that there was a correct solution that would solve the problem and allow life to return to normal, the only issue being to determine which of the proposed mitigations would best achieve that goal. The discussions quickly became political, with dogmatic positions being asserted on all sides.

Although many public health officials advocated for enforcing all such interventions, there was nonetheless an underlying sense of priorities, such as focusing on mask mandates so other approaches, such as closing schools or businesses, could be avoided. There was little evidence to support these assumptions and no logic provided for why they were chosen. But in the midst of these high-stakes discussions, a virologist, Ian Mackay, took a different view (described in Lewis, 2021). Following earlier work by Reason (1990), he argued that all interventions have imperfections and the most effective means of avoiding the imperfections in each is to combine them so the weakness in one approach is compensated by a strength in another. Reason compared this approach to a package of Swiss cheese: each slice has holes, but the holes are in different places, so when the slices are stacked together, all the holes are blocked. The problem Reason addressed was how to manage inevitable human error to avoid devastating accidents. His solution was that each attempt blocks a different hazard, so ultimately, it is in the combination, or as he called it "system," that safety is achieved (Reason, 2000). Mackay's contribution was to apply this approach to the mitigation of disease in a pandemic: no single solution alone will halt the spread of the disease but all approaches in combination will be effective.

And so it is with bilingualism. For about a decade there has been fierce debate about whether bilingualism improves cognitive systems and brain structures. The debate is polarized, aggressive, and unresolved. On one side, researchers argue that empirical evidence from multiple sources has demonstrated that bilingual participants outperform monolinguals on a range of cognitive tasks, with most discussion focused on executive functions (Baum and Titone, 2014; Bialystok, 2017; Antoniou, 2019); those on the opposite side argue that attempts to replicate those experiments fail to reveal group differences so the reported differences must be spurious (Paap and Greenberg, 2013; von Bastian et al., 2016). Moreover, meta-analyses of the same body of research have supported both the validity of the positive claims (van den Noort et al., 2019; Grundy, 2020) and null conclusions in which there is no relation between bilingualism and cognitive level (Lehtonen et al., 2018; Donnelly et al., 2019). Although similar issues apply to the possible role of bilingualism in modifying brain structure and brain networks, those debates are less passionate and the evidence less controversial, so the present discussion will focus on the behavioral evidence connecting bilingual experience to behavioral outcomes. How can there be so much uncertainty about the relation between an identifiable experience and a set of measurable cognitive outcomes? Can the Swiss cheese model help us to understand this debate?

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RELATION BETWEEN BILINGUALISM AND COGNITION

The present argument is that the debate rests on a reductionist error in which both the definition of bilingualism and the nature of cognitive ability it allegedly modifies are oversimplified, thereby reducing the relation between them to a single-factor description. The central concept, bilingualism, is treated as a binary notion by opposing it to another oversimplification, monolingualism. Moreover, the evidence relating this binary notion to a set of outcomes is objectified and assigned a name, "The Bilingual Advantage." Once something has been concretized in this way it can be treated as an entity that exists or does not exist; all nuance evaporates. The test for reductionism is to replace a concept with its definition by inserting the phrase "nothing but." In this way, bilingualism is *nothing but* the ability to speak two languages and the cognitive consequence of bilingualism is *nothing but* superior performance on some executive function task. These concepts then take the form of a checklist: How many languages do you speak? What were the scores on the executive function tasks for these binary groups? Thus, when the group designated as "bilingual" fails to excel in some cognitive task designated as "executive function," the conclusion is that there is no relation between the concepts (see for example Nichols et al., 2020). But life rarely presents such discrete options.

Why should bilingualism have any relation to cognitive outcomes? There is no obvious reason to assume that a linguistic experience, bilingualism, would impact non-verbal cognitive outcomes. Indeed, most research investigating transfer of skills across domains shows weak evidence for this possibility, indicating at best only near transfer across similar abilities (Shipstead et al., 2012; Simons et al., 2016). However, it is well-established that both languages are simultaneously active in bilingual minds, even in strongly monolingual contexts, creating ongoing potential conflict (Kroll et al., 2012). Since bilinguals rarely make intrusion errors (Gollan and Ferreira, 2009), some mechanism must be responsible for managing attention to the target language while excluding the unwanted language. The general view is that this mechanism is based in the domain-general attention system used for executive functioning (Bialystok et al., 2009). Supporting evidence from imaging studies has demonstrated that overlapping attention networks are used both for language selection and non-verbal cognitive control (Luk et al., 2012; Wong et al., 2016). This use of general attention systems for language processing by bilinguals links the two domains and opens the possibility for interactions between them.

The argument, therefore, is that experience in managing two languages recruits the general attention mechanisms used for other cognitive activities, thereby changing them. However, demonstrating this relation empirically is complex largely because of the difficulty in defining "bilingualism." In most psychological research in which groups are compared, the designation of the groups is objectively transparent and the tested outcome has a simple relation to group membership. Thus, studies can compare 4-year-olds and 6-year-olds on a cognitive reasoning task, younger and older adults on a memory recall task, men and women on a spatial processing task (although this binary is becoming increasingly complex), or musicians and non-musicians on an auditory perception task. Because the criteria for group membership are clear and the outcome task is related to a hypothesis about the difference between those groups, the results can be easily interpreted: older children are more cognitively advanced than younger children so outperform them on a reasoning task (Richland et al., 2006), younger adults have better memory than older adults so recall more items on specific memory tasks (Thomas and Hasher, 2012), men outperform women in spatial processing (Parsons et al., 2004), and musicians have more acute auditory perception than non-musicians (Boh et al., 2011). There is also a clear specificity in these relations: musical experience improves auditory acuity. In all these cases, too, studies sometimes show no difference between groups, and crucially, sometimes the expected effect is reversed, demonstrating younger children outperforming older children on a cognitive task (Otgaar et al., 2016) or older adults outperforming younger adults on a memory task (Castel, 2005). These exceptions are not taken as counterevidence to the general principle but rather as circumstances that reveal the inherent complexity in these behaviors without compromising the accepted difference between the groups.

Unlike other individual differences, bilingualism is not a binary category—it is a slice of Swiss cheese buried within a package of slices that together impact cognitive function. Sometimes the holes in the bilingualism slice are blocked by other slices that compensate for those gaps (high SES? Education?) but sometimes it is bilingual experience that is primarily responsible for the outcome presumably because of holes in the other slices (delay of symptoms of dementia?). At the risk of entering an infinite regress, bilingualism itself can be considered as a package of Swiss cheese, with different manifestations of bilingual experience placing the holes in different places that together define the experience. There is also ambiguity about the overall goal: Is it general cognitive ability, performance on specific cognitive tasks, or executive function ability? Finally, the mechanism for the relation in terms of attention across domains is less specific than the connection between musical experience and auditory acuity. Therefore, the complexity in understanding the relation between bilingualism and cognitive outcomes comes from defining bilingualism, defining the outcome, and identifying the mechanism that relates them. If the outcome of interest is the somewhat amorphous issue of developing and maintaining cognitive function across the lifespan, then the question is whether adding a slice of bilingualism has an impact on this cognitive package.

Explaining the factors that contribute to high functioning cognitive systems is surely at least as complex as defeating a viral pandemic. A single layer of cheese, such as the mask mandate, was never going to conquer the pandemic, and a single approach to boosting cognitive function, such as bilingual experience, cannot guarantee outcomes. There has never been a claim that this is a single-factor model in which bilingual experience is irrevocably responsible for better cognitive outcomes, but there is clear evidence that it *contributes* to those outcomes. Crucially, including that bilingualism slice is almost never associated with poorer cognitive outcomes. The implications of this metaphor are that bilingualism alone will not guarantee positive effects on cognition, but that overall outcomes are better when bilingualism is included. This summary fits well with the actual body of evidence.

WHERE THE HOLES ARE

The central idea in the cheese metaphor is that each intervention will carry its own weaknesses—it will have holes. Anticipating where those holes are for bilingualism is especially challenging because each experience of bilingualism is different. Although such differences as age of acquisition of the additional language(s), duration of active bilingualism, intensity of use, proficiency in each language, and the like (Luk and Bialystok, 2013), have been acknowledged for some time, detailed examination of them has only recently become an important area of research. Thus, different cognitive outcomes have been reported for individuals who became bilingual early or later in life (Luk et al., 2011; Pelham and Abrams, 2014; Vega-Mendoza et al., 2015), were tested as children or adult bilinguals (Bialystok et al., 2005; Dash et al., 2019), and engaged in frequent language switching or not (Festman et al., 2010; Prior and Gollan, 2011, 2013; Verreyt et al., 2016). All these studies found a connection between specific aspects of bilingual experience and cognitive outcome, but the role of these features in modulating the results makes it difficult to propose general assertions about the relation between bilingualism *per se* and cognitive outcomes or the possible underlying mechanism responsible for those effects.

One approach to addressing variations in bilingualism is to quantify the experience in terms of some of these factors. In these studies, bilinguals are not necessarily compared to monolinguals (although they can be) but rather are positioned along a continuum of bilingualism. The gradient can be composed of a single factor, such as age of acquisition of the new language, or a range of factors including aspects of experience, language proficiency, and language use, as in the Language and Social Background Questionnaire (Anderson et al., 2018). The instrument elicits details about background, experience, use patterns and so on, to produce scores on three factors—home language use, social language use, second-language proficiency—which are then weighted to create an overall bilingualism score. Other instruments have been created for this purpose and achieve similar results (Marian et al., 2007; Li et al., 2014). In these studies, more experience with bilingualism is associated with both better test performance (Guerrero et al., 2016; Pot et al., 2018; DeLuca et al., 2020; Bialystok and Shorbagi, 2021) and better brain structure (Hervais-Adelman et al., 2018; Del Maschio et al., 2019; DeLuca et al., 2019; Sulpizio et al., 2020). These detailed associations undermine conclusions from binary procedures that classify participants in terms of their response to a simple question about how many languages they speak (Dick et al., 2019; Nichols et al., 2020) and have refined our understanding of the relation between bilingualism and cognition.

Recent studies have also described the role of the linguistic and sociolinguistic context in shaping bilingual experience and its effect on cognitive and brain outcomes. The most detailed model of this type is the Adaptive Control Hypothesis (Green and Abutalebi, 2013). The authors identify three interactional contexts in which two languages can be used and argue that each context engages different cognitive processes leading to different consequences for mind and brain. In a single language context, each language is used in a specific setting, as in one language at home and a different language at work. This context imposes few cognitive demands because there are multiple cues for language selection, so the main demand is to stay focused on the goal and select the correct language without interference from the other. The second context, dual language, is more challenging because both languages are used in the same setting but with different individuals. In addition to monitoring the language needed for this interlocutor, the context also requires switching, disengagement, and response inhibition to maintain focus on the correct language. Finally, dense code switching defines situations in which both languages are used by all individuals, so focus on the target language is less important. Because everyone can speak both languages, communication is not necessarily disrupted if there is a language switch. All three contexts require proficient bilingualism, but each places different demands on the cognitive systems needed to manage language use and so is associated with different outcomes.

Another approach to describing relevant differences in bilingual environments was proposed by Gullifer and colleagues through the notion of language "entropy" to reflect the variety and complexity of social situations in which both languages are used (Gullifer and Titone, 2020). They argue that greater social diversity of language use leads to a larger impact on the cognitive outcomes associated with bilingualism. By combining estimates of entropy with other individual differences, such as age of bilingual acquisition and intensity of bilingual experience, they offer a more complete account of the complexity of bilingualism (Gullifer et al., 2020). These metrics relate to brain structure in terms of functional connectivity while performing an executive function task (Gullifer et al., 2018) and overall better performance on that task (Gullifer and Titone, 2021). In short, the small variations in bilingual experience reflected in language entropy were positively associated with cognitive and brain outcomes.

These examples in which bilingual experience has been quantified in terms of the details of individual experiences and the situations in which the languages are used demonstrate the inadequacy of a monolithic concept called "bilingualism," particularly one that is defined by its distinction from another monolithic concept, "monolingualism." Even monolingualism exists in a context. Monolinguals living in a strongly homogeneous context, monolinguals living in a diverse context where bilingual use is prevalent, and bilinguals were taught a new language, Finnish; although word learning was similar across groups, electrophysiological responses to a phonetic feature distinctive in Finnish was only similar for bilinguals and monolinguals living in a diverse context (Bice and Kroll, 2019).

The argument to this point is that the complexity and diversity of bilingual experience rules out one-to-one mappings between bilingualism and cognitive performance. Instead, small differences in bilingual experience modify its relation to overall cognitive functioning. In this sense, bilingualism is a flawed intervention that nonetheless contributes to a larger goal.

REINFORCING THE COGNITIVE DAM

In the case of the multiple slices of Swiss cheese needed to mitigate a global pandemic, success was determined by some metric of pandemic severity. This outcome could be measured in several ways, such as number of cases, number of hospitalizations, or test positivity rate, and each outcome might be differentially impacted by each mitigation slice. And although the various outcome measures are likely correlated, they are not identical; number of cases is related to the number of hospitalizations but there are important differences between them. This multifaceted relation between individual mitigation strategies and the overall goal rules out simple interpretations, such as the effect of mask mandates on ending a pandemic, even though each slice contributes to that goal.

For bilingualism, there is a lack of clarity about the cognitive outcomes it is expected to impact. Although most of the literature has focused on executive function tasks, some studies have extrapolated these ideas to a range of cognitive abilities for which no relation to bilingualism would be expected. In general, there is no impact of bilingualism on verbal tasks or verbal conditions of cognitive tasks (Luo et al., 2013), simple tasks that can be performed with little effortful control (Comishen and Bialystok, 2021), and cognitive domains for which conflict resolution is not central, such as reasoning in the Tower of London Task (Papageorgiou et al., 2019). Yet, the absence of an effect in these cases is sometimes used to reject claims connecting bilingualism to cognition. In addition to explaining how each contributor to cognition works individually and defining its features, in this case, bilingualism, it is equally essential to set clear definitions for the outcome, in this case, cognition.

DOES BILINGUALISM AFFECT COGNITIVE OUTCOMES?

The implication of this perspective is that there is a real effect of bilingualism on cognitive function with a small effect size that can be overshadowed by other factors. But that is the way complex phenomena are determined. Drawing on research from genetics in which it eventually became clear that there was no simple mapping from single genes to outcomes, Gotz et al. (2021) argue that the same principles apply to psychological phenomena, including cognitive ability. They claim that complex psychological phenomena are determined by many factors, each of which typically has a small effect size, and that the search for a one-to-one relation between predictors and outcomes is reductionist and ultimately, incorrect. For this reason, attempts to isolate a single factor or interpret a complex outcome in terms of a single factor are misguided. Moreover, they argue that contrary to the usual assumptions, large effect sizes are likely more unreliable and unreplicable than are the small effects that may or not be statistically significant in a given study but are pervasive *across* studies. They implore researchers in psychology to reconsider the focus on large effect sizes and instead "reward accurate and meaningful effects rather than exaggerated and unreliable effects" (p. 5).

The effect of bilingualism on cognition is clearly in the range of small effect sizes. Most meta-analyses of this literature show an overall advantage for positive studies with a small effect size of about 0.15–0.20 before such corrections as publication bias or outlier removal are applied (see Grundy, 2020), but the result is interpreted in different ways: Some authors accept the significant effect and others argue that the effect size is not large enough to conclude that the positive results are reliable. However, these effect sizes are within the range found in meta-analyses of other moderating effects on cognition. For example, the effect size for the role of exercise on cognitive outcomes is between 0.10 and 0.25 (Etnier et al., 1997; Chang et al., 2012), yet there is no debate over the idea that exercise impacts cognitive outcomes. In that case, exercise might be another slice of Swiss cheese in the cognitive package, but the importance of its inclusion in the package is viewed positively.

The implication of this metaphor for understanding the effect of bilingualism on cognitive outcomes is that one cannot expect a simple relationship between the concepts. Bilingual experience has many varieties, and it is only one slice in a package that includes such factors as socioeconomic status, immigration status, cultural background, genetic endowment, general health, and such that impact cognitive outcomes. But the effect of bilingualism is real, and it contributes to the robustness of cognitive ability. And just as it is important to understand the way factors such as socioeconomic status impact cognitive level, so too it is essential to understand how bilingualism works. Although the effects are quite small for young adults (Bialystok et al., 2005), they are larger in older age, contributing to postponement of symptoms of dementia with aging (Bialystok, 2021). Crucially, bilingualism is almost never associated with poorer cognitive outcomes. Put this way, the essence of the controversy is in the reductionism that has led to the expectation that a simplistic definition of bilingualism must lead to improved cognitive test scores, and when it does not, the entire argument is rejected. Masks alone will not end a pandemic. What is needed is a multifactor approach to bilingual experience that takes account of which other slices are in the package and where the holes are on the slice of bilingualism.

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REFERENCES

Anderson, J. A. E., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Antoniou, M. (2019). The advantages of bilingualism debate. *Annu. Rev. Linguist.* 5, 1–21. doi: 10.1146/annurev-linguistics-011718-011820

Baum, S., and Titone, D. (2014). Moving toward a neuroplasticity view of bilingualism, executive control, and aging. *Appl. Psycholinguist.* 35, 857–894. doi: 10.1017/S0142716414000174

Bialystok, E. (2017). The bilingual adaptation: how minds accommodate experience. *Psychol. Bull.* 143, 233–262. doi: 10.1037/bul0000099

Bialystok, E. (2021). Bilingualism: pathway to cognitive reserve. *Trends Cogn. Sci.* 25, 355–364. doi: 10.1016/j.tics.2021.02.003

Bialystok, E., Craik, F. I. M., Green, D. W., and Gollan, T. H. (2009). Bilingual minds. *Psychol. Sci. Public Interest* 10, 89–129. doi: 10.1177/1529100610387084

Bialystok, E., Martin, M. M., and Viswanathan, M. (2005). Bilingualism across the lifespan: the rise and fall of inhibitory control. *Int. J. Bilingualism* 9, 103–119. doi: 10.1177/13670069050090010701

Bialystok, E., and Shorbagi, S. H. (2021). Subtle increments in socioeconomic status and bilingualism jointly affect children's verbal and nonverbal performance. *J. Cogn. Dev.* 22, 467–490. doi: 10.1080/15248372.2021.1901711

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196:104644. doi: 10.1016/j.bandl.2019.104644

Boh, B., Herholz, S. C., Lappe, C., and Pantev, C. (2011). Processing of complex auditory patterns in musicians and nonmusicians. *PLoS ONE* 6:e21458. doi: 10.1371/journal.pone.0021458

Castel, A. D. (2005). Memory for grocery prices in younger and older adults: the role of schematic support. *Psychol. Aging* 20, 718–721. doi: 10.1037/0882-7974.20.4.718

Chang, Y. K., Labban, J. D., Gapin, J. I., and Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res.* 1453, 87–101. doi: 10.1016/j.brainres.2012.02.068

Comishen, K., and Bialystok, E. (2021). Increases in attentional demands are associated with language group differences in working memory performance. *Brain Cogn.* 147:105658. doi: 10.1016/j.bandc.2020.105658

Dash, T., Berroir, P., Joanette, Y., and Ansaldo, A. I. (2019). Alerting, orienting, and executive control: the effect of bilingualism and age on the subcomponents of attention. *Front. Neurol.* 10:1122. doi: 10.3389/fneur.2019.01122

Del Maschio, N., Sulpizio, S., Toti, M., Caprioglio, C., Del Mauro, G., Fedeli, D., et al. (2019). Second language use rather than second language knowledge relates to changes in white matter microstructure. *J. Cult. Cogn. Sci.* 4, 165–175. doi: 10.1007/s41809-019-00039-z

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage* 204:116222. doi: 10.1016/j.neuroimage.2019.116222

Dick, A. S., Garcia, N. L., Pruden, S. M., Thompson, W. K., Sutherland, M. T., and Gonzalez, R. (2019). No evidence for a bilingual executive function advantage in the ABCD study. *Nat. Hum. Behav.* 3, 692–701. doi: 10.1038/s41562-019-0609-3

Donnelly, S., Brooks, P. J., and Homer, B. D. (2019). Is there a bilingual advantage on interference-control tasks? A multiverse meta-analysis of global reaction time and interference cost. *Psychonomic Bull. Rev.* 26, 1122–1147. doi: 10.3758/s13423-019-01567-z

Etnier, J. L., Salazar, W., Landars, D. M., Petruzzello, S. J., Han, M., and Nowell, P. (1997). The influence of physical fitness and exercise upon cognitive functioning: a meta-analysis. *J. Sport Exerc. Psychol.* 19, 249–277. doi: 10.1123/jsep.19.3.249

Festman, J., Rodriguez-Fornells, A., and Munte, T. F. (2010). Individual differences in control of language interference in late bilinguals are mainly related to general executive abilities. *Behav. Brain Funct.* 6:5. doi: 10.1186/1744-9081-6-5

Gollan, T. H., and Ferreira, V. S. (2009). Should I stay or should I switch? A cost-benefit analysis of voluntary language switching in young and aging bilinguals. *J. Exp. Psychol.* 35, 640–665. doi: 10.1037/a0014981

Gotz, F. M., Gosling, S. D., and Rentfrow, P. J. (2021). Small effects: the indispensable foundation for a cumulative psychological science. *Perspect. Psychol. Sci.* doi: 10.1177/1745691620984483. [Epub ahead of print].

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Grundy, J. G. (2020). The effects of bilingualism on executive functions: an updated quantitative analysis. *J. Cult. Cogn. Sci.* 4, 177–199. doi: 10.1007/s41809-020-00062-5

Guerrero, S. L., Smith, S., and Luk, G. (2016). "Home language usage and executive function in bilingual preschoolers," in *Cognitive Control and Consequences of Multilingualism*, ed J. Schwieter (Amsterdam: John Benjamins), 351–374. doi: 10.1075/bpa.2.15leo

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., et al. (2020). Bilingual language experience as a multidimensional spectrum: associations with objective and subjective language proficiency. *Appl. Psycholinguist.* 42, 245–278. doi: 10.1017/S0142716420000521

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism* 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., and Titone, D. (2021). Engaging proactive control: influences of diverse language experiences using insights from machine learning. *J. Exp. Psychol.* 150, 414–430. doi: 10.1037/xge0000933

Hervais-Adelman, A., Egorova, N., and Golestani, N. (2018). Beyond bilingualism: multilingual experience correlates with caudate volume. *Brain Struct. Funct.* 223, 3495–3502. doi: 10.1007/s00429-018-1695-0

Kroll, J. F., Dussias, P. E., Bogulski, C. A., and Valdes-Kroff, J. (2012). "Juggling two languages in one mind: what bilinguals tell us about language processing and its consequences for cognition," in *The Psychology of Learning and Motivation, Vol. 56B*, ed Ross (Cambridge, MA: Academic Press), 229–262. doi: 10.1016/B978-0-12-394393-4.00007-8

Lehtonen, M., Soveri, A., Laine, A., Jarvenpaa, J., De Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* 144, 394–425. doi: 10.1037/bul0000142

Lewis, M. (2021). *The Premonition*. W.W. Norton.

Li, P., Zhang, F., Tsai, E., and Puls, B. (2014). Language history questionnaire (LHG 2.0): a new dynamic web-based research tool. *Bilingualism* 17, 673–680. doi: 10.1017/S1366728913000606

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: interaction between language proficiency and usage. *J. Cogn. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Luk, G., De Sa, E., and Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism* 14, 588–595. doi: 10.1017/S1366728911000010

Luk, G., Green, D. W., Abutalebi, J., and Grady, C. (2012). Cognitive control for language switching in bilinguals: a quantitative meta-analysis of functional neuroimaging studies. *Lang. Cogn. Process.* 27, 1479–1488. doi: 10.1080/01690965.2011.613209

Luo, L., Craik, F. I. M., Moreno, S., and Bialystok, E. (2013). Bilingualism interacts with domain in a working memory task: evidence from aging. *Psychol. Aging* 28, 28–34. doi: 10.1037/a0030875

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., and Owen, A. M. (2020). Bilingualism affords no general cognitive advantages: a population study of executive function in 11,000 people. *Psychol. Sci.* 31, 548–567. doi: 10.1177/0956797620903113

Otgaar, H., Howe, M. L., Brackmann, N., and Smeets, T. (2016). The malleability of developmental trends in neutral and negative memory illusions. *J. Exp. Psychol.* 145, 31–55. doi: 10.1037/xge0000127

Paap, K. R., and Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* 66, 232–258. doi: 10.1016/j.cogpsych.2012.12.002

Papageorgiou, A., Bright, P., Periche Tomas, E., and Filippi, R. (2019). Evidence against a cognitive advantage in the older bilingual population. *Q. J. Exp. Psychol.* 72, 1354–1363. doi: 10.1177/1747021818796475

Parsons, T. D., Larson, P., Kratz, K., Thiebaux, M., Bluestein, B., Buckwalter, J. G., et al. (2004). Sex differences in mental rotation and spatial rotation in a virtual environment. *Neuropsychologia* 42, 555–562. doi: 10.1016/j.neuropsychologia.2003.08.014

Pelham, S. D., and Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *J. Exp. Psychol.* 40, 313–325. doi: 10.1037/a0035224

Pot, A., Keijzer, M., and de Bot, K. (2018). Intensity of multilingual language use predicts cognitive performance in some multilingual older adults. *Brain Sci.* 8:92. doi: 10.3390/brainsci8050092

Prior, A., and Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish-English and Mandarin-English bilinguals. *J. Int. Neuropsychol. Soc.* 17, 682–691. doi: 10.1017/S1355617711000580

Prior, A., and Gollan, T. H. (2013). The elusive link between language control and executive control: a case of limited transfer. *J. Cogn. Psychol.* 25, 622–645. doi: 10.1080/20445911.2013.821993

Reason, J. (1990). *Human Error*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9781139062367

Reason, J. (2000). Human error: models and management. *BMJ* 320, 768–770. doi: 10.1136/bmj.320.7237.768

Richland, L. E., Morrison, R. G., and Holyoak, K. J. (2006). Children's development of analogical reasoning: insights from scene analogy problems. *J. Exp. Child Psychol.* 94, 249–273. doi: 10.1016/j.jecp.2006.02.002

Shipstead, Z., Redick, T. S., and Engle, R. W. (2012). Is working memory training effective? *Psychol. Bull.* 138, 628–654. doi: 10.1037/a0027473

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., et al. (2016). Do "brain-training" programs work? *Psychol. Sci. Public Interest* 17, 103–186. doi: 10.1177/1529100616661983

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., and Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage* 205:116306. doi: 10.1016/j.neuroimage.2019.116306

Thomas, R. C., and Hasher, L. (2012). Reflections of distraction in memory: transfer of previous distraction improves recall in younger and older adults. *J. Exp. Psychol.* 38, 30–39. doi: 10.1037/a0024882

van den Noort, M., Struys, E., Bosch, P., Jaswetz, L., Perriard, B., Yeo, S., et al. (2019). Does the bilingual advantage in cognitive control exist and if so, what are its modulating factors? *A systematic review. Behav. Sci.* 9:27. doi: 10.3390/bs9030027

Vega-Mendoza, M., West, H., Sorace, A., and Bak, T. H. (2015). The impact of late, non-balanced bilingualism on cognitive performance. *Cognition* 137, 40–46. doi: 10.1016/j.cognition.2014.12.008

Verreyt, N., Woumans, E. V. Y., Vandelanotte, D., Szmalec, A., and Duyck, W. (2016). The influence of language-switching experience on the bilingual executive control advantage. *Bilingualism* 19, 181–190. doi: 10.1017/S1366728914000352

von Bastian, C. C., Souza, A. S., and Gade, M. (2016). No evidence for bilingual cognitive advantages: a test of four hypotheses. *J. Exp. Psychol.* 145, 246–258. doi: 10.1037/xge0000120

Wong, B., Yin, B., and O'Brien, B. (2016). Neurolinguistics: structure, function, and connectivity in the bilingual brain. *BioMed. Res. Int.* 2016:7069274. doi: 10.1155/2016/7069274

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A Domain-General Monitoring Account of Bilingual Language Control in Recognition: The Role of Language Dominance and Bilingual Experience

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The ability of bilingual individuals to manage two competing languages is assumed to rely on both domain-specific language control and domain-general control mechanisms. However, previous studies have reported mixed findings about the extent and nature of cross-domain generality. The present study examined the role of language dominance, along with bilingual language experience, in the relationship between word recognition and domain-general cognitive control. Two single-language lexical decision tasks (one in L1 and another in L2) and a domain-general flanker task were administered to bilinguals who live in the sociolinguistic context of a minority and a majority language, namely, Uyghur (L1) and Chinese (L2), respectively. The results showed a diversity in language dominance patterns with better performance in L2 than L1 in the recognition modality, even for participants who self-identified as globally being dominant in L1. This finding reflected all bilinguals' self-evaluation that their preferred language for reading was L2, suggesting that language dominance is dynamic, depending on what language modality is measured. Furthermore, it was found that an earlier onset age of L2 acquisition (but not recent exposure) and a higher across-modality dominance in L2 were related to faster L2 word recognition. When self-reported language dominance was operationalised as a grouping variable, it was further found that both across-modality L1- and L2-dominant bilingual participants demonstrated a significant relationship between L2 word recognition and domain-general monitoring control, while only L1-dominant bilinguals additionally tapped into inhibitory control, indexed by the flanker effect during L2 word recognition. These findings suggest that language dominance has an impact on the extent and nature of the overlap in control mechanisms across specific linguistic and domain-general cognitive domains and add evidence to a domain-general monitoring account of bilingual word recognition.

Keywords: minority language, language dominance, cognitive control, flanker task, word recognition

INTRODUCTION

The ability of the bilingual mind to restrict lexical access to appropriate lexical representations in the word recognition process has aroused considerable attention from researchers. Numerous recent studies have shaped the account that in the domain of language recognition, irrespective of a single or dual-language context, lexical stimuli non-selectively activate lexical representations in the target language as well as competitors from the non-target language (Linck et al., 2008; van Assche et al., 2009; Wu and Thierry, 2010; Zhou et al., 2010; Moon and Jiang, 2012; Nakayama et al., 2012; Miwa et al., 2014; Hoversten et al., 2015; Gangopadhyay et al., 2019). Evidence for non-selective co-activation has been found in languages with the same script, such as Dutch–English (de Groot et al., 2000; Dijkstra et al., 2000; Lemhofer and Dijkstra, 2004; van Heuven et al., 2008; van Assche et al., 2009) and Spanish–English (Macizo et al., 2010; Hoversten et al., 2015; Pu et al., 2019). However, it has also been found in bilingual individuals (henceforth, bilinguals) who speak two languages with distinct scripts, such as Chinese–English (Wu and Thierry, 2010; Zhou et al., 2010), Japanese–English (Nakayama et al., 2012; Miwa et al., 2014) and Korean–English (Moon and Jiang, 2012). For instance, Wu and Thierry (2010) tested Chinese–English bilinguals in a single L2-English context in which English words were presented in pairs and participants had to decide on their semantic relatedness, but bilingual participants were unaware that some semantic-unrelated word pairs had an implicit feature, such as a sound repetition in the L1-Chinese translation (e.g., the word pair 'classic–surprise' translated into Chinese with a sound repetition of 'jing': 'jingdian–jingya'). Based on the analysis of the neuroimaging technique of event-related potentials (ERP), it was found that the implicit sound repetition in the Chinese translations induced a positive priming (facilitating) effect in judging the semantic relatedness in English. This result suggests that for two languages with distinct scripts, processes underlying L2 word recognition also imply the activation of L1 lexical items.

Even though these studies have shown that language non-selective access exists in the bilingual recognition process, it is still unclear what type of bilingual language control is involved in addressing the competition of the co-activated languages and in selecting the appropriate language. Regarding the underlying mechanism of bilingual language control for language selection, inhibitory control may serve an important role during the processes of bilingual language production and recognition. In the inhibitory control (IC) model proposed by Green (1998), the selection of the intended language in bilingual speech production is realised through the language task schemas to exert a top-down (domain-general) inhibitory control over the interference of the co-activated but competing lexical representations from the unintended language. Moreover, Green and Abutalebi (2013) proposed that bilingual speakers' demands in cognitive control may be adaptive to different interactional language contexts. For instance, more inhibitory control may be recruited when bilinguals are exposed to single- and dual-language contexts than to a dense code-switching context, because the latter context featuring a high frequency of language switching may constitute a more cooperative than conflictual relationship between the two languages, compared to the former two interactional language contexts.

Concerning bilingual visual word recognition, the theoretical model of bilingual interactive activation (BIA; Grainger and Dijkstra, 1992; van Heuven et al., 1998) suggests that the lexical input activates the two competing languages, and the lexical items in the non-relevant language are suppressed by receiving domain-general inhibitory control *via* language nodes (indicating language membership); in turn, the relevant language remains highly activated due to lexical features maximally corresponding to the input stimuli and is then selected. Nevertheless, the succeeding BIA+ (Dijkstra and van Heuven, 2002) and multilink models (Dijkstra et al., 2019) remove the role of inhibitory control and draw a distinction between the encapsulated word identification system and the task/decision system. Paap et al. (2019) have further proposed that active maintenance and selection of the relevant language can be sufficiently realised through an inhibitory mechanism that is part of the language processing system itself rather than through the recruitment of (domain-general) cognitive inhibitory control.

Regarding whether domain-general inhibition plays a central role in bilingual language process, a recent study by Bialystok and Craik (2022) provides an alternative account based on attentional control. It is argued that attentional control, namely, abilities to guide attention to the target stimulus, may be a better account for the underlying mechanism of bilinguals than inhibitory control which emphasises abilities to suppress the non-target distractor. It further suggests that no matter which domain-general control is involved, bilinguals only recruit domain-general control when the task demands an excessive amount of control abilities.

Language Control and Domain-General Control in Bilingual Language Recognition

Concerning the involvement of domain-general control mechanisms in bilingual language recognition, a growing number of studies (Blumenfeld and Marian, 2011; Blumenfeld et al., 2016; Freeman et al., 2017) have started to investigate the direct relationship between domain-specific (linguistic) control and domain-general control. Specifically, researchers have adopted the correlational approach, in which bilinguals' performance on a word recognition task (as an indication of bilingual language control) is compared to their performance on a non-verbal task (as an indication of domain-general control). For instance, Freeman et al. (2017) measured Spanish–English bilinguals' language recognition control with a priming version of a single-language (English) lexical decision task where an English auditory prime preceded the visual presentation of an English stimulus (word or a non-word), and participants were required to decide whether the stimulus was a real English word or not. When the auditory prime was a cognate (a word in English and Spanish with similarity in form [spelling and sound] and meaning), the non-target Spanish pronunciation was supposed to be highly activated. Therefore, if the succeeding

English non-word stimulus overlapped with this cognate prime in the phonological form (e.g., cognate prime 'stable' ['estable' in Spanish]; non-word stimulus: 'esteriors'), substantial cross-language competition might be elicited. It was found that a smaller Stroop effect (better cognitive control) was correlated with reduced cross-language interference (indexed by the difference between a non-word with phonological overlap with the preceding cognate prime and a non-word with no phonological overlap with the preceding cognate prime), elicited by phonological co-activation due to the presence of cognates.

Even if the non-target language is not being manipulated, as was the case in the study by Freeman et al. (2017) through manipulation of the cognate status of the target language, a domain-general contribution to bilingual language recognition in a single-language lexical decision task can be observed. Gangopadhyay et al. (2019) conducted an auditory version of a single-language (English) lexical decision task to measure language recognition control and two non-linguistic tasks (a flanker task as an indication of interference suppression at the stimulus level and a go/no-go task as an indication of response inhibition) to measure inhibitory control. The same set of linguistic and cognitive tasks were administered to bilinguals and monolinguals at two separate time points (i.e., years 1 and 2) with an interval of a year. At both years 1 and 2, better domain-general inhibition in the bilingual participants was associated with more accurate (but not faster) recognition processing of both words and non-words. Moreover, in the longitudinal analyses, it was found that higher overall accuracy (with both words and non-words) on the language task in year 1 may predict better inhibitory control in year 2.

Other studies have used a language switching paradigm to measure language control in the process of visual word recognition (e.g., Struys et al., 2019) and have compared performance on switch trials of these tasks with domain-general control. Using this methodology, Struys et al. (2019) proposed that sustained and proactive monitoring control indexed by overall performance in the Simon task was the driving mechanism underlying bilingual language recognition.

While these studies suggest domain-general cognitive involvement in language control, not all studies and tasks investigating the relationship between domain-specific and domain-general control have consistently found this involvement (for a review, see Calabria et al., 2018). The following section will explore the proposition by Anthony and Blumenfeld (2019) that these contradictory results may stem from unclear distinctions between bilinguals in terms of bilingual profiles. Language dominance is suggested to play a role in the degree of the link between linguistic control and cognitive control.

The Role of Language Dominance in Cross-Domain Overlap

There is some evidence that bilinguals with high proficiency in an L2 perform more efficiently compared to L1-dominant bilinguals in language control (e.g., Anthony and Blumenfeld, 2019) and domain-general cognitive control (e.g., Tse and Altarriba, 2015). These findings suggest that when L2 proficiency increases, bilinguals more easily obtain access to L2 lexical–semantic representations. This finding can be theoretically explained by the BIA model (Grainger and Dijkstra, 1992; van Heuven et al., 1998). With respect to bilingual language recognition, the BIA model proposes that language recognition is characterised by a bottom-up activation of the interactive network of lexical representations from two languages; therefore, the process of word identification is highly dependent on the resting-level activation or initial strength of lexical activation at rest. The language in which the bilingual is highly proficient possesses a greater initial strength in activation than the less-dominant language, indicating that when L2 proficiency rises, bilingual language recognition in bilinguals with high L2 proficiency may differ from the same process in bilinguals with low L2 proficiency. A series of language recognition studies using the masked translation priming paradigm demonstrated that for bilinguals with high proficiency in L2, the non-target language (L2) translation equivalent of the target language (L1) was found to facilitate lexical identification in the target L1, whereas L1-dominant bilinguals showed no or only a limited priming effect in the L2–L1 direction (Basnight-Brown and Altarriba, 2007; Perea et al., 2008; Dunabeitia et al., 2010; Wang, 2013; Nakayama et al., 2016; but see Lee et al., 2018).

The role of language dominance in bilingual recognition control is also shown in studies using a language comprehension version of the language switching paradigm in which words are visually presented, with a distinction between repeat trials (two consecutive trials in the same language) or switch trials (the prior and succeeding trial in different languages; for a review, see Declerck and Philipp, 2015). It is proposed that if bilingual recognition control recruits inhibitory control, the dominant language may need to be highly inhibited when words are presented in the non-dominant language; it may then require a higher cost to reactivate the dominant language than the non-dominant language when it was previously the non-target language. Some studies (e.g., Litcofsky and van Hell, 2017; Mosca and de Bot, 2017) have shown that language dominance has an impact on the degree or nature of bilingual recognition control in that larger switch costs existed when switching into the L1-dominant language than into the less-dominant L2. Bultena et al. (2015) indicated that the degree of cost when switching into an L2 was related to the level of L2 proficiency. However, other studies have reported symmetrical costs between switching into a strong L1 and weak L2 (Thomas and Allport, 2000; Macizo et al., 2012; Struys et al., 2019). This absence of a language dominance effect may suggest that language dominance plays a limited role in language recognition control.

A moderating role of language dominance on the connection between bilingual language and domain-general cognitive control can be deduced, therefore, from the difference in linguistic performance between proficient or non-proficient bilinguals. However, despite this indirect evidence, few studies have sought direct evidence of the role of language dominance in the cross-domain relationship—that is, the effect of language dominance on the direct correlation between linguistic and non-linguistic performance. More research is needed on the effect of language dominance in this respect.

Effect of Sociolinguistic Context on Language or Cognitive Control

Another factor that may have an impact on the overlap between domain-specific and domain-general control mechanisms is the sociolinguistic context to which bilingual individuals are exposed. According to the adaptive control hypothesis (Green and Abutalebi, 2013), bilingual language control mechanisms adapt to various patterns of language use, which may be related to the sociolinguistic context of bilingual interaction. Bosma and Blom (2019) found that bilinguals in a sociolinguistic context with a minority (L1) and majority (L2) language pair can experience considerable adaptability in language control. A majority language has a predominant status in a wide range of interactional language contexts, whereas a minority language typically has a less official status, is restricted to a few interactional contexts (mostly at home in family settings) and is exclusively spoken by indigenous people or immigrants in that region. Because of these differences in status, lexical or grammatical insertions from the majority language into the minority language occur much more frequently than from the minority into the majority language (Couto and Gullberg, 2019). This linguistic phenomenon has an effect on the recruitment of cognitive control networks. Regarding the modality of language production, Bosma and Blom demonstrated that when a conversation was initiated in the L2 majority language (i.e., limited switching into the minority language at the sociolinguistic level), inhibitory control was required to maintain the separation of two languages; however, in the other language direction (speaking an L1 minority language initially where the mixing of two languages is allowed and lexical representations in either language can freely be selected in the production stage), no inhibitory control was involved. The extent to which this minority/majority language sociolinguistic effect on cognitive control can be found in the modality of language recognition still needs further exploration.

Tao et al. (2017) provided further evidence for the effect of sociolinguistic environment on domain-general control in a study of Dai (a minority language spoken by ethnic Dai)–Chinese bilinguals. A composite task, comprising an adapted version of a Simon and Stroop task, was adopted to measure attentional control (attending to the interference at the stimulus level when the non-target picture was not semantically related to the target word) and inhibitory control (suppressing the interference at the response level when the position of the non-target stimulus was incongruent with the response key). By considering the effect of language proficiency, the study found that in the L1-minority language block, the highly proficient bilinguals performed better than the non-proficient bilinguals in sustainable attentional control to monitor stimulus-level interference, while in the L2-majority language block, highly proficient bilinguals performed better in inhibitory control than non-proficient bilinguals. These studies offer strong evidence that the sociolinguistic environment may contribute to differences in the domain-general contribution to L1 and L2 word recognition. However, to our knowledge, no study has yet focused on the moderating effect of language dominance on the connection between bilingual recognition and domain-general control in a specific sociolinguistic context, with a dominance shift over time from the minority to the majority language.

Linguistic Context of the Present Study

The aim of the present study is to explore the role of bilingual language dominance in the interconnection between bilingual word recognition and non-linguistic cognitive control skills in the asymmetrical sociolinguistic context of the Xinjiang Uyghur Autonomous Region (Xinjiang) in China, with Uyghur (minority L1)–Chinese (majority L2) bilinguals as participants. The Uyghur language is the indigenous language of the region and has an official status at all societal levels, from the informal community context to the formal domains of administration, education and social media (Ma, 2009). The Chinese language (or Standard Chinese) is the national language used among all ethnic groups and in all regions in China. In terms of language typology and script systems, the two languages are very distinct. The Uyghur language, as a member of the Altaic language family, is a phonographic language written in a version of the Arabic alphabet, while the Chinese language, belonging to the Sino-Tibetan language family, is a logographic language written in characters composed of strokes.

Diversity exists within the sociolinguistic context in which Uyghur–Chinese bilinguals acquire or use their two languages, particularly regarding their educational background (Ma, 2009; Guo and Gu, 2018). In the formal educational context, Uyghur individuals are able to attend bilingual education schools (i.e., ethnic minority schools or minority/majority joint schools) or Chinese-medium schools. Uyghurs can develop varying degrees of language proficiency, depending on the educational tracks they opt for. For instance, a Uyghur may transfer between distinct education trajectories when they achieve the required academic and language abilities; for example, they may attend bilingual education schools with both Uyghur and Chinese during primary-level instruction and then switch to the track of Chinese-medium schools at the secondary level or vice versa (Ma, 2009). Recent studies on the informal communication context have shown that even though the Uyghur language might play a dominant role in private communication, young Uyghurs with prolonged experience in using Chinese as a language of instruction tend to engage in language switching or mixing with high frequency, particularly when interacting with their siblings and friends (Masut, 2014; Guo and Gu, 2018). In terms of reading, Masut (2014) found that at least 50% of Uyghurs who had attended Chinese-medium schools opted for the exclusive use of Chinese in reading news (either online or through newspapers), magazines and books. Given that sociolinguistic context is critically relevant to individual language proficiency (de Houwer, 2018), it can be inferred that these variations in educational background in the minority–majority sociolinguistic context may result in large intra-group differences in language dominance for Uyghur–Chinese bilinguals.

Research Questions and Hypotheses of the Current Study

In the present study, the first objective is to explore whether the different degrees of bilingual language dominance in Uyghur–Chinese bilinguals affect visual word recognition. A single-language lexical decision task is employed as this is the most extensively used task for measuring word recognition (Libben and Jarema, 2002). Stimuli in this task are presented only in one language to resemble the activity of real-life reading. Given that BIA model proposes that as language proficiency in one language increases, that language may become highly activated during word recognition, we hypothesise that if language dominance may have an impact on bilinguals' performance of word recognition in the single-language context, the more dominant the language is for bilinguals, the faster and the more accurate they are in recognising words (or non-words) in that language. However, we expect that the minority–majority bilingual context would constitute an asymmetry in language use for the study participants and that language dominance may be dynamically adapted to this language environment, with continuous exposure to the predominant language changing the relative strength of the two languages (Montrul, 2015; Silva-Corvalán and Treffers-Daller, 2015). Moreover, because language dominance tends to be dynamic in nature, in that distinct language skills or tasks may reflect varying degrees of language dominance (Bahrick et al., 1994; Treffers-Daller, 2015), global (across-modality) language dominance may not fully represent the dynamic feature of language dominance in each language modality. Following this line of thought, it is possible that in the word recognition task, bilinguals who have experienced dominance shift over time from their L1 to their L2 will show faster L2 word recognition. It is also worthwhile examining the relationship between language experience and language control performance as previous studies have demonstrated the effects of short-term language exposure (Bonfieni et al., 2019; Struys et al., 2019) and the age of L2 acquisition (the initial point of long-term L2 exposure) in the language control mechanism (Bonfieni et al., 2019; Sulpizio et al., 2020). We expect factors related to language experience to contribute to language recognition in the L1 or L2 word recognition process.

The second research objective is to investigate the extent to which the variable of language dominance may have an impact on the relationship between domain-specific and domain-general control. In our study, language control is assessed by the lexical decision task, and domain-general cognitive control is examined by a stimulus–stimulus (i.e., the flanker task) compatibility task (Kornblum et al., 1999). The reason for using the stimulus–stimulus cognitive task is that word recognition is a bottom-up process in which bilinguals need to recognise the target word (input stimulus) from the co-activated lexical candidates that share similarity with the target word (interference rising at the stimulus level or word identification). Therefore, analogous to bilingual word recognition, the flanker effect is generated by an overlap between two conflicting dimensions at the stimulus (input) level—that is, the direction of the surrounding arrows (non-target stimulus) and the direction of the central target stimulus. Due to the shared stimulus–stimulus mechanism, we expect the flanker effect to be a proper indication of the inhibitory control mechanisms related to interference suppression that may be involved in word recognition.

Moreover, the flanker task can serve a dual purpose in that it yields measures of inhibitory control and conflict monitoring control, indexed by overall performance (across trial type; Costa et al., 2009; Singh and Mishra, 2013; Struys et al., 2019; Chan et al., 2020), which suits the present study's examination of both forms of control. Previous studies have revealed a link between auditory comprehension and inhibitory control (e.g., Blumenfeld et al., 2016). Struys et al. (2019) complemented these findings by examining domain generality in visual word recognition, observing that domain-general monitoring was a potential underlying mechanism in bilingual language control. Therefore, it is reasonable to assume that domain-general monitoring control may be relevant for bilingual language recognition.

In the present study, we are interested in the possible contribution of domain-general control mechanisms to various processes related to word recognition in bilinguals, with attention paid to three aspects. The first aspect is the recognition processes of L1 and L2 real words. These measures represent recognition processes by which the identification of the real word can be achieved without a full analysis of the stimulus. The cohort model of word recognition (Marslen-Wilson and Welsh, 1978) proposes that for existing words, the word is recognised once the point of uniqueness is reached because it matches a trace in the mental lexicon and can be retrieved before the full unit-by-unit analysis of the entire word. The second aspect is the underlying mechanisms of the L1 and L2 non-word effect, which reflect the efficiency of lexical rejection, where the identification of the non-existing word requires a full analysis of the stimulus due to the absence of any trace of the non-word that can be retrieved in the mental lexicon. The third aspect is global performance in the word recognition task, which represents overall lexical processing ability while recognising words and rejecting non-words. Based on the theory of BIA model indicating the presence of inhibitory control in the language recognition process, as well as on recent empirical research (e.g., Struys et al., 2019) showing the involvement of monitoring control in language recognition, we expect inhibition and monitoring to be the two underlying mechanisms that suppress interference from possible across- and within-language competitors to the presented words or non-words. That is, we hypothesise that word recognition measured by L1 and L2 word conditions, the non-word effect or the global performance in the language task overlaps with domain-general inhibitory control, indexed by the flanker effect, and with domain-general monitoring control, measured by overall flanker performance.

By taking into consideration the effect of language dominance, we predict that the varying degrees of language dominance elicited in a minority and a majority language context may lead to different patterns of cross-domain generality. Specifically, previous studies (e.g., Costa et al., 2009) have shown that bilinguals with high proficiency in an L2 demonstrated a greater performance in monitoring control compared to monolinguals, especially in a highly demanding context with a comparable probability of encountering a congruent trial and an incongruent trial. It is logical to expect that as the L2 proficiency increases, bilinguals will switch from relying primarily on reactive control to relying primarily on proactive control to address a demanding language competition in which two languages with equal strength and degrees of activation interfere significantly with each other when one language is the target and the other is not. Therefore, we expect bilinguals with higher proficiency (or even dominance) in the L2 to have experienced more demanding language management than those who have maintained unchanging L1 dominance and may consequently have a great dependency on recruiting monitoring control.

The minority/majority sociolinguistic context may generate potential differences in the recruitment of the underlying mechanisms between the L1 and L2. Specifically, the single-language context of the majority L2 may elicit the recruitment of inhibitory control to avoid (sociolinguistically) unwanted intrusions from the L1, while the use of the L1 minority language involves no or limited inhibition of the L2 majority language. Therefore, we expect domain-general inhibitory control to be exploited exclusively in the L2 context. Moreover, considering the effect of language dominance, we further expect that when bilinguals are more dominant in the L1 minority language, a great reliance on inhibitory control may occur to suppress the interference of the dominant L1 in the L2 context.

MATERIALS AND METHODS

Participants

Seventy bilinguals (average age = 19.64 years, SD = 1.41; males = 24, females = 46) were recruited as participants. All participants granted informed consent preceding participation in the empirical tasks. The participants spoke Uyghur as their native language and Chinese as their second language and were undergraduate students from a Chinese-medium university in the city of Xi'an in China. All participants were native speakers of the Uyghur language, because they all firstly acquired the language of Uyghur from birth and reported having spoken that language exclusively with their parents; they all acquired Chinese as the second language on average at the age of 6 in the kindergarten or school context. As reviewed in the previous section, the divergent education trajectories of Uyghurs and their different patterns of language use in the informal communicative context may have led to varying degrees of language dominance.

Language Background LEAP-Q

To further evaluate their language dominance, participants were asked to fill in an adapted version of the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007) to assess their language backgrounds (see **Table 1**). All 70 participants reported that their three languages (Uyghur, Chinese and English) were acquired sequentially, and all participants acquired the same L1 (Uyghur) and L2 (Chinese). The Uyghur–Chinese bilinguals showed a significant difference [t (69) = 7.64, $p < 0.001$] in each language concerning self-evaluated overall language proficiency on an 11-point (from 0 to 10 with 0 included) scale. The average overall proficiency score for L1-Uyghur (M = 8.99, SD = 1.11) was higher than for L2-Chinese (M = 7.87, SD = 1.29). However, participants self-evaluated no significant difference [t (69) = 1.00, p = 0.321] in their preference for language use between using the L1 (M = 48.30%, SD = 15.40) and L2 (M = 45.00%, SD = 13.4). Concerning the participants' self-evaluated scores specifically related to reading preference, L2-Chinese (M = 49.50%, SD = 14.77) was chosen significantly more frequently [$t(69) = -2.14$, $p < 0.05$] than L1-Uyghur (M = 41.71%, SD = 17.02) for reading a book, but participants still self-reported that their reading skill for the L1 (M = 9.01, SD = 1.28) was higher than for the L2 (M = 8.03, SD = 1.38), $t(69) = 6.33$, $p < 0.001$. This might suggest that in the actual reading activity, participants had the sense that they more frequently used the L2 as a preferred reading language than the L1, but this potential dominance shift over time in reading was not fully reflected in their scores for self-reported reading skill. Furthermore, a closer examination of language proficiency at the individual level of bilinguals showed a pattern of higher proficiency in L2 than L1. This proficiency pattern accounted for 41% of bilingual participants in terms of self-reported overall language proficiency (across skills). Moreover, the same pattern of higher proficiency in L2 than in L1 occurs in 43% of bilingual participants in self-evaluating their writing proficiency, 41% in reading proficiency, 40% in speaking proficiency and 40% in listening proficiency.

In the present study, the self-assessment data of language proficiency and language use preference in each language were

TABLE 1 | Language background and language dominance information of bilingual participants.

	Uyghur-Chinese bilinguals (*N* = 70)
Age	19.64 (1.41)
Male/Female	24/46
IQ	46.51 (5.21)
L1 recent exposure[1]	47.80% (14.48)
L2 recent exposure	40.71% (12.61)
Age of L2 acquisition	6.14 (2.23)
L1-Uyghur proficiency[2]	8.99 (1.11)
L2-Chinese proficiency	7.87 (1.29)
L1-Uyghur use preference (in %)	48.30% (15.40)
L2-Chinese use preference (in %)	45.00% (13.4)
L1-Uyghur strength (composite score)[3]	55.90 (11.90)
L2-Chinese strength (composite score)	50.90 (11.80)
Index of dominance[4]	4.99 (19.20)
Final dominance score (z-score of index of dominance)[5]	0 (1)

[1]*Participants self-evaluated their recent language exposure in percentages. The L1 and L2 language exposure did not add up to 100%, because a third language was also reported in the questionnaire.*
[2]*Participants self-reported language proficiency range from 0 (low proficient) to 10 (high proficient) on an 11-point Likert-scale for each literacy skill.*
[3]*Language strength is the sum of 4 self-reported scores for language proficiency and 3 self-reported scores for language use preference (transformed).*
[4]*Index of dominance was the difference score between L1-Uyghur strength and L2-Chinese strength (subtracting L2-Chinese strength from L1-Uyghur strength).*
[5]*Final z-score of index of dominance ranged from −2.24 to 2.71 with a mean of 0.*
Mean values and standard deviations (in parentheses) are presented.

integrated into one index for each language. Previous studies (Grosjean, 2015; Silva-Corvalán and Treffers-Daller, 2015; Caffarra et al., 2016) have indicated that language dominance is a complex composite that is related to the variation among bilingual individuals in their preferred language across different contexts. Therefore, in addition to language proficiency, language use preference, reflecting an individual's attitude towards the actual use of each language, can be considered as a meaningful component of language dominance. This method of using language skill and use preference to measure language dominance has been performed in a previous study (Wu and Struys, 2021). Language proficiency in the dominance measure was a self-evaluated score based on a scale from 0 to 10 for each language skill and for each language. Language use preference was self-rated using percentages to indicate what percentage of each language (i.e., L1, L2, and L3) could be used in a specific scenario, such as reading a book, engaging in a conversation and writing a letter, with the sum of the preference percentages for the three languages equalling 100% for each scenario. For example, in the case of reading a book, a respondent might show a preference for spending 50% of the time reading in the L1, 45% in the L2 and the remaining 5% in the L3.

To better integrate the two elements into the dominance measure, the scale needed to be unified, with the preference percentage data transformed into a score on the same scale as language proficiency. The interconnection between the two sets of values is that language preference evaluated in each linguistic context corresponds to the respective skills in each language, such as reading a book, having a conversation (involving listening and speaking) and writing a letter. A three-step procedure for obtaining the composite score for each language was followed. First, the proficiency score for the three languages in terms of a specific literacy skill was added; for example, a bilingual participant's reading skills evaluated as 9 for the L1, 8 for the L2 and 4 for the L3 yielded a sum score of 21 for reading. Second, the preference percentage relevant to that literacy skill was multiplied with the sum score of that skill; for instance, if the same bilingual reported the preference of reading a book in the L1 as 50%, in the L2 as 45% and in the L3 as 5%, the language preference percentage in relation to reading would be transformed into scores of 10.5 (21*50%) for the L1, 9.45 (21*45%) for the L2 and 1.05 (21*5%) for the L3. Subsequently, following this method, each language had three transformed scores to indicate the participant's preference in using that language for reading a book, having a conversation and writing a letter. Each language was also assigned four proficiency scores based on two productive and two receptive language skills. In total, a bilingual possessed seven scores for each language. Third, the overall strength of each language was indexed using a composite score obtained by adding all seven scores from proficiency and preference. In the following step to calculate language dominance, the measurement of language dominance for each participant was operationalised according to the two-step method proposed by Treffers-Daller and Korybski (2015). The first step was to represent the index of language dominance by subtracting the composite score of Chinese (L2) from that of Uyghur (L1). Second, a standardised dominance score was obtained by converting the index of dominance into a z-score. This final dominance score of the Uyghur–Chinese bilinguals ranged from −2.24 to 2.71, with a mean of 0. In this continuous scale of dominance score, bilinguals' final score of more approximate to or above +1 means higher L1 dominance, while the final score of more approximate to or below −1 means higher L2 dominance.

Designed Tasks and Procedure

All 70 participants took part individually in a lexical decision task, a flanker task and a non-verbal Intelligence Quotient (IQ) test sequentially, with short breaks between each task. A block of practice trials was provided for participants to familiarise themselves with the task requirements before the actual execution of each task. The data for all tasks were collected using a Macbook Pro laptop with a 15.4-inch screen. The programming languages HTML 5 and JavaScript were used for the stimulus design and presentation, and the tasks were presented on a Google Chrome browser. The MySQL database was utilised to record data collected for all the tasks.

Raven's Progressive Matrices

Intelligence was tested due to its close relationship with cognitive control (Arffa, 2007). IQ was evaluated using the standard version of Raven's Progressive Matrices (Raven, 1938), a non-linguistic IQ test that focuses on metacognitive problem-solving and deductive ability and consists of 60 matrices in five blocks (12 matrices for each), which are arranged on an increasing scale of difficulty. The maximum score for the test is 60 points, with one point gained for the correct answer to one matric. The average IQ score for all 70 participants was 46.51 ($SD = 5.21$).

Lexical Decision Task

A visual version of a language-specific (single-language) lexical decision task (Meyer and Schvaneveldt, 1971) was adopted in the present study. Two lexical decision tasks were administered (one in L1-Uyghur and another in L2-Chinese), each containing stimuli of words and non-words in the respective language. Given that lexical decision tasks are sensitive to the effects of word frequency and length (de Groot et al., 2002), these factors were taken into account during the selection of real words from the two languages. The Chinese words were selected from the Character Frequency List of Modern Chinese (Da, 2005), while the Uyghur words were high-frequency words from the unpublished raw data of modern Uyghur words collected from Uyghur websites, newspaper and magazine articles (Abliz, 2015, Unpublished data). Using Zipf-frequency scores (van Heuven et al., 2014) as an index of word frequency for the two languages, the Chinese word stimuli ($M = 5.81$, $SD = 0.35$) were comparable [t (94) = −1.42, $p = 0.160$] with the Uyghur word stimuli ($M = 5.94$, $SD = 0.53$). In light of the differences between alphabetical and logographical languages, word length across languages was matched as follows: one Uyghur word was composed of four to six letters with one- (e.g., دوست, /dost/, meaning 'friend' in English) or two syllables (e.g., كىتاب, /kitab/, meaning 'book' in English), while one Chinese word consisted of a single-component character (e.g., 半, /ban/, meaning 'half' in English) or a two-radical component character (e.g., 加, /jia/, meaning 'plus' in English) with five to seven strokes. Uyghur non-words (four to six letters) were created by randomly using consonants (C) and vowels (V) to form a non-existent composite that violated the syllable structure of CV(C)(C), while Chinese non-words (five to seven strokes) were generated by randomly combining radicals into a non-existent character with the radicals placed incorrectly. Non-words in each language were checked by native speakers of that language to verify that they were non-words. The complete word and non-word stimuli lists are provided in Appendix 1 in Supplementary Data.

The total number of stimuli in each language block was 96 trials, of which 48 were words and 48 non-words. Participants responded to the trials with keyboard presses; they were instructed to press A for real words and L for non-words. Experimental instructions were given in the Chinese language. All the participants were tested with the same order of the Chinese lexical decision task preceding the Uyghur one. All stimuli were presented in random order, and a fixation cross (1,000 ms) was presented prior to a blank interval (250 ms) and the stimulus itself. Each stimulus was presented in black ink on a white background screen and was terminated after a response or lasted for 2000 ms in the absence of a response.

Flanker Task

A series of five arrows with exactly the same distance between each arrow was the stimulus in the flanker task (Eriksen and Eriksen, 1974). Participants were instructed to respond to the direction (leftward or rightward) of the central arrow by pressing the left key (A on the keyboard) or right key (L on the keyboard) and to ignore the direction of the distractors or surrounding arrows. In a congruent trial, the direction of the central arrow was the same as that of the flanker arrows, while in a neutral trial, the flanker arrows were straight lines with no direction (e.g., — —→— —). The total number of trials was 126, and all trial types were equally distributed across the entire task (42 congruent, 42 neutral and 42 incongruent). The proportion of each direction was equal (e.g., 21 trials for left pointing and 21 for right pointing in the congruent trial). The stimuli were presented randomly, and each stimulus appeared after a fixation (500 ms), followed by a blank interval (250 ms). The stimulus was on display until participants responded to it or for a maximum of 2,500 ms.

Analyses

The response times (RTs) of the correct responses and accuracy rates (proportion of correct responses to the total number of trials) from the linguistic and cognitive tasks were included in the analyses. In each task, data trimming was conducted for each participant, with RTs deviating more than 2.5 *SD* from the mean across all correct trials and RTs lower than 300 ms or greater than 1,500 ms excluded (Kaandorp et al., 2017). In the lexical decision task, 3.60% of the data (467 out of 12,986 trials) were eliminated, and 2.29% of the data (199 out of 8,685 trials) in the flanker task were excluded.

RESULTS

The accuracy and RTs data were analysed using mixed logistic regression models (Jaeger, 2008) and linear mixed effects regression models (Baayen et al., 2008), respectively. Follow-up regression analyses were used to assess the significant interaction effect by examining each level of the combinations of the related variables (Gollan and Goldrick, 2016). Sum coding was conducted when the fixed predictors in the model were categorical variables, such as Language. For instance, the categorical variable Language was contrast-coded by assigning −0.5 for Chinese, and + 0.5 for Uyghur (Schad et al., 2020). Through sum coding, the categorical variables were centred, and the main effect of each variable was properly tested. As the continuous variable Language Dominance was composed of standardised *z*-scores centred at 0, no further coding treatment was performed. Significance was evaluated by model comparisons. The chi-square statistics from the Type III sum of squares analysis were an indication of significance (Zahn, 2010). All statistical analyses were conducted in version 3.6.3 of the software R (R Core Team, 2020) with the packages of versions 1.1–21 lme4 (Bates et al., 2015) and 3.1–1 lmerTest (Kuznetsova et al., 2017).

Lexical Decision Task

The individual data for accuracy rates (descriptive statistics shown in **Table 2**) were analysed using a logistic regression model. The two categorical predictors Word Type and Language, and the continuous variable Language Dominance were fit into the model as the fixed predictors. To properly model the random effects, the variables Subjects and Word Items were integrated into the model as intercept random effects (Barr et al., 2013). Concerning the sum coding for the two categorical variables Word Type and Language, the value assignment for Word Type was −0.5 for non-word and + 0.5 for word; for Language, it was −0.5 for Chinese and + 0.5 for Uyghur.

TABLE 2 | Mean accuracy rates in percentage (%), mean response times (ms) of correct trials and the 95% confidence intervals (CI) from the lower bond to the upper bond for the lexical decision task by Word Type and Language.

	Accuracy rates		Response times	
	Mean	**95% CI**	**Mean**	**95% CI**
Non-word Uyghur	96.42	95.21–97.33	872	854–890
Word Uyghur	97.02	95.98–97.79	854	836–872
Non-word Chinese	98.71	98.13–99.11	780	762–798
Word Chinese	99.36	99.02–99.58	769	751–787

A summary of the results for the accuracy logistic model is provided in **Table 3**. The results reveal a significant main effect of Word Type [see **Figure 1**; $\beta = 0.45$, $SE\ \beta = 0.15$, $\chi^2 (1) = 9.17$, $p < 0.01$], with less accurate responses in the non-word trials ($M = 97.84$, *95% CI* = 97.21–98.33%) than to word trials ($M = 98.61$, *95% CI* = 98.09–98.99%). A significant main effect of Language was also found [$\beta = -1.30$, $SE\ \beta = 0.15$, $\chi^2 (1) = 79.55$, $p < 0.001$], showing that more accurate responses were present in the L2 Chinese ($M = 99.09$, *95% CI* = 98.77–99.32%) than in the L1 Uyghur ($M = 96.73$, *95% CI* = 95.71–97.52%). Other effects were non-significant and can be found in **Table 3**.

For the RT analyses, the same fixed predictors and random factors used in the models for the accuracy scores were fit into the linear regression model. The output of this RT model is summarised in **Table 4**. The results showed a significant main effect of Word Type ($\beta = -14.94$, $SE\ \beta = 2.71$, $\chi^2 (1) = 28.64$, $p < 0.001$), with bilinguals responding more slowly to non-words ($M = 826$ ms, *95% CI* = 809–843 ms) than words ($M = 811$ ms, *95% CI* = 794–829 ms). A significant main effect of Language was found ($\beta = 88.07$, $SE\ \beta = 2.67$, $\chi^2 (1) = 1089.04$, $p < 0.001$) as response times to the L1 Uyghur ($M = 863$ ms, *95% CI* = 845–880 ms) were longer than to the L2 Chinese ($M = 775$ ms, *95% CI* = 757–792 ms). A significant interaction was found between Word Type and Language Dominance [$\beta = 7.28$, $SE\ \beta = 2.19$, $\chi^2 (1) = 11.02$, $p < 0.001$]. The follow-up regression model demonstrated that as bilinguals showed the self-reported overall language dominance shift (over time) into L2, the difference in response latencies between words and non-words becomes greater for both languages [$\beta = 6.82$, $SE\ \beta = 2.28$, $\chi^2 (1) = 8.95$, $p < 0.01$]. Moreover, Language and Language Dominance significantly interacted [$\beta = -35.44$, $SE\ \beta = 2.19$, $\chi^2 (1) = 260.78$, $p < 0.001$]. The follow-up regression model showed that bilinguals recognised the Chinese language significantly faster [$\beta = 18.94$, $SE\ \beta = 9.25$, $\chi^2 (1) = 4.19$, $p < 0.05$] when they were more dominant in L2 Chinese, but no effect of dominance in the L1 was found on response times to the Uyghur language [$\beta = -17.04$, $SE\ \beta = 11.83$, $\chi^2 (1) = 2.08$, $p = 0.150$]. Other main or two-way interaction effects were non-significant and can be found in **Table 4**.

However, there was a significant three-way interaction (see **Figure 2**) between Word Type, Language and Language Dominance [$\beta = 11.60$, $SE\ \beta = 4.39$, $\chi^2 (1) = 6.99$, $p < 0.01$; see **Table 2** for descriptive statistics]. The follow-up regression models at each level of the four combinations of Word Type and Language revealed that when bilinguals had a higher dominance in the L2, they were able to recognise Chinese words significantly faster [$\beta = 19.76$, $SE\ \beta = 9.63$, $\chi^2 (1) = 4.21$, $p < 0.05$] and reject Chinese non-words marginally significantly faster [$\beta = 18.27$, $SE\ \beta = 9.46$, $\chi^2 (1) = 3.73$, $p = 0.053$]. The rejection of Uyghur non-words [$\beta = -24.34$, $SE\ \beta = 12.41$, $\chi^2 (1) = 3.84$, $p < 0.05$] was significantly faster when bilinguals were more dominant in the L1, whereas no significant effect of Language Dominance was found in recognising Uyghur words [$\beta = -10.50$, $SE\ \beta = 12.30$, $\chi^2 (1) = 0.73$, $p = 0.393$].

Flanker Task

The descriptive statistics for performance for the flanker task are given in **Table 5**. The accuracy data were analysed using a logistic model composed of the fixed predictors Stimulus Type and Language Dominance and the random factors of Subjects. For the sum coding for Stimulus Type, different sets of values were assigned to congruent trials (0.5, 0), neutral trials (−0.5, −0.5) and incongruent trials (0, 0.5). As the variable Stimulus Type was composed of three levels, pairwise comparisons were also used to demonstrate the contrasts between each level of the variable. The findings showed a significant main effect of Stimulus Type [$\chi^2 (2) = 88.92$, $p < 0.001$]. The pairwise comparisons revealed that the flanker effect was significant, with higher accuracy scores in congruent conditions ($M = 99.72$, *95% CI* = 99.46–99.86%) than in incongruent conditions ($M = 96.71$, *95% CI* = 95.84–97.41%), $\beta = 2.51$, $SE\ \beta = 0.35$, $z = 7.17$, $p < 0.001$, as well as that the accuracy performance in neutral trials ($M = 99.39$, *95% CI* = 99.46–99.86%) was the same as in congruent trials ($\beta = 0.80$, $SE\ \beta = 0.41$, $z = 1.97$, $p = 0.119$) but more accurate than in incongruent trials ($\beta = -1.71$, $SE\ \beta = 0.25$, $z = -6.91$, $p < 0.001$). Neither a main effect of Language Dominance nor an interaction between Stimulus Type and Language Dominance ($ps > 0.458$) was found.

The regression model of the RTs adopted the same fixed predictors and random factors and found a significant main effect for Stimulus Type [$\chi^2 (2) = 1417.20$, $p < 0.001$]. The pairwise comparisons showed that bilinguals responded to neutral trials

TABLE 3 | Results of logistic mixed effects model on accuracy data in the lexical decision task.

	Model summary			Model effect significance		
	β	$SE\ \beta$	z	χ^2	df	p
Fixed effects						
(Intercept)	4.04	0.13	31.09	**966.29**	**1**	**<0.001**
Word Type	0.45	0.15	3.03	**9.17**	**1**	**<0.01**
Language	−1.30	0.15	−8.92	**79.55**	**1**	**<0.001**
Dominance	0.03	0.09	0.35	0.12	1	0.724
Word Type * Language	−0.52	0.29	−1.76	3.08	1	0.079
Word Type * Dominance	−0.08	0.13	−0.66	0.44	1	0.508
Language * Dominance	0.14	0.13	1.16	1.34	1	0.248
Word Type * Language * Dominance	0.15	0.25	0.60	0.36	1	0.550

Language Dominance is shortened as Dominance. Significant differences are presented in bold.

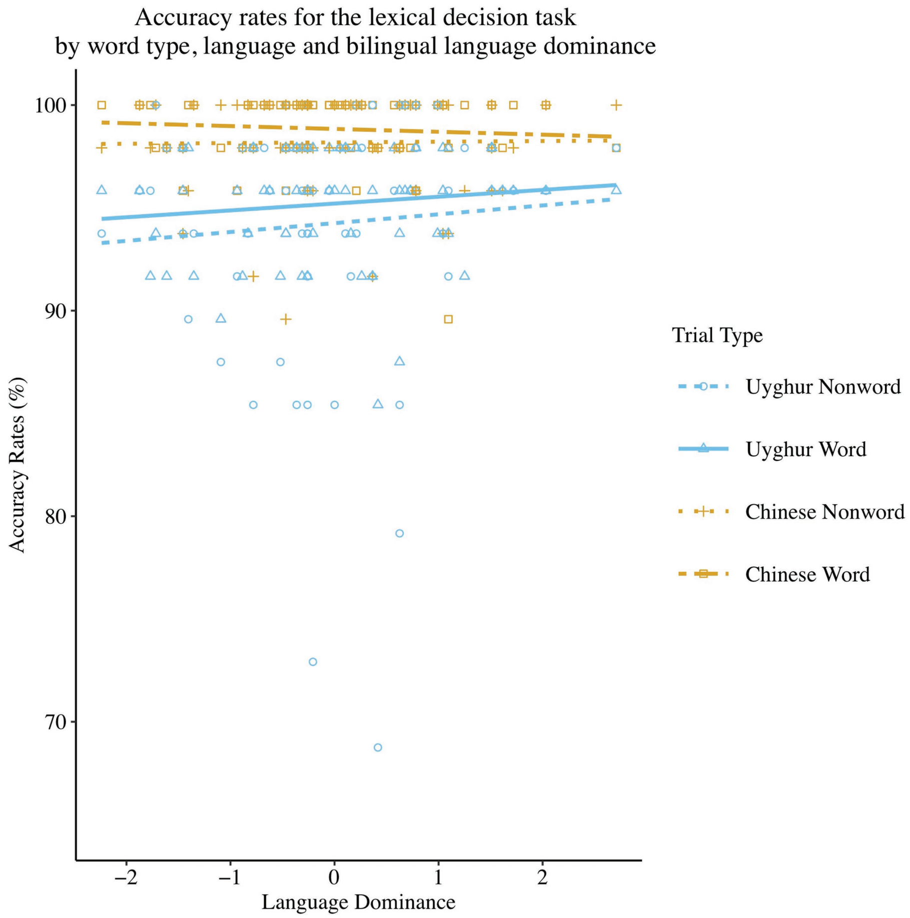

FIGURE 1 | Scatterplot and regression fit lines demonstrating the relationship between Language Dominance and mean accuracy at all the combinations of variables of Language and Word Type in the lexical decision task. The score on the x-axis closer to or above +1 means a higher dominance in L1, while the score closer to or below −1 means a higher dominance in L2.

TABLE 4 | Results of linear mixed effects regression model on response times in the lexical decision task.

	Model summary			Model effect significance		
	β	***SE*** β	***t***	χ^2	**df**	***p***
Fixed effects						
(Intercept)	818.70	8.84	92.57	**8569.63**	**1**	**<0.001**
Word Type	−14.49	2.71	−5.35	**28.64**	**1**	**<0.001**
Language	88.07	2.67	33.00	**1089.04**	**1**	**<0.001**
Dominance	1.09	8.75	0.12	0.02	1	0.901
Word Type * Language	−7.16	5.38	−1.33	1.77	1	0.183
Word Type * Dominance	7.28	2.19	3.32	**11.02**	**1**	**<0.001**
Language * Dominance	−35.44	2.19	−16.15	**260.78**	**1**	**<0.001**
Word Type * Language * Dominance	11.60	4.39	2.64	**6.99**	**1**	**<0.01**

Language Dominance is shortened as Dominance. Significant differences are presented in bold.

($M = 667$ ms, *95% CI* $= 647–687$ ms) significantly faster than congruent ($M = 681$ ms, *95% CI* $= 661 – 701$ ms), $\beta = 13.80$, $SE\ \beta = 2.18$, $t = 6.33$, $p < 0.001$ and incongruent trials ($M = 746$ ms, *95% CI* $= 726–766$ ms), $\beta = 78.60$, $SE\ \beta = 2.22$, $t = 35.42$, $p < 0.001$. A flanker effect was found in that the response speed to incongruent trials was significantly slower than to congruent trials ($\beta = 64.80$, $SE\ \beta = 2.22$, $t = -29.21$, $p < 0.001$). The results showed the absence of a main effect for Language Dominance and no interaction effect between these two factors of Stimulus Type and Language Dominance ($ps > 0.144$).

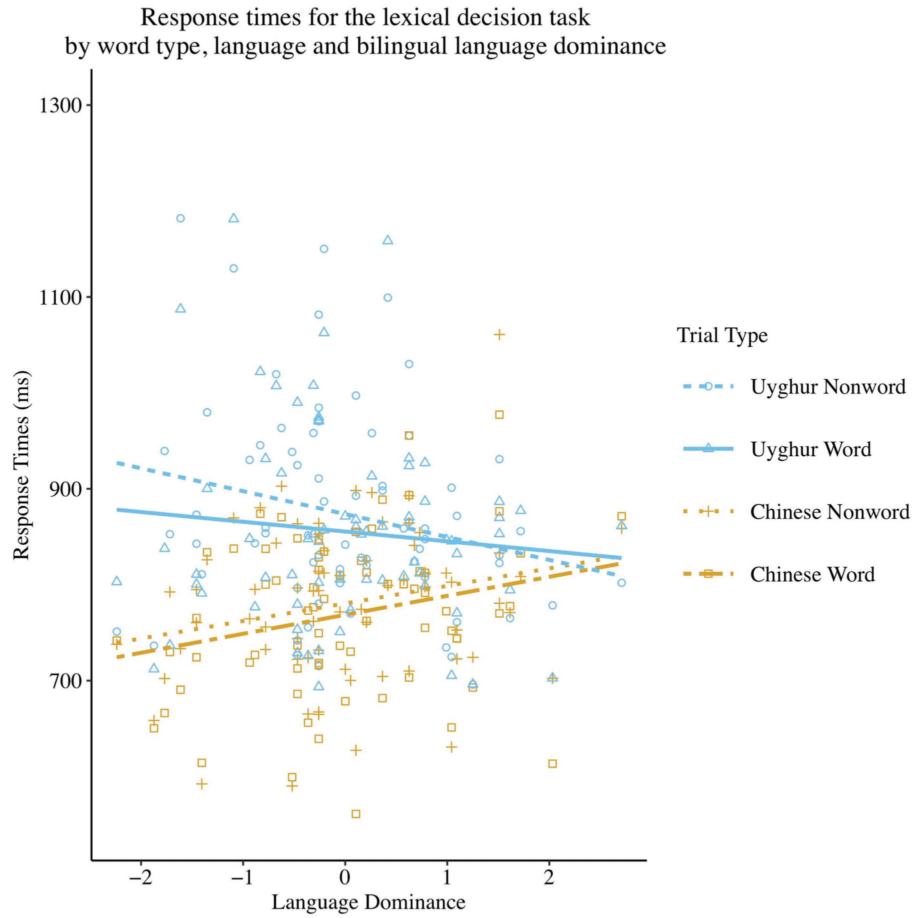

FIGURE 2 | Scatterplot and regression fit lines demonstrating the relationship between Language Dominance and mean response times at all the combinations of variables of Language and Word Type in the lexical decision task. The score on the x-axis closer to or above +1 means a higher dominance in L1, while the score closer to or below −1 means a higher dominance in L2.

TABLE 5 | Mean accuracy rates in percentage (%), mean response times (ms) of correct trials and the 95% confidence intervals (CI) from the lower bond to the upper bond for the flanker task by Stimulus Type.

	Accuracy rates		Response times	
	Mean	**95% CI**	**Mean**	**95% CI**
Congruent	99.72	99.46–99.86	681	661–701
Neutral	99.39	99.03–99.62	667	647–687
Incongruent	96.71	95.84–97.41	746	726–766

Correlation Analyses

Correlations Among Measures of Language Recognition and Bilingual Experience

Firstly, Pearson correlation analyses were adopted to investigate whether language dominance contributed to the potential recruitment of control mechanisms during word recognition in the single-language context, and to examine the extent to which long- or short-term language experience, comprising recent language exposure (short-term) and initial age of L2 acquisition (long-term), was interrelated with language dominance and recognition ability in the single-language context. The correlation analyses were conducted between the measures of language dominance (indexed by *z*-scores), recent language exposure, the initial age of L2 acquisition and L1 and L2 word recognition ability (performance on L1 and L2 word trials). The correlation results in terms of RTs and accuracy rates are presented in **Tables 6, 7**. There was a significantly positive correlation between L2 word recognition and self-reported overall language dominance only in terms of RTs [r (68) = 0.24, $p < 0.05$]. Moreover, L2 word recognition was significantly related to age of L2 acquisition only in terms of RTs [r (68) = 0.34, $p < 0.01$].

Correlations Among Measures of Language Recognition and Cognitive Control

Secondly, further Pearson correlation analyses were conducted to explore the extent to which reliance on domain-general cognitive control occurs in the language-specific context of visual word recognition in bilinguals. Two dimensions of cognitive control—inhibitory and monitoring control abilities—were taken into consideration as potential underlying mechanisms shared with

TABLE 6 | Bilinguals' Pearson correlation analyses between language dominance (dominance), recent exposure, onset age of L2 acquisition (AoA L2), and language recognition performance in response times (RTs) in the lexical decision task.

	Language dominance	L1 exposure	L2 exposure	AoA L2	L1 word RTs	L2 word RTs
Language dominance	-					
L1 exposure	0.57****	-				
L2 exposure	−0.48****	−0.86****	-			
AoA L2	0.16	0.01	−0.03	-		
L1 word RTs	−0.10	−0.01	−0.03	−0.07	-	
L2 word RTs	0.24*	0.08	−0.15	0.34**	0.45***	-

*N = 70; A larger score of language dominance indicates a greater dominance in L1. *p < 0.05; **p < 0.01; ***p < 0.001; ****p < 0.0001.*

TABLE 7 | Bilinguals' Pearson correlation analyses between language dominance, recent exposure, onset age of L2 acquisition (AoA L2), and language recognition performance in accuracy rates (ACC) in the lexical decision task.

	Language dominance	L1 exposure	L2 exposure	AoA L2	L1 word ACC	L2 word ACC
Language dominance	-					
L1 exposure	0.57****	-				
L2 exposure	−0.48****	−0.86****	-			
AoA L2	0.16	0.01	−0.03	-		
L1 word ACC	0.12	0.17	−0.15	0.05	-	
L2 word ACC	−0.08	0.16	0.00	0.06	0.04	-

*N = 70. A larger score of language dominance indicates a greater dominance in L1. ****p < 0.0001.*

domain-specific (linguistic) control. Therefore, we examined cross-domain dependency at two levels. The first analysis was conducted to correlate the flanker effect (contrast between congruent and incongruent trials), indexing inhibitory control, with L1 or L2 word recognition (RTs or accuracy rates on word trials), L1 and L2 non-word effect (contrast between word and non-word recognition) and global performance for each single-language lexical decision task. The second analysis was conducted to correlate overall performance indexing monitoring control in the flanker task with the same language control measures as stated above. The correlation analyses mentioned above were executed for both RTs and accuracy rates. The results are shown in **Table 8**. In terms of RTs, it was found that all bilinguals' better overall flanker task performance, suggested to be representing monitoring control, correlated with faster speed in L1 (r (68) = 0.30, $p < 0.05$) and L2 word [r (68) = 0.73, $p < 0.001$] recognition, and with faster speed in L1 (r (68) = 0.29, $p < 0.05$) and L2 global [r (68) = 0.76, $p < 0.001$] performance. For the accuracy analyses, L2 word recognition and L2 global performance were related to a smaller flanker effect, suggested to be representing inhibitory control [$r_{\text{L2-word}}$ (68) = −0.24, $p < 0.05$; $r_{\text{L2-global}}$ (68) = −0.32, $p < 0.01$]. The same L2 measures were correlated with better overall flanker task performance, suggested to be representing monitoring control [$r_{\text{L2-word}}$ (68) = 0.37, $p < 0.01$; $r_{\text{L2-global}}$ (68) = 0.44, $p < 0.001$].

Role of Language Dominance in Relationship Between Language Recognition and Cognitive Control

Thirdly, we took a closer investigation on the role of language dominance in the correlation between domain-specific and domain-general control. Two separate correlation analyses were executed for L1- and L2-dominant bilinguals respectively, employing the same linguistic and non-linguistic measures previously adopted for all participants. Using the mean value of the language dominance z-score as the cutoff for dominance grouping, 33 of the participants were classified as L1-dominant bilinguals and 37 as L2-dominant bilinguals. Given that the L1-dominant (M = 44.73, SD = 5.08) and L2-dominant (M = 48.11, SD = 4.86) groups differed significantly [t (68) = −2.85, $p < 0.01$] from each other in the IQ measure, a partial correlation analysis was executed by controlling for IQ. The correlation results in terms of RTs and accuracy scores for each group are reported in **Table 9**.

In L2-dominant bilinguals, only overall flanker task performance (suggested to be representing monitoring control) correlated with a number of language measures: faster speed in L1 [r (34) = 0.36, $p < 0.05$] and in L2 word recognition [r (34) = 0.69, $p < 0.001$]; with faster speed in L1 global performance [r (34) = 0.36, $p < 0.05$], and with faster speed [r (34) = 0.75, $p < 0.001$] and higher accuracy [r (34) = 0.41, $p < 0.05$] in L2 global performance.

For L1-dominant bilinguals, the findings in the accuracy analyses showed that not only overall flanker task performance, suggested to be representing monitoring control [r (30) = 0.57, $p < 0.001$], but also the flanker effect, suggested to be representing inhibitory control [r (30) = −0.46, $p < 0.01$] correlated with higher accuracy in L2 word recognition. In terms of RTs analyses, L1-dominant bilinguals showed a correlation between better overall flanker task performance and faster L2 word recognition [r (30) = 0.75, $p < 0.001$] and L2 global performance [r (30) = 0.75, $p < 0.001$].

TABLE 8 | All bilinguals' Pearson correlations between language control measured by the lexical decision task (LDT) and cognitive control measured by the flanker task at the dimension of response times (RTs) and accuracy rates (ACC).

Language control	Cognitive control	Coefficients for RTs (*N* = 70)	Coefficients for ACC (*N* = 70)
L1 word	Flanker effect	−0.06	−0.08
	Flanker monitoring	0.30*	0.06
L2 word	Flanker effect	0.02	−0.24*
	Flanker monitoring	0.73****	0.37**
L1 non-word effect	Flanker effect	0.01	0.10
	Flanker monitoring	−0.04	−0.02
L2 non-word effect	Flanker effect	0.12	0.04
	Flanker monitoring	−0.01	0.01
L1 global LDT	Flanker effect	−0.06	−0.14
	Flanker monitoring	0.29*	0.06
L2 global LDT	Flanker effect	0.05	−0.32**
	Flanker monitoring	0.76****	0.44***

**p* < 0.05; ***p* < 0.01; ****p* < 0.001; *****p* < 0.0001.

TABLE 9 | Pearson correlations, respectively, for L1- and L2-dominant bilinguals (controlling for IQ), between language control measured by the lexical decision task (LDT) and cognitive control measured by the flanker task at the dimension of response times (RTs) and accuracy rates (ACC).

Language control	Cognitive control	Coefficients for L2-dominant bilinguals (*N* = 37)		Coefficients for L1-dominant bilinguals (*N* = 33)	
		RTs	ACC	RTs	ACC
L1 word	Flanker effect	−0.05	0.03	−0.15	−0.17
	Flanker monitoring	0.36*	0.01	0.29	0.08
L2 word	Flanker effect	0.01	0.11	−0.07	−0.46**
	Flanker monitoring	0.69****	0.20	0.75****	0.57***
L1 non-word effect	Flanker effect	0.03	0.27	0.15	−0.14
	Flanker monitoring	−0.04	−0.12	0.08	0.16
L2 non-word effect	Flanker effect	0.03	0.29	0.15	−0.16
	Flanker monitoring	0.17	−0.17	−0.20	0.26
L1 global LDT	Flanker effect	−0.05	−0.23	−0.10	−0.05
	Flanker monitoring	0.36*	0.12	0.33	−0.03
L2 global LDT	Flanker effect	0.02	−0.20	−0.04	−0.46**
	Flanker monitoring	0.75****	0.41*	0.75****	0.52**

**p* < 0.05; ***p* < 0.01; ****p* < 0.001; *****p* < 0.0001.

DISCUSSION

The focus of the present study was two-fold: first, it intended to investigate whether the variables of language dominance, onset age of L2 acquisition and recent language exposure showed an effect on the variation in word recognition in two languages in a minority–majority bilingual context. Second, it explored whether language dominance had an impact on the relationship between linguistic recognition and non-linguistic domain-general control.

Better Performance in L2 Recognition With a Limited Role of Overall Language Dominance

The present study employed two single-language versions of the lexical decision task to assess the visual word recognition processing of Uyghur–Chinese bilinguals with varying degrees of language dominance in the minority–majority language sociolinguistic context. We found better performance in L2 than L1 in the actual lexical decision task, in which all bilinguals, irrespective of self-reported overall (or across-modality) language dominance, showed significantly better scores in L2 than in L1 word recognition, both in terms of RT and accuracy analyses. This finding of faster L2 performance in lexical decision tasks may be attributed to higher-level educational and academic experience (more written language use) in the L2 than L1 because of the higher status given to the L2 in the minority–majority language context (Goodrich and Lonigan, 2018). Our results showed that in spite of bilinguals' self-identification as being overall more dominant in their L1, no differences were found, especially in reading dominance, and L2 scores were better in visual word recognition. This result lends support to a dynamic and language task sensitive account of language dominance, with language dominance varying for each language modality (Bahrick et al., 1994; Treffers-Daller, 2015).

We detected a striking difference in the bilinguals' self-reported reading skill and their reading preference in relation to their L1 and L2. While bilinguals reported a higher preference for reading in the L2, they self-reported higher reading skills in the L1. When compared to their scores for the word recognition task, the participants' self-reported preference seemed to be more in line with their actual performance than their self-reported ability. The comparison between the response times for the word recognition task and the reported difference between reading preference and reading skills may indicate that reading preference is a better indicator of actual skill than self-reported assessment. The current findings thus suggest the need to complement self-reported proficiency scores with preference ratings, especially in a sociolinguistic setting in which languages have an unequal status and a dominance shift over time might occur in the indigenous population.

Our first prediction was that higher dominance in one language might contribute to more efficient and accurate word recognition in that language, measured with the two dimensions of real word and non-word recognition. Partially consistent with this prediction, our findings showed a significantly direct relationship between the speed of L2 word recognition and self-reported L2 language dominance and a marginally significant relationship between L2 non-word and self-reported L2 language dominance. However, for word recognition in the L1, only L1 non-word rejection was associated with self-reported L1 language dominance. These findings are somewhat in line with the previous study that has demonstrated that L2 language proficiency was related to L2 word recognition performance represented by L2 switch costs in a language switching context (Bultena et al., 2015). Our results further suggest that in the recognition modality, a dominance shift over time mainly affects the process of L2 word recognition and that variations in L2 word recognition are dynamically sensitive to language dominance shift over time, without adversely affecting L1 performance.

Finer-grained analyses were also performed to check for individual differences among the bilinguals and their relationships to the recognition process in both languages. In line with preceding studies (e.g., Bonfieni et al., 2019; Sulpizio et al., 2020), we found an effect of the onset age of L2 acquisition on word recognition. Specifically, the findings demonstrated that an earlier onset age of L2 acquisition correlated with faster L2 word recognition, indicating that long-term exposure to the L2 may be critical to the better performance in L2 than L1 in the recognition modality. Interestingly, we also found a positive correlation between the speed of L2 and L1 word recognition, indicating a partly shared mechanism underlying word recognition in both languages. Given that L2 word recognition was related to the age of L2 acquisition, this finding further indicated that even though a dominance shift over time into the L2 exists, L1 word recognition is not adversely affected by this phenomenon. However, the findings also showed that no similar effect of the age of L2 acquisition was detected in relation to L1 word recognition. This seems to indicate that while the onset age of L2 acquisition might account for variations in L2 word recognition, it does not show any dependency on the relationship between L1 and L2 word recognition. Hence, it can be deduced that a non-linear relationship exists between the age of L2 acquisition or recent language exposure and word recognition. Future studies should examine whether factors, such as different patterns of language use (e.g., high frequency of language switching or not), contribute to the positive interaction between L1 and L2 word recognition.

The Role of Language Dominance in the Association Between Bilingual Word Recognition and Domain-General Language Control

We assessed the overlap between measures of linguistic and non-linguistic control by correlating performance in the single-language lexical decision task with performance in the flanker task. Our prediction was that the measures of domain-specific control (i.e., word recognition, non-word effect and global language performance) were related to the measures of domain-global control (i.e., flanker effect and overall flanker task performance). One of our present findings is consistent with the study by Gangopadhyay et al. (2019) as there were no correlations between the non-word effect (indexed by the contrast between words and non-words) and domain-general control. Specifically, the non-word effect was neither correlated with inhibitory control, indexed by the flanker effect, nor with monitoring control, indexed by overall performance in the flanker task. To some extent, this result implies that engaging in the lexical processing of rejecting within-language lexical competitors may be a domain-specific process for bilinguals. This may suggest that the process of rejecting non-words is encapsulated within the language system (Paap et al., 2019).

However, our prediction, enlightened by prior studies (Costa et al., 2009; Struys et al., 2019), was confirmed in that monitoring control seemed to be an underlying process of L1 and L2 word recognition in visual lexical processing. In line with previous findings (Struys et al., 2019), our results regarding RTs showed that for all bilinguals, word recognition measured by L1 and L2 response latencies in word trials and global performance in each single-language lexical decision task was correlated with cognitive monitoring control, measured by overall performance in the flanker task. This suggests that bilinguals with efficient overall performance in the flanker task demonstrate faster performance in word recognition. This relationship supports the prior finding that dependency on domain-general control can be manifested when a linguistic task and non-linguistic cognitive task are structurally matched (De Baene et al., 2015) in the sense that both tasks feature an equal proportion of easy (word or congruent trials) and difficult (non-word or conflict trials) conditions, presented in an unpredictable order.

Partially consistent with our prediction that inhibitory control can be involved in both L1 and L2 word recognition, the present findings regarding accuracy rates showed that all bilinguals demonstrated a link between inhibitory control, indexed by the flanker effect, and L2 word recognition, indexed by L2 word trials and global L2 performance. This result is consistent with studies that have focused on domain generality in the bilingual recognition process (Blumenfeld and Marian, 2011; Blumenfeld et al., 2016) and reported that the recruitment of inhibitory control underlies L2 access in the process of auditory word recognition. It also lends support to the BIA model (Grainger and Dijkstra, 1992; van Heuven et al., 1998), which proposes the recruitment of top-down domain-general inhibitory control in word recognition processing. However, since inhibitory control is selectively present in L2 word recognition but not in L1 word recognition, this may further indicate that inhibitory control is sensitive to the relative strength of each language, with control being especially necessary in the language acquired later, irrespective of its current dominance. Moreover, our findings may support the notion that the minority–majority bilingual context entails an application of the coupled control mode (Green and Wei, 2014; Bosma and Blom, 2019) in which the majority L2 context seldom allows lexical insertion from the L1 minority language and thus requires inhibitory control to suppress interference from the minority L1. Such training in the sociolinguistic experience probably increases the engagement of inhibitory control.

To further examine the effect of language dominance on cross-domain overlap, follow-up separate examinations using language dominance as a categorical variable were conducted for L1- and L2-dominant bilinguals to check whether the two dominance groups differed in terms of interaction between linguistic and cognitive control. Consistent with our prediction, the correlation analyses in the dimension of accuracy showed that the degree and nature of cross-domain generality depended on language dominance. Specifically, we found that a dual mechanism of inhibitory, indexed by the flanker effect, and monitoring control, indexed by overall flanker performance, underlies L2 word recognition for L1-dominant bilinguals, whereas L2-dominant bilinguals only relied on monitoring control for L2 word recognition. That is, inhibitory control was exclusively recruited by L1-dominant bilinguals to prevent the interference of their globally dominant language (L1) during L2 performance in the recognition modality. This finding about the selective presence of inhibitory control in L1-dominant bilinguals for L2 word recognition is consistent with prior studies involving a language switching context (e.g., Mosca and de Bot, 2017), showing that inhibitory control, indexed by switch costs, was only present when bilinguals were involved with L2 word recognition before language switching, due to the previous L2 word recognition context incurring inhibitory control to constrain the dominant L1 from enhancing activation of the L2.

Our findings also suggest that once L2 proficiency has globally achieved a high level (or a dominance shift over time into L2 exists across all language skills), bilinguals no longer employ inhibitory control to facilitate the accuracy of L2 word recognition. Instead, monitoring control becomes the exclusive domain-general mechanism for L2-dominant bilinguals to process both L1 and L2 word recognition. The reason for this may be that compared to L1-dominant bilinguals, who globally maintain language strength in their native L1, L2-dominant bilinguals may increasingly enhance their L2 proficiency and thus experience a more demanding context in which their monitoring control is consistently recruited to manage the two comparably activated language systems. This finding is consistent with prior studies (Costa et al., 2009; Singh and Mishra, 2013; Chan et al., 2020), which have suggested that bilinguals with dominance in their L2 benefit from monitoring control. Our study contributes to the monitoring account that when bilinguals show a dominance shift over time into their L2, a tendency towards the exclusive involvement of the monitoring control in the word recognition process occurs.

Importantly, our results in the dimension of RTs further showed that for both the L1- and L2-dominant bilingual groups, their better overall flanker performance in the non-linguistic flanker task was correlated with more efficiency in L2 word recognition or global L2 performance in the lexical decision task. This finding suggests that in the specific context of better performance in L2 than L1 in the modality of recognition, monitoring control is crucial to L2 word recognition and might fulfil a faciliatory role in gaining access to the L2, both for those who are globally non-dominant in the L2 (L1-dominant bilinguals) and for those who have the L2 as a globally dominant language (L2-dominant bilinguals).

By taking a comprehensive view, our results suggest that monitoring is shared across L1- and L2-dominant bilinguals for both RTs and accuracy but that inhibitory control only contributes to accurate L2 word recognition in L1-dominant bilinguals. Our findings contribute to the idea that the efficiency of proactively executing domain-general monitoring control in the linguistic task is non-selective to language dominance in the context of a general dominance shift over time due to the sociolinguistic setting to which the bilinguals were exposed. Inhibitory control, in contrast, seems to be relevant only for bilinguals who are in the process of undergoing this dominance shift over time but who have not yet completed it across all language modalities. Our findings point to a dominance-based domain-general contribution to word recognition: while inhibitory control may facilitate word recognition in a language in which the bilingual has relatively low proficiency at the onset stages of second language acquisition, monitoring control may become a more important facilitator when proficiency increases. Once dominance shifts over time, monitoring control may remain relevant for word recognition in a language acquired later (even though performance is better), while the contribution of inhibitory control is reduced or even disappears. This phenomenon may occur because monitoring is particularly important when two languages are more or less balanced in strength and when control can be applied proactively through experience, while inhibitory control is particularly needed when two languages differ substantially in strength and when control is not yet highly practiced and requires reactive application.

We would like to emphasise that our findings should be assessed in light of this study's limitations. One of limitations in our current study is that the flanker task is selected as the sole measure of domain-general control. This could be overcome in future studies by adding multiple measures of domain-general control, not only including measures of interference control as tapped into by the flanker task, but also looking at other inhibition-related tasks, such as (non-verbal variants of) the Stroop task, and the Simon task. Another limitation is that the measure of overall performance across trial type in the flanker task may not be a pure index of monitoring, because the time taken to monitor for conflicts may be embedded within stages involved with encoding, response selection and response execution. A third limitation in the current study is that only self-reported scores on the Uyghur and Chinese language were adopted for the measures of language dominance. In future studies, direct measures derived from language tests should be additionally exploited to reflect overall language dominance. For instance, each language can be tested through a single-language verbal fluency task as a measure of productive vocabulary abilities and the Peabody picture vocabulary test as a measure of receptive abilities. These two direct language tests can be used together as a composite index for evaluating language dominance. An additional limitation is related to the test order of the two language tasks (first in Chinese and then in Uyghur for all participants) and the instructions only given in Chinese. Previous research has suggested (for a review, see de Groot and Christoffels, 2006; Olson, 2017) that the language mode in which bilinguals find themselves might have an effect on the amount of control that is required on the non-target language. Features, such as test order or language of instruction, could have an impact on this language mode. We recommend, therefore, future studies that would like to replicate this study, to minimise the effect of language mode by counterbalancing not only the order of the tasks but also the languages used in instructions.

CONCLUSION

Focusing on bilinguals in a minority–majority language sociolinguistic context, the current study investigated the role of bilingual dominance along with linguistic (onset age of L2 acquisition) and sociolinguistic experience (recent language exposure) in the language recognition process. It also explored the effect of language dominance on the link between language recognition (domain-specific) control and cognitive (domain-general) control. We found better performance for the majority L2 in visual lexical access in the single-language context for all bilinguals. Our findings revealed better performance in L2 than L1 in visual word recognition and suggest that the initial age of L2 acquisition (but not recent language exposure) and across-modality language dominance as a continuous variable contribute to variation in L2 recognition. Our results also support a monitoring account for bilingual language recognition in the L2, independent of language dominance. Importantly, language dominance as a categorical variable was found to play a role in across-domain generality as L2-dominant bilinguals had an exclusive reliance on domain-general monitoring control, while L1-dominant bilinguals drew on both inhibitory and monitoring control to process the later-acquired L2 in the recognition modality. Our study indicates that language dominance, operationalised as a continuous and categorical variable, shows its effect not only directly in the lexical recognition process but also indirectly as an impact on the domain-general contribution to recognition, depending on whether the bilingual reported overall dominance in their L1 or L2.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Academic Committee of Shaanxi Normal University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RW contributed to the conception of the study, design of the experiments, collection and analysis of data, wrote the manuscript, and revised the manuscript critically for important intellectual content. ES advised on the conception and design of the study and provided critical revisions on the manuscript for important intellectual content. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.854898/full#supplementary-material

REFERENCES

Anthony, J., and Blumenfeld, H. K. (2019). Language dominance predicts cognate effects and inhibitory control in young adult bilinguals. *Biling. Lang. Cogn.* 22, 1068–1084. doi: 10.1017/s1366728918001013

Arffa, S. (2007). The relationship of intelligence to executive function and non-executive function measures in a sample of average, above average, and gifted youth. *Arch. Clin. Neuropsychol.* 22, 969–978. doi: 10.1016/j.acn.2007.08.001

Baayen, R. H., Davidson, D. J., and Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *J. Mem. Lang.* 59, 390–412. doi: 10.1016/j.jml.2007.12.005

Bahrick, H. P., Hall, L. K., Goggin, J. P., Bahrick, L. E., and Berger, S. A. (1994). Fifty years of language maintenance and language dominance in bilingual hispanic immigrants. *J. Exp. Psychol. Gen.* 123, 264–283. doi: 10.1037/0096-3445.123.3.264

Barr, D. J., Levy, R., Scheepers, C., and Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: keep it maximal. *J. Mem. Lang.* 68, 255–278. doi: 10.1016/j.jml.2012.11.001

Basnight-Brown, D. M., and Altarriba, J. (2007). Differences in semantic and translation priming across languages: the role of language direction and language dominance. *Mem. Cogn.* 35, 953–965. doi: 10.3758/bf03193468

Bates, D., Machler, M., Bolker, B. M., and Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67, 1–48. doi: 10.18637/jss.v067.i01

Bialystok, E., and Craik, F. I. M. (2022). How does bilingualism modify cognitive function? Attention to the mechanism. *Psychon. Bull. Rev.*, 1–24. doi: 10.3758/s13423-022-02057-5

Blumenfeld, H. K., and Marian, V. (2011). Bilingualism influences inhibitory control in auditory comprehension. *Cognition* 118, 245–257. doi: 10.1016/j.cognition.2010.10.012

Blumenfeld, H. K., Schroeder, S. R., Bobb, S. C., Freeman, M. R., and Marian, V. (2016). Auditory word recognition across the lifespan links between linguistic and nonlinguistic inhibitory control in bilinguals and monolinguals. *Linguist. Approaches Biling.* 6, 119–146. doi: 10.1075/lab.14030.blu

Bonfieni, M., Branigan, H. P., Pickering, M. J., and Sorace, A. (2019). Language experience modulates bilingual language control: the effect of proficiency, age of acquisition, and exposure on language switching. *Acta Psychol.* 193, 160–170. doi: 10.1016/j.actpsy.2018.11.004

Bosma, E., and Blom, E. (2019). A code-switching asymmetry in bilingual children: code-switching from Dutch to Frisian requires more cognitive control than code-switching from Frisian to Dutch. *Int. J. Biling.* 23, 1431–1447. doi: 10.1177/1367006918798972

Bultena, S., Dijkstra, T., and Van Hell, J. G. (2015). Language switch costs in sentence comprehension depend on language dominance: evidence from self-paced reading. *Biling. Lang. Cogn.* 18, 453–469. doi: 10.1017/s1366728914000145

Caffarra, S., Zimnukhova, S., and Mancini, S. (2016). What usage can do: The effect of language dominance on simultaneous bilinguals' morphosyntactic processing. *Linguist. Vanguard* 2:20160020. doi: 10.1515/lingvan-2016-0020

Calabria, M., Costa, A., Green, D. W., and Abutalebi, J. (2018). Neural basis of bilingual language control. *Ann. N. Y. Acad. Sci.* 1426, 221–235. doi: 10.1111/nyas.13879

Chan, C. G. H., Yow, W. Q., and Oei, A. (2020). Active bilingualism in aging: balanced bilingualism usage and less frequent language switching relate to better conflict monitoring and goal maintenance ability. *J. Gerontol. B Psychol. Sci. Soc. Sci.* 75, E231–E241. doi: 10.1093/geronb/gbaa058

Costa, A., Hernandez, M., Costa-Faidella, J., and Sebastian-Galles, N. (2009). On the bilingual advantage in conflict processing: now you see it, now you don't. *Cognition* 113, 135–149. doi: 10.1016/j.cognition.2009.08.001

Couto, M. C. P., and Gullberg, M. (2019). Code-switching within the noun phrase: evidence from three corpora. *Int. J. Biling.* 23, 695–714. doi: 10.1177/1367006917729543

Da, J. (2005). Character frequency list of modern Chinese. Available at: https://lingua.mtsu.edu/chinese-computing/statistics/char/list.php?Which=MO (Accessed March 23, 2017).

De Baene, W., Duyck, W., Brass, M., and Carreiras, M. (2015). Brain circuit for cognitive control is shared by task and language switching. *J. Cogn. Neurosci.* 27, 1752–1765. doi: 10.1162/jocn_a_00817

de Groot, A. M. B., Borgwaldt, S., Bos, M., and van den Eijnden, E. (2002). Lexical decision and word naming in bilinguals: language effects and task effects. *J. Mem. Lang.* 47, 91–124. doi: 10.1006/jmla.2001.2840

de Groot, A. M. B., and Christoffels, I. K. (2006). Language control in bilinguals: monolingual tasks and simultaneous interpreting. *Biling. Lang. Cogn.* 9, 189–201. doi: 10.1017/s1366728906002537

de Groot, A. M. B., Delmaar, P., and Lupker, S. J. (2000). The processing of interlexical homographs in translation recognition and lexical decision: support for non-selective access to bilingual memory. *Q J Exp Psychol A* 53, 397–428. doi: 10.1080/713755891

de Houwer, A. (2018). "The role of language input environments for language outcomes and language acquisition in young bilingual children," in *Bilingual Cognition and Language: The State of the Science Across its Subfields*. eds. D. Miller, F. Bayram, J. Rothman and L. Serratrice (Amsterdam: John Benjamins), 127–154.

Declerck, M., and Philipp, A. M. (2015). A review of control processes and their locus in language switching. *Psychon. Bull. Rev.* 22, 1630–1645. doi: 10.3758/s13423-015-0836-1

Dijkstra, T., Timmermans, M., and Schriefers, H. (2000). On being blinded by your other language: effects of task demands on interlingual homograph recognition. *J. Mem. Lang.* 42, 445–464. doi: 10.1006/jmla.1999.2697

Dijkstra, T., and van Heuven, W. J. B. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Biling. Lang. Cogn.* 5, 175–197. doi: 10.1017/S1366728902003012

Dijkstra, T., Wahl, A., Buytenhuijs, F., Van Halem, N., Al-Jibouri, Z., De Korte, M., et al. (2019). Multilink: a computational model for bilingual word recognition and word translation. *Biling.: Lang. Cogn.* 22, 657–679. doi: 10.1017/s1366728918000287

Dunabeitia, J. A., Perea, M., and Carreiras, M. (2010). Masked translation priming effects With highly proficient simultaneous bilinguals. *J. Exp. Psychol.* 57, 98–107. doi: 10.1027/1618-3169/a000013

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Freeman, M. R., Blumenfeld, H. K., and Marian, V. (2017). Cross-linguistic phonotactic competition and cognitive control in bilinguals. *J. Cogn. Psychol.* 29, 783–794. doi: 10.1080/20445911.2017.1321553

Gangopadhyay, I., Weismer, S. E., and Kaushanskaya, M. (2019). Domain-general inhibition and lexical processing in monolingual and bilingual children: a longitudinal approach. *Cogn. Dev.* 49, 68–80. doi: 10.1016/j.cogdev.2018.11.008

Gollan, T. H., and Goldrick, M. (2016). Grammatical constraints on language switching: language control is not just executive control. *J. Mem. Lang.* 90, 177–199. doi: 10.1016/j.jml.2016.04.002

Goodrich, J. M., and Lonigan, C. J. (2018). Language-minority children's sensitivity to the semantic relations between words. *J. Exp. Child Psychol.* 167, 259–277. doi: 10.1016/j.jecp.2017.11.001

Grainger, J., and Dijkstra, T. (1992). "On the representation and use of language information in bilinguals," in *Cognitive Processing in Bilinguals*. ed. R. J. Harris (Amsterdam: Elsevier), 207–220.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn.* 1, 67–81. doi: 10.1017/s1366728998000133

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Green, D. W., and Wei, L. (2014). A control process model of code-switching. *Lang. Cogn. Neurosci.* 29, 499–511. doi: 10.1080/23273798.2014.882515

Grosjean, F. (2015). "The complementarity principle and its impact on processing, acquisition, and dominance," in *Language Dominance in Bilinguals: Issues of Measurement and Operationalization*. eds. C. Silva-Corvalán and J. Treffers-Daller (Cambridge: Cambridge University Press), 66–84.

Guo, X., and Gu, M. (2018). Reconfiguring Uyghurness in multilingualism: an internal migration perspective. *Ethn. Racial Stud.* 41, 2028–2047. doi: 10.1080/01419870.2017.1343485

Hoversten, L. J., Brothers, T., Swaab, T. Y., and Traxler, M. J. (2015). Language membership identification precedes semantic access: suppression during bilingual word recognition. *J. Cogn. Neurosci.* 27, 2108–2116. doi: 10.1162/jocn_a_00844

Jaeger, T. F. (2008). Categorical data analysis: away from ANOVAs (transformation or not) and towards logit mixed models. *J. Mem. Lang.* 59, 434–446. doi: 10.1016/j.jml.2007.11.007

Kaandorp, M. W., Smits, C., Merkus, P., Festen, J. M., and Goverts, S. T. (2017). Lexical-access ability and cognitive predictors of speech recognition in noise in adult Cochlear implant users. *Trends Hear.* 21. doi: 10.1177/2331216517743887

Kornblum, S., Stevens, G. T., Whipple, A., and Requin, J. (1999). The effects of irrelevant stimuli: 1. The time course of stimulus–stimulus and stimulus–response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *J. Exp. Psychol. Hum. Percept. Perform.* 25, 688–714. doi: 10.1037/0096-1523.25.3.688

Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2017). lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82, 1–26. doi: 10.18637/jss.v082.i13

Lee, Y., Jang, E., and Choi, W. (2018). L2-L1 translation priming effects in a lexical decision task: evidence from low proficient Korean-English bilinguals. *Front. Psychol.* 9:267. doi: 10.3389/fpsyg.2018.00267

Lemhofer, K., and Dijkstra, T. (2004). Recognizing cognates and interlingual homographs: effects of code similality in language-specific and generalized lexical decision. *Mem. Cogn.* 32, 533–550. doi: 10.3758/bf03195845

Libben, G., and Jarema, G. (2002). Mental lexicon research in the new millennium. *Brain Lang.* 81, 2–11. doi: 10.1006/brln.2002.2654

Linck, J. A., Hoshino, N., and Kroll, J. F. (2008). Cross-language lexical processes and inhibitory control. *Ment. Lex.* 3, 349–374. doi: 10.1075/ml.3.3.06lin

Litcofsky, K. A., and van Hell, J. G. (2017). Switching direction affects switching costs: behavioral, ERP and time frequency analyses of intra-sentential codeswitching. *Neuropsychologia* 97, 112–139. doi: 10.1016/j.neuropsychologia.2017.02.002

Ma, R. (2009). The development of minority education and practice of bilingual education in Xinjiang Uyghur autonomous region. *Front. Educ. China* 4, 188–251. doi: 10.1007/s11516-009-0012-3

Macizo, P., Bajo, T., and Cruz Martin, M. (2010). Inhibitory processes in bilingual language comprehension: evidence from Spanish-English interlexical homographs. *J. Mem. Lang.* 63, 232–244. doi: 10.1016/j.jml.2010.04.002

Macizo, P., Bajo, T., and Paolieri, D. (2012). Language switching and language competition. *Second. Lang. Res.* 28, 131–149. doi: 10.1177/0267658311434893

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The language experience and proficiency questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Marslen-Wilson, W. D., and Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cogn. Psychol.* 10, 29–63. doi: 10.1016/0010-0285(78)90018-x

Masut, S. (2014). Xinjiang "minkaohan" qunti weihanyu yuyan jiechu de shehui bianliang fenxi — yi "minkaohan" weihan shuangyu shiyong weili [An analysis of social variables of Uyghur and Chinese language contact among "Minkaohan" Group in Xinjiang: taking "Minkaohan" Uyghur-Chinese bilingual language use as an example]. *Yuyan yu fanyi* 30, 67–73.

Meyer, D. E., and Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words—evidence of a dependence between retrieval operations. *J. Exp. Psychol.* 90:227. doi: 10.1037/h0031564

Miwa, K., Dijkstra, T., Bolger, P., and Baayen, R. H. (2014). Reading English with Japanese in mind: effects of frequency, phonology, and meaning in different-script bilinguals. *Biling: Lang. Cogn.* 17, 445–463. doi: 10.1017/s1366728913000576

Montrul, S. (2015). *The Acquisition of Heritage Languages*. Cambridge: Cambridge University Press.

Moon, J., and Jiang, N. (2012). Non-selective lexical access in different-script bilinguals. *Biling. Lang. Cogn.* 15, 173–180. doi: 10.1017/s1366728911000022

Mosca, M., and de Bot, K. (2017). Bilingual language switching: production vs. recognition. *Front. Psychol.* 8:934. doi: 10.3389/fpsyg.2017.00934

Nakayama, M., Ida, K., and Lupker, S. J. (2016). Cross-script L2-L1 noncognate translation priming in lexical decision depends on L2 proficiency: evidence from Japanese-English bilinguals. *Biling. Lang. Cogn.* 19, 1001–1022. doi: 10.1017/s1366728915000462

Nakayama, M., Sears, C. R., Hino, Y., and Lupker, S. J. (2012). Cross-script phonological priming for Japanese-English bilinguals: evidence for integrated phonological representations. *Lang. Cogn. Process.* 27, 1563–1583. doi: 10.1080/01690965.2011.606669

Olson, D. J. (2017). Bilingual language switching costs in auditory comprehension. *Lang. Cogn. Neurosci.* 32, 494–513. doi: 10.1080/23273798.2016.1250927

Paap, K. R., Anders-Jefferson, R., Mikulinsky, R., Masuda, S., and Mason, L. (2019). On the encapsulation of bilingual language control. *J. Mem. Lang.* 105, 76–92. doi: 10.1016/j.jml.2018.12.001

Perea, M., Dunabeitia, J. A., and Carreiras, M. (2008). Masked associative/semantic priming effects across languages with highly proficient bilinguals. *J. Mem. Lang.* 58, 916–930. doi: 10.1016/j.jml.2008.01.003

Pu, H., Medina, Y. E., Holcomb, P. J., and Midgley, K. J. (2019). Testing for nonselective bilingual lexical access using L1 Attrited bilinguals. *Brain Sci.* 9:126. doi: 10.3390/brainsci9060126

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Raven, J. C. (1938). *Progressive Matrices: A Perceptual Test of Intelligence*. London: H. K. Lewis.

Schad, D. J., Vasishth, S., Hohenstein, S., and Kliegl, R. (2020). How to capitalize on a priori contrasts in linear (mixed) models: A tutorial. *J. Mem. Lang.* 110:104038. doi: 10.1016/j.jml.2019.104038

Silva-Corvalán, C., and Treffers-Daller, J. (2015). "Digging into dominance: A closer look at language dominance in bilinguals," in *Language Dominance in Bilinguals: Issues of Measurement and Operationalization*. eds. C. Silva-Corvalán and J. Treffers-Daller (Cambridge: Cambridge University Press), 1–14.

Singh, N., and Mishra, R. K. (2013). Second language proficiency modulates conflict-monitoring in an oculomotor Stroop task: evidence from Hindi-English bilinguals. *Front. Psychol.* 4:322. doi: 10.3389/fpsyg.2013.00322

Struys, E., Woumans, E., Nour, S., Kepinska, O., and Van den Noort, M. (2019). A domain-general monitoring account of language switching in recognition tasks: evidence for adaptive control. *Biling. Lang. Cogn.* 22, 606–623. doi: 10.1017/s1366728918000342

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., and Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage* 205:116306. doi: 10.1016/j.neuroimage.2019.116306

Tao, Y., Liu, Z., Tempel, T., Chen, R., Ma, X., Wang, X. X., et al. (2017). Inhibitory control in speech comprehension among Dai-Han bilingual children. *Front. Psychol.* 8:1391. doi: 10.3389/fpsyg.2017.01391

Thomas, M. S. C., and Allport, A. (2000). Language switching costs in bilingual visual word recognition. *J. Mem. Lang.* 43, 44–66. doi: 10.1006/jmla.1999.2700

Treffers-Daller, J. (2015). "Language dominance: The construct, its measurement, and operationalization," in *Language Dominance in Bilinguals: Issues of Measurement and Operationalization*. eds. C. Silva-Corvalán and J. Treffers-Daller (Cambridge: Cambridge University Press), 235–265.

Treffers-Daller, J., and Korybski, T. (2015). "Using lexical diversity measures to operationalize language dominance in bilinguals," in *Language Dominance in Bilinguals: Issues of Measurement and Operationalization*. eds. C. Silva-Corvalán and J. Treffers-Daller (Cambridge: Cambridge University Press), 106–133.

Tse, C. S., and Altarriba, J. (2015). Local and global task switching costs in bilinguals who vary in second language proficiency. *Am. J. Psychol.* 128, 89–106. doi: 10.5406/amerjpsyc.128.1.0089

van Assche, E., Duyck, W., Hartsuiker, R. J., and Diependaele, K. (2009). Does bilingualism change native-language Reading? Cognate effects in a sentence context. *Psychol. Sci.* 20, 923–927. doi: 10.1111/j.1467-9280.2009.02389.x

van Heuven, W. J. B., Dijkstra, T., and Grainger, J. (1998). Orthographic neighborhood effects in bilingual word recognition. *J. Mem. Lang.* 39, 458–483. doi: 10.1006/jmla.1998.2584

van Heuven, W. J. B., Mandera, P., Keuleers, E., and Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *Q. J. Exp. Psychol.* 67, 1176–1190. doi: 10.1080/17470218.2013.850521

van Heuven, W. J. B., Schriefers, H., Dijkstra, T., and Hagoort, P. (2008). Language conflict in the bilingual brain. *Cereb. Cortex* 18, 2706–2716. doi: 10.1093/cercor/bhn030

Wang, X. (2013). Language dominance in translation priming: evidence from balanced and unbalanced Chinese English bilinguals. *Q. J. Exp. Psychol.* 66, 727–743. doi: 10.1080/17470218.2012.716072

Wu, R. L., and Struys, E. (2021). Language dominance and sociolinguistic experience are related to language control and domain-general monitoring control: An investigation in bilinguals who live in a minority/majority sociolinguistic setting. *Front. Psychol.* 12:594648. doi: 10.3389/fpsyg.2021.594648

Wu, Y. J., and Thierry, G. (2010). Chinese-English bilinguals Reading English hear Chinese. *J. Neurosci.* 30, 7646–7651. doi: 10.1523/jneurosci.1602-10.2010

Zahn, I. (2010). Working with unbalanced cell sizes in multiple regression with categorical predictors. Available at: http://psychology.okstate.edu/faculty/jgrice/psyc5314/SS_types.pdf (Accessed March 16, 2020).

Zhou, H. X., Chen, B. G., Yang, M. Y., and Dunlap, S. (2010). Language nonselective access to phonological representations: evidence from Chinese-English bilinguals. *Q. J. Exp. Psychol.* 63, 2051–2066. doi: 10.1080/17470211003718705

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Dynamic Effects of Immersive Bilingualism on Cortical and Subcortical Grey Matter Volumes

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Bilingualism has been shown to induce neuroplasticity in the brain, but conflicting evidence regarding its specific effects in grey matter continues to emerge, probably due to methodological differences between studies, as well as approaches that may miss the variability and dynamicity of bilingual experience. In our study, we devised a continuous score of bilingual experiences and we investigated their non-linear effects on regional GM volume in a sample of young healthy participants from an immersive and naturalistic bilingual environment. We focused our analyses on cortical and subcortical regions that had been previously proposed as part of the bilingual speech pipeline and language control network. Our results showed a non-linear relationship between bilingualism score and grey matter volume of the inferior frontal gyrus. We also found linear increases in volumes of putamen and cerebellum as a function of bilingualism score. These results go in line with predictions for immersive and naturalistic bilingual environments with increased intensity and diversity of language use and provide further evidence supporting the dynamicity of bilingualism's effects on brain structure.

Keywords: bilingualism, neuroplasticity, grey matter, volume, immersion, dynamic, non-linear

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INTRODUCTION

Bilingualism-the experience of being exposed to two languages and manage them in everyday life-has been shown to induce neuroplasticity in the brain (Grundy et al., 2017). During language production, bilinguals need to select one language and suppress the other, while adequately articulating the target language, which results in increased demands for linguistic control and, consequently, in changes in brain structure and function to accommodate these heightened demands (Tao et al., 2021). Different models have attempted to describe the location and characteristics of these changes, and the particular features of the bilingual experience that contribute to them. For instance, the Adaptive Control Hypothesis (ACH) proposed that any effects of bilingualism on brain structure are dependent on the interactional context in which the individual uses their languages and the specific control processes that different contexts entail: *single language contexts* in which languages are used separately in different environments; *dual-language contexts* in which both languages are used but separately with different speakers; and *dense code-switching contexts* where speakers use both languages interleaving them in their discourse (Green and Abutalebi, 2013). Based on previous evidence, they propose a brain network for language control and speech, composed by inferior frontal, parietal, anterior cingulate, motor and premotor cortices, thalamus, caudate nucleus, putamen, cerebellum and insula (Abutalebi and Green, 2016). These regions are hypothesized to be differentially affected by bilingual experience depending on the interactional context: while dense code-switching contexts would engage more the cerebellum and left inferior frontal cortex, dual or multiple language interactional contexts would engage bilateral inferior frontal, anterior cingulate and parietal cortices, caudate nucleus, putamen, and the thalamus. Other authors have proposed that a brain adaptation pattern arises with increased *length* of immersion in bilingual environments, characterized by an initial tissue volume increase in frontostriatal regions, followed by reductions in volume and lower functional recruitment of frontal executive regions, as well as greater recruitment and further expansions of posterior and subcortical areas, a phenomenon they call the "bilingual anterior-to-posterior and subcortical shift" (BAPSS; Grundy et al., 2017). However, mixed evidence regarding the specific brain changes produced by bilingual *experience* continues to emerge. Namely, when investigating grey matter (GM) differences between bilinguals and monolinguals, the former generally show higher volume, density and cortical thickness, as well as shape expansions, in cortical, subcortical and cerebellar areas, but some studies have also found results in the opposite direction – lower volumes in bilinguals—or no differences at all between the groups [see Tao et al. (2021) for a systematic review].

Apparent inconsistencies between studies when investigating bilingualism and GM structure may stem from multiple sources. Methodological issues—e.g., the use of different measures—and sample differences have been suggested as the main origins of variation (García-Pentón et al., 2015). In fact, many investigations carried out to date used samples of bilinguals with very distinct characteristics. While some studies only considered simultaneous bilinguals—that is, bilinguals who first learned both languages at the same time (Burgaleta et al., 2016), others only included bilinguals who were not simultaneously exposed to both languages but acquired the second language (L2) early in life (Olulade et al., 2016), or late sequential bilinguals whose age of acquisition (AoA) of L2 was greater than seven (Pliatsikas et al., 2017; Deluca et al., 2019a). Moreover, the age cutoffs for different groups of bilinguals—simultaneous, early or late—are arbitrary and sometimes differ between studies (Mechelli et al., 2004; Ressel et al., 2012; Klein et al., 2014), which adds to the confusion. Levels of immersion in L2 also remarkably vary between studies, with some investigations comparing monolinguals to proficient bilinguals that frequently use L2 (Deluca et al., 2019a), while others investigate non-immersed bilinguals (Korenar et al., 2021). The Unifying the Bilingual Experience Trajectories (UBET) framework (DeLuca et al., 2020), which brings together previous models on the trajectory of neurocognitive adaptations due to bilingualism, emphasizes that different characteristics of bilingual experiences—intensity and diversity, language switching, relative proficiency, and duration—lead to adaptations in efficiency and control demands that have different consequences on cognition and brain structure. In particular, they hypothesize that increased duration and a balanced proficiency between the languages will increase *efficiency*, associated with increases in GM volume of subcortical and posterior regions, and return to baseline volumes in cortical areas that had expanded in previous initial stages of the bilingual experience. They also propose that increases in diversity, intensity, and language switching will increase *control demands*, resulting in GM volume increases in areas involved in control processes such as the inferior frontal gyrus (IFG), anterior cingulate cortex (ACC) or inferior parietal lobule, as an adaptation to these demands. Moreover, they draw attention to the consequences of the socio-linguistic environment on the interaction between bilingualism characteristics and their consequences. For instance, in countries where only one language is official and widely used in society, the use of a second one will probably be restricted to specific community contexts, which might result in compartmentalized usage of languages, different language proficiency levels, or low levels of immersion (Vaughn et al., 2019; Claussenius-Kalman et al., 2020). This type of bilingual use would be expected to require increased executive control demands whenever the least practiced language is used, with more recruitment of frontal and cortical structures, in contrast to environments with a balanced use of languages and opportunities of intense immersion, which are expected to shorten the latency by which efficiency effects materialize (DeLuca et al., 2020).

Crucially, many studies that investigated effects of bilingualism on GM structure treated bilingualism as a categorical variable, an approach that has been recently challenged (Luk and Bialystok, 2013; Anderson et al., 2018; Deluca et al., 2019a; Pliatsikas et al., 2019). When dividing participants in two groups based on their experience with languages and treating each group as a homogeneous category, relevant bilingual variability within the groups is likely missed (Grundy et al., 2017), since few people have "pure" and indistinguishable monolingual and bilingual experiences (Luk and Bialystok, 2013). Consequently, it has been argued that bilingualism would be better described as a continuum arising from bilingual experience-based factors, since these show *when* bilingualism starts to influence the system and *how* it interacts with it (Deluca et al., 2019a). Following up on the criticism on the categorical approach, recent studies have started to investigate the effects of *quantified* bilingualism on GM structure, reporting effects such as significant correlations between length of L2 immersion and globus pallidus expansions (Pliatsikas et al., 2017), and reshaping of left thalamus and right caudate nucleus volumes and decreases in left middle temporal gyrus as a function of amount of exposure to L2 (Burgaleta et al., 2016). To investigate similar effects, recent studies have looked at how structural changes can be predicted by bilingualism composite "scores" provided by tools such as the Language and Social Background Questionnaire [LSBQ, Anderson et al. (2018)], the Language Experience and Proficiency Questionnaire [LEAP-Q, Kaushanskaya et al. (2020)], and the Language History Questionnaire [LHQ3, Li et al. (2020)], all of which measure bilingualism experience-based factors such as language proficiency, AoA, or frequency of use in different contexts. For example, Deluca and colleagues (Deluca et al., 2019a) used as predictors of brain change scores derived from the LSBQ, including L2 use in social/community settings, and in home settings, as well as L2 AoA and length of immersion. Results showed that L2 AoA positively correlated with GM expansions in the left nucleus accumbens and bilateral thalamus, length of L2 immersion predicted reshaping in right caudate nucleus, expansions in right putamen and contractions in bilateral thalamus and nucleus accumbens, and social use also predicted significant expansions in left caudate nucleus, left nucleus accumbens and right thalamus. Other investigations have also found significant relationships between specific aspects of the bilingual experience and GM structure, such as negative correlations between both AoA and current exposure to L2 and GM volume in right IFG (Wei et al., 2015), reductions in left thalamus and right caudate nucleus, but expansions in left middle temporal gyrus, as a function of amount of time listening and speaking the dominant language (Burgaleta et al., 2016), and positive correlations between expansions in right globus pallidus and length of immersion in a country where L2 is dominant (Pliatsikas et al., 2017). Interestingly, another study found accent scores to be significantly correlated with GM volume in left putamen only in sequential bilinguals–the more native-like they sounded, the more left putaminal volume they showed (Berken et al., 2016). Similar patterns have been reported in studies looking at the relationship between WM integrity and AoA of L2 (Nichols and Joanisse, 2016; Rossi et al., 2017), length of L2 training/immersion (Mamiya et al., 2016), and L2 proficiency (Nichols and Joanisse, 2016; Singh et al., 2018). Taken together, this evidence suggests that the relationship between bilingual experience and brain changes may be better grasped by approaches that quantify the bilingual experience rather than more traditional categorical descriptions of bilingualism.

However, it still remains the case that even investigations that used correlational approaches might fail to describe the full patterns underlying bilingualism-induced neuroplasticity because of the use of linear approaches. These approaches assume continuous growth or reduction of brain structures as a function of bilingual experience, which is an unlikely pattern due to the mixed findings of multiple bilingualism studies (Tao et al., 2021); indeed, theories on experience-based neuroplasticity have assumed non-linear volumetric changes in the brain, with volumetric increases during skill acquisition followed by decreases that suggest efficient brain reorganisation (Lövdén et al., 2013). Therefore, non-linear approaches may be better suited to describe the changing tendencies of brain adaptations along the bilingual experience. The Dynamic Restructuring Model (DRM), a recent proposal that attempts to coherently merge all the apparently inconsistent evidence, describes bilingualism's effects on brain structure as dynamic and non-linear, that is, following patterns of expansion and renormalization (Pliatsikas, 2020). Specifically, the DRM proposes three main stages of bilingual experience, characterized by different brain adaptations: initial exposure, consolidation, and peak efficiency. At the initial exposure stage, the model proposes that cortical GM volumes increase especially in anterior regions related to executive control, and parietal and temporal areas related to specific aspects of language learning. Subcortical and cerebellar GM volumes are also proposed to expand in this stage, due to the increases in demands for language control and selection between motor programmes. These expansions revert and renormalize cortically in the consolidation stage, potentially due to the optimization of lexical learning and control through the elimination of redundant local connections and conservation of only the most efficient. Still, cerebellar and subcortical regions continue increasing in volume, since bilinguals still need to exert language control and selection. The last stage, which is described by the author as the most difficult to characterize due to the scarcity of evidence, would be distinguished by further cerebellar increases, renormalization of the caudate nucleus and stabilization of the putamen and globus pallidus.

Notably, a recent study investigating young healthy bilinguals provides evidence in support of these non-linear patterns of GM changes (Korenar et al., 2021). Korenar and colleagues used generalized additive mixed models (GAMMs) to investigate non-linear effects of bilingual experience, as measured by a composite score that is calculated by the LSBQ (Anderson et al., 2018), on regional subcortical volumes. They found linear volume increases in putamen and thalamus as a function of bilingualism, but non-linear patterns of expansion-renormalization in bilateral caudate nuclei and expansion-plateauing in the nucleus accumbens. These results were interpreted in terms of the DRM predictions (Pliatsikas, 2020): the continuous increase in volume for putamen and thalamus goes in line with the constant need for bilinguals to select motor programmes of the target language and exert cognitive control, whereas the observed pattern in caudate nucleus reflects its central role in lexical control and selection, crucial in initial stages of bilingual experience, but likely optimised as experience increases. Moreover, the pattern observed in nucleus accumbens is interpreted to reflect the initial reward in pursuing social interactions that might reach a plateau when bilinguals reach language efficiency. Nevertheless, this study focused only on subcortical structures, and investigated a very specific sample of bilinguals: highly proficient non-immersed speakers of an L2 and with limited opportunity for active naturalistic bilingual language use. Thus, it remains to be determined whether non-linear bilingualism's effects on brain structure extend to cortical regions and to populations with more sustained long-term immersive bilingual experiences.

In the present study, our main objective was to investigate non-linear effects of bilingual experiences on the GM structure in a healthy sample of bilinguals from the region of València. Both Spanish and Catalan are official languages widely used in society in that region, so bilinguals have the opportunity to use both of them in an active and naturalistic context. Our sample presented a wide variety of bilingual experiences, ranging from simultaneous immersed to late non-immersed bilinguals, in order to fully capture the variability of bilingual experiences and their dynamic effects. We developed a bilingualism score from a questionnaire that was appropriate to the particular linguistic environment of our participants, and this score was used as a predictor of grey matter volume in specific regions. Following up on recent work (Pliatsikas et al., 2020; Korenar et al., 2021), we used GAMMs to account for non-linear volumetric effects of bilingualism, by focusing on the regions of the speech pipeline and language control network proposed in the ACH (Green and Abutalebi, 2013). This method enabled us to model complex patterns of GM volume changes as a function of bilingual experiences, which constitutes one of the main strengths and novel aspects of our investigation, as opposed to previous studies that used categorical and linear approaches. This also allows us to account for non-linear GM changes due to age, previously described to follow an inverted U shape of initial volume increases during childhood, followed by abrupt reductions in adolescence and more stable pruning during adulthood (Giedd et al., 1999). For example, such patterns have been documented in the parietal lobe, also extending to medial and superior frontal cortices, the cingulum, postcentral cortex and occipital lobe (Tamnes et al., 2010). These patterns have been reported to differ between bilinguals and monolinguals during childhood and adolescence, with bilinguals showing less age-related reductions of frontal and parietal regions (Pliatsikas et al., 2020). Following up on previous investigations (Burgaleta et al., 2016; Pliatsikas et al., 2017; Deluca et al., 2019a; Korenar et al., 2021), we expected to find linear increases in GM volume of putamen, thalamus and cerebellum as a function of bilingualism score, as well as increases followed by reductions in the caudate nucleus. Due to the characteristics of the immersive bilingual environment of our sample, where a balanced used of the two languages is common, and in line with previous models' predictions (Grundy et al., 2017; DeLuca et al., 2020; Pliatsikas, 2020), we expected to expand on previous evidence (Korenar et al., 2021) by finding volume increases in cortical areas—IFC, ACC, and parietal cortex—as a function of bilingualism score, accommodating for the continuous control demands exerted by a context of high diversity and intensity of use, but also a shortened latency for the return to baseline volumes due to increasing efficiency.

MATERIALS AND METHODS

Participants

Data from 334 healthy participants was included in this study (147 females; 187 males; mean age = 23, SD = 6, range = 18–53). All participants were right-handed, had normal or corrected-to-normal vision, and reported no previous history of neurological, psychiatric or language disorders. All participants were born in Spain and living in the region of València at the time of testing. This is a territory where both Catalan and Spanish are taught during formal education and co-officially used in public administration. Since both languages are understood by most of the population (Generalitat Valenciana. Direcció General de Política Lingüística i Gestió del Multilingüïsme, 2015), a person can choose to use one or the other depending on the context, motivated by factors such as personal preferences, habits or perceived command on the languages of the interlocutor and oneself. As a consequence, participants in our sample spoke fluently only Spanish or Spanish and Catalan, and lived a complex variety of bilingual experiences, close to being "monolingual" and at different degrees of "bilingual." This means that some of them had simultaneously acquired Spanish and Catalan (46%), while others acquired the second language later in life (54%). Moreover, some of them had a balanced use of both languages to different degrees (46%), which entailed different degrees of immersion in Catalan (years of immersion range = 0–52), while others were clearly exposed to one language over the other in their daily lives (64%).

Data from 60 of our participants had already been used in a previous study (Burgaleta et al., 2016) that serves as basis for our investigation. Therefore, this data was only used for the extraction of the bilingualism score based on our bilingualism questionnaire (See Data analysis—Bilingualism score) and subsequently excluded from further analyses, resulting in a final sample of 274 subjects (115 females; 159 males; mean age = 23, SD = 6, range = 18–53; 45,7% of simultaneous bilinguals, 42,6% immersed, 67,4% non-immersed; years of immersion range = 0–49).

Written informed consent before scanning was obtained from each subject and they received monetary compensation for their time and effort. The study was approved by the Ethics Committee of the Universitat Jaume I.

Bilingualism Questionnaire

To assess the characteristics of the bilingual experiences of our participants, they were administered an in-house questionnaire. This questionnaire contained two sections. In the first one, demographic information was gathered, and participants were asked about their proficiency (from 1 = perfect, to 4 = very low), general frequency of use in percentages and AoA of Catalan and Spanish. In the second part, information regarding frequency of use (proportion of Spanish/Catalan use) in specific contexts (home, school, and others) and periods of time (childhood, adolescence, adulthood) was gathered (see **Supplementary Material** for original questionnaire and a translation into English). This resulted in a comprehensive collection of information regarding lifelong bilingual experiences of the participants in our sample.

Magnetic Resonance Imaging Data Acquisition

Images were acquired on a 1.5-T Siemens Avanto scanner (Erlangen, Germany). Participants were placed inside the scanner in the supine position, and their heads were immobilized with cushions. Whole-brain 3-D images were collected for 6 min using a T1-weighted MPRAGE sequence, with the following parameters: TE = 3.8 ms; TR = 2200 ms; flip angle = 15°; matrix = 256 × 256 × 160 mm; voxel size = 1 mm^3.

Data Analysis

Image Preprocessing

All analyses were performed using the standard preprocessing pipeline of CAT12 (Computational Anatomy Toolbox; C. Gaser, Jena University Hospital, Jena, Germany[1]). After an initial bias correction of intensity non-uniformities, individual volumes of GM, WM, and cerebrospinal fluid were estimated applying the standard segmentation procedure of the toolbox, and images were registered to the template provided. Then, to study region-specific volumetric differences, region of interest (ROI) analysis implemented in CAT12 was performed. In this analysis, also called region-based morphometry (RBM), an anatomical atlas is transformed into native subject space, and the sum of the

[1] http://dbm.neuro.uni-jena.de/cat/

local GM inside the ROIs of the atlas is estimated. We restricted our analysis to the language control and speech production network proposed in the ACH (Green and Abutalebi, 2013), including IFG, ACC, parietal, motor and premotor cortices, thalamus, caudate, putamen, cerebellum and insula (see **Table 1** for mean volumes of ROIs by hemisphere). Volumes of all ROIs were extracted using the LONI Probabilistic Brain Atlas [LPBA40; Shattuck et al. (2008)] provided by the toolbox, except for left and right cerebellum, thalamus and ACC, extracted using the Computational Brain Anatomy (CoBrA) atlas[2] and the automated anatomical labelling atlas 3 [AAL3; Rolls et al. (2020)], because these subdivisions were not defined in the LPBA40. Finally, total intracranial volume (TIV) was estimated.

Bilingualism Score

In order to obtain a single score that reflected the degree of bilingualism of our participants, an exploratory factor analysis (EFA) was carried out from the data obtained in our bilingualism questionnaire, following the procedure used in a previous study (Anderson et al., 2018).

All analyses were performed using Rstudio (R version 3.6.3). First, a matrix of correlations was estimated between the 41 bilingualism items in our questionnaire, using *mixedCor* function from the *psych* package. Eighteen items fulfilled the criterion of correlating higher than $r = 0.3$ or lower than $r = -0.3$ with more than 50% of the rest of the items of the questionnaire. This implied discarding items related to Spanish proficiency (understanding, reading, writing, listening and fluency), probably due to the low variability in these scores found in our sample (e.g., for Spanish comprehension, mean = 1.03, SD = 0.18). A first EFA was carried out using the correlation matrix of those 18 items, and the inspection of their loadings led to the exclusion of 4 more, since they could not be clearly associated to a single factor (they were found to load strongly or very similarly in more than one). After this, 14 items were left to be analyzed (see **Table 2**). The Kaiser-Meyer-Olin (KMO) test (Kaiser and Rice, 2016) verified the sampling adequacy for our analysis (KMO = 0.92) and all the individual KMO values for the items were higher than 0.85. Bartlett's test for sphericity indicated that correlations between our items were sufficiently large for factor analysis [$\chi^2_{(91)} = 6759.24$, $p < 0.001$], and we got an alpha of 0.97, indicating a high internal consistency of the items in our questionnaire.

Next, a parallel analysis was performed using the matrix of correlations of the remaining 14 items, in order to determine the number of factors to be retained in the EFA. The output and scree plot suggested three factors. An EFA was carried out using an ordinary-least-squares minimum residual approach and an oblique rotation (*promax*), obtaining three factors and its factor loadings (**Table 2**). The three factors in combination explained 85% of the variance. Inspection of the distribution of the loadings revealed that Factor 1 is related to use of Catalan and Spanish at school and Catalan proficiency, Factor 2 reflects general use of both languages in contexts outside home and school, and Factor 3 represents use at home.

After obtention of factor structure, scores for each of the factors were calculated using *factor.scores* function in R and using the Harman method, which finds weights based on "idealized" variables (Grice, 2001). Lastly, a composite bilingualism score was computed by summing the factor scores weighted by each factor's variance (Anderson et al., 2018). The final score ranged from −1.25 to 0.67 (SD = 0.47, skewness = −0.987, kurtosis = 0.127; see **Supplementary Material** for a graphical representation of the distribution). We verified the meaning of our score by exploring its relationship with the items of our questionnaire and found that the higher bilingual scores were present in the participants who reported a more balanced use of Catalan and Spanish, as well as balanced proficiency (high proficiency in both languages), while lower scores were found in the participants who reported unbalanced use and lower Catalan proficiency. Thus, our general bilingualism score reflects lifelong balanced use of both languages and proficiency. It is

[2]https://github.com/cobralab/atlases

TABLE 1 | Mean and standard deviation of grey matter (GM) volumes (cm^3) of our region of interests (ROIs).

	Mean GM volume (Standard deviation)	
	Left hemisphere	Right hemisphere
Inferior frontal gyrus	24.78 (2.96)	25.41 (3.05)
Parietal (supramarginal gyrus)	8.94 (1.10)	8.52 (1.09)
Anterior cingulate cortex	51.74 (11.78)	44.32 (10.34)
Precentral gyrus	12.53 (1.46)	12.40 (1.36)
Middle frontal gyrus	24.78 (2.96)	25.41 (3.05)
Thalamus	4.58 (0.47)	4.94 (0.50)
Caudate	3.68 (0.44)	3.55 (0.42)
Putamen	4.61 (0.53)	4.60 (0.52)
Cerebellum	50.04 (4.90)	51.13 (4.97)
Insula	6.55 (0.70)	6.50 (0.74)

TABLE 2 | Standardized loadings of each item and factor, as a result of our exploratory factor analysis (EFA), with the strongest loading for each item indicated in bold.

	Use at home	Proficiency and use at school	General use in other contexts
% Of time hearing Cat	0.16	−0.21	**0.94**
% Of time hearing Sp	−0.08	0.16	**-0.91**
Cat/Sp use at home–child	**0.83**	0.19	0.02
Cat/Sp use at school–child	0.06	**0.59**	0.24
Cat/Sp use at home–adolescent	**0.82**	0.11	0.12
Cat/Sp use at school–adolescent	−0.14	**0.65**	0.41
Cat/Sp use at home–adult	**0.82**	0.09	0.15
Cat/Sp use at workplace–adult	−0.10	0.27	**0.61**
Cat/Sp use another context–adult	0.03	0.23	**0.64**
Writing in Cat	−0.01	**1.01**	−0.07
Pronunciation in Cat	0.18	**0.87**	−0.05
Fluency in Cat	0.25	**0.84**	−0.06
Reading in Cat	0.02	**1.03**	−0.10
Understanding of Cat	0.08	**0.95**	−0.07

% = percentage, Cat = Catalan, Sp = Spanish.

also important to note that one of the factors that forms our composite score contains proficiency in Catalan, since a balanced use of both languages at school (a significant amount of school hours in Catalan, at least 30%) is relevantly related to perception of proficiency on that language, as opposed to proficiency in Spanish, which shows little variation in scores due to its dominant role in society, expressed in specific contexts such as speaking to new people, in department stores or when using social networks (Generalitat Valenciana. Direcció General de Política Lingüística i Gestió del Multilingüïsme, 2015). Finally, our score might be reminiscent of language entropy (Gullifer and Titone, 2020) in that it measures the amount of balance between languages, but it also contains information regarding balance in proficiency and lifelong use.

Statistical Analysis

Data were analysed using R (version 3.6.3.)[3], applying GAMMs by using *gam()* function of the mgcv package (Wood, 2011). GAMMs are generalized linear mixed models with linear predictors that involve a sum of smooth functions of covariates or splines (Wood, 2017)—i.e., the linear component of the model is replaced with an additive component (Hastie and Tibshirani, 1995), allowing to model non-linear data. These splines are only applied if there is enough evidence for a curve in the data, since wiggliness (number of curves) penalizes the estimated model fit. GAMMs compute the estimated degrees of freedom (edf), which indicate whether the predictor is in a non-linear (edf > 1) or a linear relationship (edf $= 1$) with the dependent variable. We ran a series of GAMMs in order to investigate the effects of individual bilingual experiences as measured by our bilingualism composite score on GM of each one of our ROIs.

In a first-level analyses, we used GAMMs in which we fitted a regression spline for the main effect of bilingualism score on GM volume of each ROI, with participant as a random effect, and also considering the main effect of TIV in order to control for the different head sizes of our participants. We examined the interaction effect of bilingualism score and age on GM volumes, due to the large age range in our sample and accounting for non-linear brain changes related to age and bilingualism that have been previously reported (Pliatsikas et al., 2020). We also included the interaction of bilingualism score and hemisphere in our analyses, to account for previous evidence of lateralized bilingualism effects (Deluca et al., 2019a). To do so, following up on previous studies (Pliatsikas et al., 2020; Korenar et al., 2021), we included hemisphere in our models as an ordered factor with two levels (left-right) and we ran two GAMMs, each one with one hemisphere level as reference. The interaction effect between bilingualism score and hemisphere would only be considered reliable if significant in both models.

In a second-level analyses, we analyzed the main effect of bilingual score on GM volumes collapsed across hemisphere, due to the lack of significant interactions with this variable at the first level, and including age, hemisphere and TIV as covariates. We also included participant as a random effect.

[3]https://www.r-project.org/

For all our results, we considered $p < 0.05$ as a threshold of significance, after correcting for family-wise error rate (FWE) using the Bonferroni correction.

Assessment of Model Fits

In order to assess the model fits of all the second-level models, we used the gam.check() function mgcv (Wood, 2011). All the final models converged with six to nine iterations, and the number of functions which gave rise to the regression splines were in all cases higher than the estimated degrees of freedom. For all variables of interest, *p*-values above the 0.05 significance threshold there were obtained, and the k-index was in all cases close to or above 1, which suggests that there were no significant or missed patterns in the residuals of the models (Wood, 2017). See Tables in **Supplementary Material** for details.

RESULTS

In the first-level analyses, we found that neither the interaction between bilingualism score and hemisphere nor between bilingualism and age were significant predictors in any of the ROI volumes (see **Supplementary Material**). Consequently, we carried out our second-level analyses collapsing the data across hemisphere for all ROIs and including hemisphere and age as covariates of no interest.

In the second-level analyses, bilingualism score emerged as a significant predictor of GM in three structures: putamen ($p = 0.034$, FWE corrected), cerebellum ($p = 0.018$, FWE corrected) and IFG ($p = 0.021$, FWE corrected). Specifically, putaminal and cerebellar volumes showed linear increases as a function of increasing bilingual experiences. For GM volume in the IFG, bilingualism emerged as a non-linear predictor that showed an initial decrease, followed by an increase in the middle part of the bilingualism spectrum, and a final decrease at the end of the continuum, resulting in an "S" shaped distribution (see **Figure 1** for details). Hemisphere emerged as a significant predictor of GM volumes of all regions except for insula, putamen and precentral gyrus, and TIV and age emerged as significant predictors for all ROIs ($p < 0.05$, FWE corrected; see **Figure 1** for details).

DISCUSSION

In the present study, we investigated the effect of quantified bilingual experiences on regional GM volumes. To do so, we focused on a healthy sample of bilinguals living in a society where both Spanish and Catalan are actively used, in contrast to environments where languages are used in more compartmentalized manner (Vaughn et al., 2019; Claussenius-Kalman et al., 2020). Due to the language use characteristics of this environment, our sample included a wide variety of bilingual experiences, from simultaneous highly immersed to late bilinguals with little exposure to L2. In order to fully capture this variety, we considered bilingualism as a continuum, avoiding the use of two separate categories for our participants—i.e., "bilinguals" and "monolinguals." We developed a bilingualism

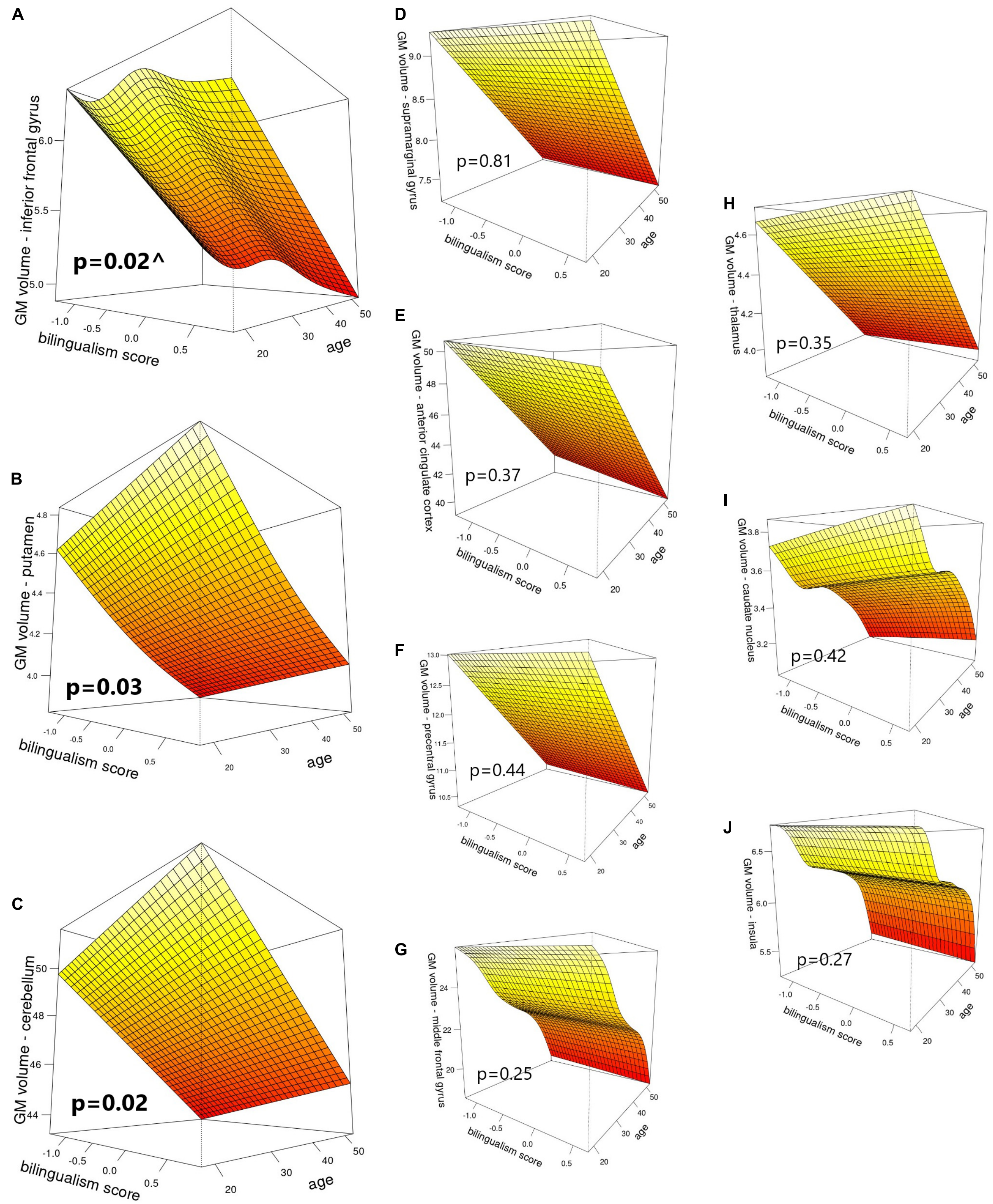

FIGURE 1 | Visual representation of bilingualism score and age as predictors of GM volumes (cm^3) in: **(A)** inferior frontal gyrus, **(B)** putamen, **(C)** cerebellum, **(D)** supramarginal gyrus, **(E)** anterior cingulate cortex, **(F)** precentral gyrus, **(G)** middle frontal gyrus, **(H)** thalamus, **(I)** caudate nucleus, and **(J)** insula. *P*-values correspond to the main effect of bilingualism score. ^ indicates edf > 1, denoting a non-linear effect.

score from data of language use and proficiency, following up from previously published methods (Anderson et al., 2018). Finally, we used non-linear models in order to account for dynamic effects of bilingualism on GM volumes, that is, expansion and renormalization patterns (Korenar et al., 2021), in a series of regions that have been implicated in bilingual language control (Abutalebi and Green, 2016). We found a non-linear relationship between our bilingualism score and GM volume in the IFG; specifically, in the lower and higher parts of the continuum of bilingual experiences, there was a decrease of volume as a function of bilingualism, while we found increases in the middle part of the continuum. We also found that GM putaminal and cerebellar volumes increased linearly as a function of bilingualism. None of these effects interacted with hemisphere, and no other significant effects were observed. The next paragraphs will elaborate on the significant findings and discuss them in the context of similar effects that have been reported in the literature.

The IFG is one of the core cortical areas implicated in language control (Abutalebi and Green, 2016), and its GM volume has been shown to increase in L2 learners with brief experience–3 weeks to 4 months–compared to monolinguals (Stein et al., 2012; Hosoda et al., 2013; Legault et al., 2019). Based on these findings, the IFG was one of the cortical regions predicted to increase its volume in initial stages of bilingualism and later renormalize as duration of bilingual experience increases (Grundy et al., 2017; Pliatsikas, 2020). This suggestion partly matches the pattern of our current findings: The volume reductions we found in IFG at the lower end of the bilingualism continuum could be explained by the characteristics of our sample: immersed bilinguals with such limited bilingual experiences could be considered "passive bilinguals" (Calabria et al., 2020; Costumero et al., 2020), i.e., they have been exposed to a second language and are able to understand it, but currently have limited opportunities to use it and/or switch between languages. Thus, IFG might have increased its volume at an earlier point of their bilingual experience and renormalization might be already in place as the opportunities to use both languages start to increase. This would also go in line with recent evidence showing that forced switching implies increased brain activity in right IFG as measured by magnetoencephalography (MEG), an effect that is absent during natural switching (Zhu et al., 2022). Given the bilingual characteristics of the region where we conducted our study, where a big majority of the population is able to understand both languages, switching is probably more natural than enforced by the context—if the interlocutor understands both languages, changes from one to the other can be performed freely, not because they are required for successful communication. Therefore, reductions in IFG volume might be related to an increase in experience with naturalistic switching and reduced involvement of the IFG. It should be noted that we did not ask our participants if they performed forced or natural switching, so this limits our interpretation. Finally, the UBET predicts that increased intensity and diversity of language use will reduce the latency by which efficiency adaptations and automation happen as a function of duration of use (DeLuca et al., 2020). Our study was carried out in an environment where two languages are broadly used and opportunities for interacting using both are plentiful, which might increase and diversify the exposure to L2 in the earliest stages of acquisition of the language and accelerate the process of optimisation and pruning of GM cortical volumes.

Our results also showed an unexpected increase of IFG volumes in the middle of the bilingual experience spectrum, right after the initial decrease, which itself was followed by a decrease at the highest levels of bilingual experience. This effect might be caused by a change in the nature of the cognitive demands that bilingualism poses after the first stages of bilingual experience, and before reaching full efficiency (Pliatsikas, 2020), such as the exposure to novel bilingual naturalistic contexts, which would suppose renewed high control demands and might be accompanied by increases in IFG volume, which also seem to normalise again with increasing experience. This pattern escapes the predictions of previous models, which makes it hard to interpret in more detail. To the best of our knowledge, such an effect had not been reported before, but this might be due to the fact that previous studies with similar socio-linguistic characteristics did not use continuous non-linear approaches on cortical GM volumes. Taken at face value, this finding suggests that the dynamicity of the effects of bilingualism in immersive environments may hold even for cortical regions, not just subcortical or the cerebellum as it was previously thought (Deluca et al., 2019b; Pliatsikas, 2020) and calls for more evidence from similar samples that are highly immersed for long periods, which will help elaborate on the relevant theories.

Our results further corroborate suggestions that bilingualism increases the volume of the putamen (Abutalebi et al., 2013; Burgaleta et al., 2016; Pliatsikas et al., 2017), and that these effects may be a function of measures of bilingual experiences, such as length of immersion in the L2 (Deluca et al., 2019a), or the general degree of bilingualism (Korenar et al., 2021). This region receives inputs from parietal associative areas and is connected to motor regions (Cacciola et al., 2017), which goes in line with evidence showing its involvement in phonological processing (Tettamanti et al., 2005), language control (Hervais-Adelman et al., 2017), motor programming (Garbin et al., 2010), and articulation of L2 (Klein et al., 1994, 1995, 2006; Simmonds et al., 2011; Berken et al., 2016, 2017). Therefore, it is hypothesized that is more often recruited by bilinguals than monolinguals, leading to volume increases, since the first learn and continuously use a wider range of speech sounds than the second (Burgaleta et al., 2016), and need to control motor programmes between the two languages (Pliatsikas, 2020). Crucially, this effect might be independent of immersion, since it has been reported in immersed and non-immersed bilinguals (Deluca et al., 2019a; Korenar et al., 2021), and may be related to simultaneous acquisition and native-like accent proficiency (Berken et al., 2016).

Similar to the putamen, our results also corroborate previous evidence showing GM volume increases in the cerebellum of immersed bilinguals (Filippi et al., 2011; Pliatsikas et al., 2014; Burgaleta et al., 2016). The cerebellum is critical to language control due to its connections to the inferior frontal cortex and thalamus (Abutalebi and Green, 2016). It has also been suggested to participate in error-based learning of complex structural rules, as a part of the procedural memory system (Ullman, 2004). Notably, GM density in the cerebellum has been linked to efficiency in suppressing the first language when using in the second (Filippi et al., 2011) and cerebellar volume is directly related to the speed of processing of grammatical rules in L2

(Pliatsikas et al., 2014). All this evidence suggests that immersive bilingual environments entail high demands of language control and grammatical processing, which involves a special recruitment of the cerebellum and an increase in its volume in all stages of the immersed bilingual experience (Deluca et al., 2019b; Pliatsikas, 2020).

Some major cortical regions that lacked significant changes in our results were ACC and inferior parietal cortex. The inferior parietal lobule is thought to be crucial for the integration of semantics and phonology of recently learned vocabulary (Richardson et al., 2010), a process that might have already taken place even in our less experienced bilingual participants, since they could be considered "passive bilinguals" (Calabria et al., 2020; Costumero et al., 2020). Alternatively, the ACC is associated to conflict monitoring, which is hypothesized to be especially required in dual-language interactional contexts (Green and Abutalebi, 2013). However, in territories where Catalan and Spanish are widely used, bilinguals tend to mix both languages during the same interaction (Rodriguez-Fornells et al., 2006; Garbin et al., 2011), resulting in a bilingual experience closer to dense code-switching, where opportunistic planning is hypothesized to be more relevant for the interaction than conflict monitoring (Green and Abutalebi, 2013). Moreover, voluntary switching, as opposed to imposed by external cues, has been shown to require less ACC and prefrontal MEG activation (Blanco-Elorrieta and Pylkkänen, 2017). Since most of the population in the region where we carried out our study understands both languages, we interpret that switching is probably more natural than forced, and this could explain the absence of significant effects in the ACC as a function of bilingual experience. The fact that we found significant effects only in IFG and cerebellum cortically also goes in line with ACH predictions for dense code-switching interactional contexts, where special recruitment of these regions is expected (Abutalebi and Green, 2016). Still, we did not measure the characteristics of our participants' conversational context, so these interpretations remain speculative. Future research should try to measure bilingualism experiences not only focusing on usage diversity, intensity, duration, and proficiency, but also on the characteristics of interactional contexts where participants make use of their languages, e.g., nature of switching practices. As for the subcortical structures described in the ACH, we did not find the expected significant changes as a function of bilingualism for the caudate nucleus and thalamus. Volumes of caudate nucleus are expected to increase in bilinguals who start acquiring vocabulary of an L2, and renormalize with increased experiences (Pliatsikas, 2020). However, previous evidence suggests that these changes are restricted to bilinguals with limited immersion, due to less proficiency and practice of L2, and would not be necessary for bilinguals in an active immersive environment, an interpretation that goes in line with the immersive context where our bilinguals find themselves and the lack of significant results we observed in this region (Pliatsikas et al., 2017). Regarding the thalamus, it is believed to intervene in the selection of relevant lexical and semantic representations in bilinguals (Abutalebi and Green, 2016), but previous studies have emphasized the specialized contribution of its nuclei to different language functions, such as naming or active speech listening, and advocated for investigating these nuclei separately (Llano, 2013; Burgaleta et al., 2016). Thus, the lack of regional subdivisions in our analyses might have masked GM volume changes in different thalamic nuclei as a function of bilingual experience.

To summarize, in this study we investigated the dynamic effects of bilingualism on GM volumes of healthy participants with a wide variety of bilingual experiences, living in a naturalistic and immersive bilingual environment. We reported a non-linear relationship between IFG and bilingualism score, a pattern that largely goes in line with predictions for effects in environments with high bilingual immersion, increased diversity and intensity of language use. We also reported linear putaminal and cerebellar GM volume increases as a function of bilingualism, which might reflect a growing need to control for motor programmes and grammatical processing. Our results further support the dynamic nature of bilingualism's effects on brain structure and show that this dynamicity is also present in immersive environments.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Universitat Jaume I. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

VC, CÁ, and CP contributed to conception and design of the study. VC and LM-M organized the database. LM-M performed the statistical analysis and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.886222/full#supplementary-material

REFERENCES

Abutalebi, J., Della Rosa, P. A., Castro Gonzaga, A. K., Keim, R., Costa, A., and Perani, D. (2013). The role of the left putamen in multilingual language production. *Brain Lang.* 125, 307–315. doi: 10.1016/j.bandl.2012.03.009

Abutalebi, J., and Green, D. W. (2016). Neuroimaging of language control in bilinguals: neural adaptation and reserve. *Bilingualism* 19, 689–698. doi: 10.1017/S1366728916000225

Anderson, J. A. E., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Berken, J. A., Gracco, V. L., Chen, J. K., and Klein, D. (2016). The timing of language learning shapes brain structure associated with articulation. *Brain Struct. Funct.* 221, 3591–3600. doi: 10.1007/S00429-015-1121-9/TABLES/4

Berken, J. A., Gracco, V. L., and Klein, D. (2017). Early bilingualism, language attainment, and brain development. *Neuropsychologia* 98, 220–227. doi: 10.1016/J.NEUROPSYCHOLOGIA.2016.08.031

Blanco-Elorrieta, E., and Pylkkänen, L. (2017). Bilingual Language Switching in the Laboratory versus in the Wild: the Spatiotemporal Dynamics of Adaptive Language Control. *J. Neurosci.* 37, 9022–9036. doi: 10.1523/JNEUROSCI.0553-17.2017

Burgaleta, M., Sanjuán, A., Ventura-Campos, N., Sebastian-Galles, N., and Ávila, C. (2016). Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *Neuroimage* 125, 437–445. doi: 10.1016/j.neuroimage.2015.09.073

Cacciola, A., Calamuneri, A., Milardi, D., Mormina, E., Chillemi, G., Marino, S., et al. (2017). A Connectomic Analysis of the Human Basal Ganglia Network. *Front. Neuroanat.* 11:85. doi: 10.3389/FNANA.2017.00085

Calabria, M., Hernández, M., Cattaneo, G., Suades, A., Serra, M., Juncadella, M., et al. (2020). Active bilingualism delays the onset of mild cognitive impairment. *Neuropsychologia* 146:107528. doi: 10.1016/J.NEUROPSYCHOLOGIA.2020.107528

Claussenius-Kalman, H., Vaughn, K. A., Archila-Suerte, P., and Hernandez, A. E. (2020). Age of acquisition impacts the brain differently depending on neuroanatomical metric. *Hum. Brain Mapp.* 41, 484–502. doi: 10.1002/HBM.24817

Costumero, V., Marin-Marin, L., Calabria, M., Belloch, V., Escudero, J., Baquero, M., et al. (2020). A cross-sectional and longitudinal study on the protective effect of bilingualism against dementia using brain atrophy and cognitive measures. *Alzheimers Res. Ther.* 12:11. doi: 10.1186/s13195-020-0581-1

Deluca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019a). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U. S. A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

Deluca, V., Rothman, J., and Pliatsikas, C. (2019b). Linguistic immersion and structural effects on the bilingual brain: a longitudinal study. *Bilingualism* 22, 1160–1175. doi: 10.1017/S1366728918000883

DeLuca, V., Segaert, K., Mazaheri, A., and Krott, A. (2020). Understanding bilingual brain function and structure changes? U bet! A unified bilingual experience trajectory model. *J. Neurolinguistics* 56:100930. doi: 10.1016/J.JNEUROLING.2020.100930

Filippi, R., Richardson, F. M., Dick, F., Leech, R., Green, D. W., Thomas, M. S. C., et al. (2011). The Right Posterior Paravermis and the Control of Language Interference. *J. Neurosci.* 31, 10732–10740. doi: 10.1523/JNEUROSCI.1783-11.2011

Garbin, G., Costa, A., Sanjuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N., et al. (2011). Neural bases of language switching in high and early proficient bilinguals. *Brain Lang.* 119, 129–135. doi: 10.1016/J.BANDL.2011.03.011

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., et al. (2010). Bridging language and attention: brain basis of the impact of bilingualism on cognitive control. *Neuroimage* 53, 1272–1278. doi: 10.1016/J.NEUROIMAGE.2010.05.078

García-Pentón, L., García, Y. F., Costello, B., Duñabeitia, J. A., and Carreiras, M. (2015). The neuroanatomy of bilingualism: how to turn a hazy view into the full picture. *Lang. Cogn. Neurosci.* 31, 303–327. doi: 10.1080/23273798.2015.1068944

Generalitat Valenciana. Direcció General de Política Lingüística i Gestió del Multilingüisme (2015). *Coneixement i ús social del valencià. Enquesta 2015. Síntesi de resultats*. Valencia: Generalitat Valenciana.

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence: a longitudinal MRI study. *Nat. Neurosci.* 210, 861–863. doi: 10.1038/13158

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Grice, J. W. (2001). Computing and evaluating factor scores. *Psychol. Methods* 6, 430–450. doi: 10.1037/1082-989X.6.4.430

Grundy, J. G., Anderson, J. A. E., and Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Ann. N. Y. Acad. Sci.* 1396, 183–201. doi: 10.1111/nyas.13333

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism* 23, 283–294. doi: 10.1017/S1366728919000026

Hastie, T., and Tibshirani, R. (1995). Generalized additive models for medical research. *Stat. Methods Med. Res.* 4, 187–196. doi: 10.1177/096228029500400302

Hervais-Adelman, A., Moser-Mercer, B., Murray, M. M., and Golestani, N. (2017). Cortical thickness increases after simultaneous interpretation training. *Neuropsychologia* 98, 212–219. doi: 10.1016/j.neuropsychologia.2017.01.008

Hosoda, C., Tanaka, K., Nariai, T., Honda, M., and Hanakawa, T. (2013). Dynamic Neural Network Reorganization Associated with Second Language Vocabulary Acquisition: a Multimodal Imaging Study. *J. Neurosci.* 33, 13663–13672. doi: 10.1523/JNEUROSCI.0410-13.2013

Kaiser, H. F., and Rice, J. (2016). Little Jiffy, Mark Iv. *Educ. Psychol. Meas.* 34, 111–117. doi: 10.1177/001316447403400115

Kaushanskaya, M., Blumenfeld, H. K., and Marian, V. (2020). The Language Experience and Proficiency Questionnaire (LEAP-Q): ten years later. *Bilingualism* 23, 945–950. doi: 10.1017/S1366728919000038

Klein, D., Milner, B., Zatorre, R. J., Meyert, E., and Evanst, A. C. (1995). The neural substrates underlying word generation: a bilingual functional-imaging study. *Proc. Natl. Acad. Sci. U. S. A.* 92, 2899–2903. doi: 10.1073/pnas.92.7.2899

Klein, D., Mok, K., Chen, J. K., and Watkins, K. E. (2014). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. *Brain Lang.* 131, 20–24. doi: 10.1016/j.bandl.2013.05.014

Klein, D., Watkins, K. E., Zatorre, R. J., and Milner, B. (2006). Word and nonword repetition in bilingual subjects: a PET study. *Hum. Brain Mapp.* 27:153. doi: 10.1002/HBM.20174

Klein, D., Zatorre, R. J., Milner, B., Meyer, E., and Evans, A. C. (1994). Left putaminal activation when speaking a second language: evidence from PET. *Neuroreport* 5, 2295–2297. doi: 10.1097/00001756-199411000-00022

Korenar, M., Treffers-Daller, J., and Pliatsikas, C. (2021). Bilingual experiences induce dynamic structural changes to basal ganglia and the thalamus. *Res. Square* [Preprint]. doi: 10.21203/RS.3.RS-1017465/V1

Legault, J., Grant, A., Fang, S. Y., and Li, P. (2019). A longitudinal investigation of structural brain changes during second language learning. *Brain Lang.* 197:104661. doi: 10.1016/J.BANDL.2019.104661

Li, P., Zhang, F., Yu, A., and Zhao, X. (2020). Language History Questionnaire (LHQ3): an enhanced tool for assessing multilingual experience. *Bilingualism* 23, 938–944. doi: 10.1017/S1366728918001153

Llano, D. A. (2013). Functional imaging of the thalamus in language. *Brain Lang.* 126, 62–72. doi: 10.1016/j.bandl.2012.06.004

Lövdén, M., Wenger, E., Mårtensson, J., Lindenberger, U., and Bäckman, L. (2013). Structural brain plasticity in adult learning and development. *Neurosci. Biobehav. Rev.* 37, 2296–2310. doi: 10.1016/J.NEUBIOREV.2013.02.014

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: interaction between language proficiency and usage. *J. Cogn. Psychol.* 25:605. doi: 10.1080/20445911.2013.795574

Mamiya, P. C., Richards, T. L., Coe, B. P., Eichler, E. E., and Kuhl, P. K. (2016). Brain white matter structure and COMT gene are linked to second-language learning in adults. *Proc. Natl. Acad. Sci. U. S. A.* 113, 7249–7254. doi: 10.1073/PNAS.1606602113/SUPPL_FILE/PNAS.201606602SI.PDF

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., et al. (2004). Structural plasticity in the bilingual brain. *Nature* 431:757. doi: 10.1038/431757a

Nichols, E. S., and Joanisse, M. F. (2016). Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning. *Neuroimage* 143, 15–25. doi: 10.1016/j.neuroimage.2016.08.053

Olulade, O. A., Jamal, N. I., Koo, D. S., Perfetti, C. A., LaSasso, C., and Eden, G. F. (2016). Neuroanatomical Evidence in Support of the Bilingual Advantage Theory. *Cereb. Cortex* 26, 3196–3204. doi: 10.1093/CERCOR/BHV152

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: the Dynamic Restructuring Model. *Biling. Lang. Cogn.* 23, 459–471. doi: 10.1017/S1366728919000130

Pliatsikas, C., DeLuca, V., Moschopoulou, E., and Saddy, J. D. (2017). Immersive bilingualism reshapes the core of the brain. *Brain Struct. Funct.* 222, 1785–1795. doi: 10.1007/s00429-016-1307-9

Pliatsikas, C., DeLuca, V., and Voits, T. (2019). The Many Shades of Bilingualism: language Experiences Modulate Adaptations in Brain Structure. *Lang. Learn.* 70, 133–149. doi: 10.1111/lang.12386

Pliatsikas, C., Johnstone, T., and Marinis, T. (2014). Grey matter volume in the cerebellum is related to the processing of grammatical rules in a second language: a structural voxel-based morphometry study. *Cerebellum* 13, 55–63. doi: 10.1007/s12311-013-0515-6

Pliatsikas, C., Meteyard, L., Veríssimo, J., DeLuca, V., Shattuck, K., and Ullman, M. T. (2020). The effect of bilingualism on brain development from early childhood to young adulthood. *Brain Struct. Funct.* 225, 2131–2152. doi: 10.1007/s00429-020-02115-5

Ressel, V., Pallier, C., Ventura-Campos, N., Diaz, B., Roessler, A., Avila, C., et al. (2012). An Effect of Bilingualism on the Auditory Cortex. *J. Neurosci.* 32, 16597–16601. doi: 10.1523/JNEUROSCI.1996-12.2012

Richardson, F. M., Thomas, M. S. C., Filippi, R., Harth, H., and Price, C. J. (2010). Contrasting Effects of Vocabulary Knowledge on Temporal and Parietal Brain Structure across Lifespan. *J. Cogn. Neurosci.* 22, 943–954. doi: 10.1162/JOCN.2009.21238

Rodriguez-Fornells, A., De Diego Balaguer, R., Del Rio, M. J., Escera, C., Festman, J., Gomila, T., et al. (2006). Executive Control in Bilingual Language Processing. *Lang. Learn.* 56, 133–190. doi: 10.1111/J.1467-9922.2006.00359.X

Rolls, E. T., Huang, C. C., Lin, C. P., Feng, J., and Joliot, M. (2020). Automated anatomical labelling atlas 3. *Neuroimage* 206:116189. doi: 10.1016/J.NEUROIMAGE.2019.116189

Rossi, E., Cheng, H., Kroll, J. F., Diaz, M. T., and Newman, S. D. (2017). Changes in White-Matter Connectivity in Late Second Language Learners: evidence from Diffusion Tensor Imaging. *Front. Psychol.* 8:2040. doi: 10.3389/FPSYG.2017.02040

Shattuck, D. W., Mirza, M., Adisetiyo, V., Hojatkashani, C., Salamon, G., Narr, K. L., et al. (2008). Construction of a 3D probabilistic atlas of human cortical structures. *Neuroimage* 39, 1064–1080. doi: 10.1016/j.neuroimage.2007.09.031

Simmonds, A. J., Wise, R. J. S., Dhanjal, N. S., and Leech, R. (2011). A comparison of sensory-motor activity during speech in first and second languages. *J. Neurophysiol.* 106, 470–478. doi: 10.1152/jn.00343.2011

Singh, N. C., Rajan, A., Malagi, A., Ramanujan, K., Canini, M., Della Rosa, P. A., et al. (2018). Microstructural anatomical differences between bilinguals and monolinguals. *Biling. Lang. Cogn.* 21, 995–1008. doi: 10.1017/S1366728917000438

Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., et al. (2012). Structural plasticity in the language system related to increased second language proficiency. *Cortex* 48, 458–465. doi: 10.1016/j.cortex.2010.10.007

Tamnes, C. K., Østby, Y., Fjell, A. M., Westlye, L. T., Due-Tønnessen, P., and Walhovd, K. B. (2010). Brain Maturation in Adolescence and Young Adulthood: regional Age-Related Changes in Cortical Thickness and White Matter Volume and Microstructure. *Cereb. Cortex* 20, 534–548. doi: 10.1093/cercor/bhp118

Tao, L., Wang, G., Zhu, M., and Cai, Q. (2021). Bilingualism and domain-general cognitive functions from a neural perspective: a systematic review. *Neurosci. Biobehav. Rev.* 125, 264–295. doi: 10.1016/J.NEUBIOREV.2021.02.029

Tettamanti, M., Moro, A., Messa, C., Moresco, R. M., Rizzo, G., Carpinelli, A., et al. (2005). Basal ganglia and language: phonology modulates dopaminergic release. *Neuroreport* 16, 397–401. doi: 10.1097/00001756-200503150-00018

Ullman, M. T. (2004). Contributions of memory circuits to language: the declarative/procedural model. *Cognition* 92, 231–270. doi: 10.1016/j.cognition.2003.10.008

Vaughn, K. A., Archila-Suerte, P., and Hernandez, A. E. (2019). Parietal lobe volume distinguishes attentional control in bilinguals and monolinguals: a structural MRI study. *Brain Cogn.* 134, 103–109. doi: 10.1016/J.BANDC.2018.12.001

Wei, M., Joshi, A. A., Zhang, M., Mei, L., Manis, F. R., He, Q., et al. (2015). How age of acquisition influences brain architecture in bilinguals. *J. Neurolinguistics* 36, 35–55. doi: 10.1016/J.JNEUROLING.2015.05.001

Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *J. R. Stat. Soc. Ser. B* 73, 3–36. doi: 10.1111/J.1467-9868.2010.00749.X

Wood, S. N. (2017). *Generalized Additive Models: An Introduction with R. Second Ed*. Boca Raton, Fl: Chapman and Hall/CRC Press, doi: 10.1201/9781315370279

Zhu, J. D., Blanco-Elorrieta, E., Sun, Y., Szakay, A., and Sowman, P. F. (2022). Natural vs forced language switching: free selection and consistent language use eliminate significant performance costs and cognitive demands in the brain. *Neuroimage* 247:118797. doi: 10.1016/J.NEUROIMAGE.2021.118797

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Age of Acquisition Modulates Alpha Power During Bilingual Speech Comprehension in Noise

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Research on bilingualism has grown exponentially in recent years. However, the comprehension of speech in noise, given the ubiquity of both bilingualism and noisy environments, has seen only limited focus. Electroencephalogram (EEG) studies in monolinguals show an increase in alpha power when listening to speech in noise, which, in the theoretical context where alpha power indexes attentional control, is thought to reflect an increase in attentional demands. In the current study, English/French bilinguals with similar second language (L2) proficiency and who varied in terms of age of L2 acquisition (AoA) from 0 (simultaneous bilinguals) to 15 years completed a speech perception in noise task. Participants were required to identify the final word of high and low semantically constrained auditory sentences such as "Stir your coffee with a *spoon*" vs. "Bob could have known about the *spoon*" in both of their languages and in both noise (multi-talker babble) and quiet during electrophysiological recording. We examined the effects of language, AoA, semantic constraint, and listening condition on participants' induced alpha power during speech comprehension. Our results show an increase in alpha power when participants were listening in their L2, suggesting that listening in an L2 requires additional attentional control compared to the first language, particularly early in processing during word identification. Additionally, despite similar proficiency across participants, our results suggest that under difficult processing demands, AoA modulates the amount of attention required to process the second language.

Keywords: electrophysiology, alpha power, bilingualism, speech-in-noise, age of acquisition

INTRODUCTION

Listening to speech in noise is a part of everyday speech processing. Whether it's the traffic outside or a conversation occurring in another room, speech partners are often engaged in not only the basics of speech production and comprehension, but the dual task of ignoring a non-target stimulus. The challenge of processing speech in noisy environments is further complicated in bilingual individuals who are required to listen and comprehend in both a native (L1) and a second (L2) language. Although research has examined speech-in-noise processing in monolinguals, there has been little focus on bilinguals despite estimates that more than half of the world's population speaks more than one language (e.g., Grosjean, 2008). In the current study, we use electrophysiological measures to examine the recruitment of attentional resources during speech-in-noise processing in an L1 and an L2 in a well-controlled sample of bilingual participants. Additionally, we examine the potential role of the timing of L2 learning (i.e., age of acquisition; AoA) on speech-in-noise processing in L2.

Behavioral studies in monolinguals have shown that listening to speech in noise decreases comprehension accuracy (Kalikow et al., 1977; Bilger et al., 1984) and increases listener effort (Zekveld et al., 2014; McMahon et al., 2016; Pichora-Fuller et al., 2016). These effects are thought to be due in part to increased demands on working memory and selective attention systems compared to listening in quiet (for a review, see Wilsch and Obleser, 2016). However, the effects of speech degradation can be reduced if the context is semantically constrained. Behaviorally, a constraining sentence context (Davis et al., 2011) or a semantically related prime (Bernstein et al., 1989; Golestani et al., 2009) have been found to improve the accuracy of target word perception when processing speech in noise.

Electrophysiologically, studies have examined speech perception in noise using the N400 event-related potential (e.g., Connolly et al., 1992; Aydelott et al., 2006; Obleser and Kotz, 2011; Strauß et al., 2013; Carey et al., 2014; Coulter et al., 2020), a negative-going component that peaks approximately 400 ms following an eliciting stimulus. The N400 is elicited by semantic stimuli and its amplitude is inversely related to the semantic expectancy of the stimulus, such that it is larger when a target is semantically unexpected compared to when it is semantically expected (Kutas and Hillyard, 1980; Kutas and Van Petten, 1994; Kutas, 1997). Studies have found that N400 amplitude and the N400 effect (the difference in amplitude between unexpected and expected conditions) are attenuated, and the latency of the N400 is delayed in noise compared to quiet (e.g., Connolly et al., 1992; Aydelott et al., 2006; Obleser and Kotz, 2011; Strauß et al., 2013; Carey et al., 2014), suggesting that despite the beneficial effect of semantic constraint on behavioral performance, a processing cost remains.

Another method for examining electrophysiological measures is to decompose the waveform into its component frequency bands and compute the power in each of the frequency bands (i.e., time-frequency analysis), which have distinct functional correlates. Relevant to the current study, previous research has identified alpha oscillations (∼8–13 Hz) as a neural signature of cognitive effort, with an increase in power in the alpha band associated with increased cognitive effort and inhibition (e.g., Klimesch et al., 2007; Jensen and Mazaheri, 2010). Previous electro- and magneto-encephalography studies of speech-in-noise processing have used alpha power as a measure of attentional processes during speech-in-noise processing. Increases in alpha band power have been associated with increases in speech degradation (e.g., Obleser et al., 2012; Becker et al., 2013) and increased demands on attentional systems and inhibitory control (see Jensen and Mazaheri, 2010; Foxe and Snyder, 2011; for review).

When auditory degradation has been combined with manipulations of working memory, the increase in alpha power is super-additive (Obleser et al., 2012). More recently, Wostmann et al. (2017) manipulated the effort required for speech comprehension by increasing the acoustic detail in to-be-ignored distractor information and concluded that alpha power is related to top-down attentional control, with greater alpha power being positively associated with the effort required for speech comprehension rather than with acoustic degradation, *per se*. Additionally, studies that presented speech in quiet but manipulated the semantic constraint of the sentence find a decrease in alpha band power with increases in semantic constraint, which is thought to indicate the use of predictive mechanisms in sentence comprehension (Rommers et al., 2017; Wang et al., 2018).

Bilingual Speech-in-Noise Comprehension

The current study builds on the existing literature by examining alpha power in L2 speech processing in noise. Previous literature on speech-in-noise processing has found L2 comprehension to be particularly sensitive to effects of noise (e.g., Mayo et al., 1997; Shi, 2010; Hervais-Adelman et al., 2014; Krizman et al., 2017). That is, the presentation of noise impairs speech comprehension in the L2 to a greater extent than in the L1. Furthermore, the limited literature suggests that L2 listeners may not be able to utilize semantic constraint under noisy conditions in the same way as in the L1. In one study, Hervais-Adelman et al. (2014) found that bilinguals only benefited from contextual information when processing speech-in-noise in their native language. More recently, Krizman et al. (2017) showed that bilinguals performed worse when perceiving sentences in noise in their L2 compared to monolinguals, whereas bilinguals performed better than monolinguals at perceiving tones in noise, suggesting that effects of acoustic degradation on L2 speech comprehension are dependent on linguistic knowledge. In contrast, other research has shown that bilinguals may benefit from a contextually supportive sentence context to a greater extent in their L2 compared to their L1 when listening to speech-in-noise (Chauvin and Phillips, in press).

Earlier research has further suggested that the effect of noise on L2 speech comprehension is moderated by L2 AoA, such that bilinguals with earlier ages of acquisition show smaller effects of noise (Mayo et al., 1997; Shi, 2010). More recently, Kousaie et al. (2019) observed that simultaneous bilinguals and those with an L2 AoA before age 5 show a benefit of contextual information in their L2 in terms of behavioral performance, whereas bilinguals who learned their L2 after age 5 did not. In addition to behavioral measures, Kousaie et al. (2019) examined neural responses during L1 and L2 speech processing in noise using functional magnetic resonance imaging, and observed that the absence of a behavioral benefit of context in the late bilinguals was accompanied by differences in neural recruitment of the inferior frontal gyrus in that group compared to simultaneous and early bilinguals. Additionally, using ERPs in a similar paradigm as Kousaie et al., Coulter et al. (2020) showed that bilinguals with different AoAs benefited from contextual information when processing sentences in their L2 in noise; however, ERP topography suggested that additional neural resources were recruited in sequential compared to simultaneous bilinguals. A common weakness in the studies that examine AoA is that AoA and proficiency are often confounded given that bilingual participants with later AoAs tend to be less proficient, although in both Kousaie et al. and Coulter et al. participant groups did not differ in terms of L2 proficiency. However, it remains unclear if the previously observed effects of AoA on L2 speech-in-noise processing are due to differences in AoA or proficiency. In fact, other behavioral research has shown that the ability to inhibit interference in a sentence interpretation task was positively correlated with L2 proficiency (Filippi et al., 2012); however, the paradigm used by Filippi et al. used was different than that used in the studies discussed above. More recently, others have also demonstrated a behavioral advantage in sentence recognition in noise in the L1 of bilinguals compared to monolinguals (Ferreira et al., 2019), while bilinguals in their L2 have been found to perform worse than monolinguals when the stimuli included a combination of words and sentences (Bsharat-Maalouf and Karawani, 2022). Importantly, Bsharat-Maalouf and Karawani (2022) also recorded electrophysiological responses to vowel sounds and found earlier auditory brain stem responses in noise in bilinguals compared to monolinguals, suggesting a different pattern of language group differences at the level of neural responses.

Current Study

The current study compares the performance of highly proficient bilinguals who differ only in L2 AoA to control for the potential confounding effect of L2 proficiency. Furthermore, by evaluating alpha power during both L1 and L2 comprehension, we investigate whether domain general attentional control accounts for differences between L1 and L2 speech processing.

Hypotheses

Based on the current literature, we expected to observe differences in alpha power as a function of the following factors: Listening Condition (Quiet vs. Noise), Language (L1 vs. L2), Semantic Constraint (High vs. Low) and AoA (continuous). Specifically, we expected to observe:

1. Increased alpha power during speech comprehension in Noise compared to Quiet conditions.
2. Increased alpha power during L2 compared to L1 speech comprehension.
3. Increased alpha power for Low compared to High Constraint sentences.
4. A positive association between alpha power during L2 speech-in-noise comprehension and AoA, if AoA has an impact on speech processing in noise in L2.

MATERIALS AND METHODS

Participants

Participants were 49 English/French bilinguals recruited from the Montréal community (mean age = 24.29 years, *SD* = 4.18; 36 females); 16 of these participants previously completed a similar speech perception in noise task during functional magnetic resonance imaging (see Kousaie et al., 2019 for details). Twenty-four participants identified English as their first language, and 25 identified French. Of the total sample, 14 participants were simultaneous bilinguals (i.e., learned both languages from birth), 6 of whom identified English as their dominant language, and 8 of whom identified French as their dominant language; See **Table 1** for a summary of participant characteristics. All participants were right-handed with normal bilateral pure-tone hearing thresholds (i.e., <25 dB at 500, 1000, 2000, and 4000 Hz). Participants gave informed consent and received monetary compensation for participating.

Materials

Speech Perception in Noise Task

The current study used the same speech perception in noise task as Coulter et al. (2020). A total of 240 sentences were adapted from the Revised Speech Perception in Noise Test (SPIN-R; Kalikow et al., 1977). The final words of the SPIN-R stimuli were of high or low predictability based on the amount of semantic context in the sentence (i.e., high- vs. low-constraint, e.g., "The lion gave an angry roar." vs. "He is thinking about the roar.";

TABLE 1 | Summary of demographic, language, and cognitive task data, *n* = 49 (unless otherwise indicated), 36 females.

	Mean (*SD*)
Age	24.29 (*4.18*)
Education	15.32 (*1.73*)
Age of L2 acquisition[a]	4.27 (*3.63*)
L1 letter fluency[a]	36.65 (*9.71*)
L1 category fluency[b]	19.21 (*6.15*)
L2 letter fluency[a]	29.46 (*9.28*)
L2 category fluency[a]	16.00 (*5.42*)
L1 coefficient of variation[a]	0.37 (*0.20*)
L2 coefficient of variation[a]	0.40 (*0.22*)
L1 self-reported speaking proficiency	6.86 (*0.41*)
L1 self-reported listening proficiency	6.94 (*0.32*)
L2 self-reported speaking proficiency	5.79 (*1.03*)
L2 self-reported listening proficiency	6.26 (*0.87*)
L1 percentage of language use[c]	58.63 (*25.83*)
L2 percentage of language use[c]	41.14 (*25.75*)
Digit span forward[b]	7.04 (*1.22*)
Digit span backward[b]	5.15 (*1.32*)
Digit span sequencing[a]	6.13 (*1.14*)
Letter-number sequencing[a]	5.69 (*1.13*)
Matrix reasoning[a]	12.04 (*2.39*)

[a] *Data are missing for one participant.*
[b] *Data are missing for two participants.*
[c] *Data are missing for five participants.*

see Kalikow et al., 1977 for details on sentence creation). Sixty high-constraint and sixty low-constraint English sentences were selected from the eight original lists of the SPIN-R test. The selected high and low constraint English sentences were matched on both number of words (high-constraint: M = 5.5, SD = *0.81*; low-constraint: M = 4.9, SD = *0.79*) and number of syllables (high-constraint: M = 6.5, SD = *0.70*; low-constraint: M = 6.6, SD = *0.70*).

An additional 120 SPIN-R sentences (60 high-constraint and 60 low-constraint) were selected and adapted to French. To match high and low constraint French sentences on sentence length, some French sentences were slightly modified translations of original SPIN-R sentences, e.g., "The bread was made from whole wheat" was adapted to "Le pain brun est fait de blé." French sentences were distinct from the English sentences used in this experiment. High and low constraint French sentences were also matched on number of words (high-constraint: M = 5.8, SD = 1.01; low-constraint: M = 5.0, SD = 1.15) and number of syllables (high-constraint: M = 7.7, SD = 1.04; low-constraint: M = 7.3, SD = 1.21). Target terminal French words were either monosyllabic or disyllabic; disyllabic terminal words were included to accommodate the other stimulus inclusion criteria. English and French terminal words were also matched on spoken frequency (English: M = 20.5, SD = 27.50; French: M = 24.4, SD = 28.90), phonological neighborhood density (English: M = 15.4, SD = 9.22; French: M = 16.4, SD = 7.38), imageability (English: M = 539.5, SD = 65.77; French: M = 563.0, SD = 48.44), and familiarity (English: M = 524.5, SD = 51.36; French: M = 517.4, SD = 55.09) using the MRC Psycholinguistic Database (Coltheart, 1981), Lexique 3 (New et al., 2001; New, 2006), and the Corpus of Contemporary American English (Davies, 2008).

All sentences were recorded by a female, simultaneous bilingual speaker of Canadian English and French. Sentences were recorded in a sound-attenuated booth using an Olympus recorder with a 44.1 kHz sample-rate and 32-bit resolution. Sentence stimuli were presented to participants in both a quiet condition and a noise condition. The background noise consisted of multi-talker babble adapted from Bilger et al. (1984) such that the original eight-talker babble was overlaid three times with a slight temporal jitter to create a babble mask that was less variable in its intensity fluctuations (Winneke and Phillips, 2011).

There were eight experimental conditions (four conditions in each language) in our 2 × 2 × 2 design: High-constraint sentences in quiet, low-constraint sentences in quiet, high-constraint sentences in noise, and low-constraint sentences in noise were presented in each language. Within each language, each target word was presented in all four conditions, but stimuli were divided into two lists so that each target word was heard only twice in each list by any given participant. For example, the terminal word "*spoon*" was heard in the high-constraint quiet and the low-constraint noise conditions in List 1 and was heard in the low-constraint quiet and high-constraint noise conditions in List 2. Each list consisted of eight experimental blocks, as described above. Lists were blocked by listening condition (quiet and noise) and language (English and French), which were counterbalanced within each list. Low constraint and high constraint sentences were pseudo-randomly intermixed within each block such that there were an equal number of each but no more than three consecutive sentences of the same type. Each participant heard only one list and lists were counterbalanced across participants.

Language Proficiency Measures

Participants completed a language history questionnaire and letter and category verbal fluency tasks, and animacy judgment tasks in each of their languages; see **Table 1**. Additional language tasks not discussed here included a story reading and comprehension task, picture description, and sentence repetition.

Participants self-rated their proficiency in speaking and understanding both of their languages on a scale from 1 to 7 (1 being not at all proficient and 7 being native-like proficiency). All participants rated themselves as being highly proficient in their L2. Speaking and listening proficiencies ranged from 5 to 7 for L1 and from 4 to 7 for L2. Participants varied in the percentage of their total conversations in which they used each of their languages, with the percentage of L2 use ranging from 5 to 95% of all conversations.

In the fluency tasks, participants were asked to say as many words as they could (excluding proper nouns, numbers, and words that differed only in their suffix) that began with a given letter of the alphabet or that fit with a given category in 1 min. The letters included *F*, *A*, and *S* for the English letter fluency and the letters *P*, *F*, and *L* for the French letter fluency. The number of words produced for all three letters, within each language, were summed to give a single letter fluency score for each language. For category fluency, the categories were *animals* and *fruit* for English and French, respectively.

For the animacy judgment task, participants judged whether a presented word was living ("m," right key press) or non-living ("z," left key press) as quickly and accurately as possible (Segalowitz and Segalowitz, 1993). During the task, each word was presented in white 18-point Courier New font on a black background using E-Prime 2.0 software on a Dell Precision M2800 15" laptop running Windows 7 professional. Trials ended when the participant responded, and there was a 250-ms interstimulus interval. Participants first completed a neutral block, where they had to judge if the stimulus was a letter or a number. After the neutral block, participants completed separate blocks of the task in each language. Each block began with eight practice trials, followed by 64 unique nouns. The French words were not translations of the English words, and blocks were matched for the number of animate and inanimate judgments. Data from the animacy judgment task were used to calculate the coefficient of variation, a measure of automaticity in language processing (Segalowitz and Segalowitz, 1993) that has previously been taken as an objective measure of relative L2 proficiency (e.g., Segalowitz and Frenkiel-Fishman, 2005; Kousaie and Phillips, 2012, 2017).

Measures of Cognitive Ability

Participants completed several subtests of the Weschler Adult Intelligence Scale, Fourth edition (WAIS-IV; Wechsler, 2008) to ensure that cognitive functioning was within the normal range. Participants completed the Digit Span (forward, backward, and sequencing), Letter-Number Sequencing, and Matrix Reasoning subtests; see **Table 1** for scaled scores. For the digit span tasks, participants were read a series of digits by the experimenter and were asked to repeat the digits in the same order as they were presented (i.e., forward), in the backward order (i.e., backward) or in ascending order (i.e., sequencing). The number of digits started at two and increased by one digit to a maximum of nine for the forward and sequencing subtests, and a maximum of eight for the backward subtest. The task ended when the participant got both trials of a span length incorrect.

In the Letter-Number Sequencing task, participants were presented with a series of numbers and letters and were asked to repeat the numbers first in ascending order, followed by the letters in alphabetical order. The series started with one number and one letter and increased by one item up to a maximum of eight items. The task ended when the participant got all three trials of a span length incorrect.

For the Matrix Reasoning subtest, participants were presented with a series of 26 designs increasing in complexity and were required to identify patterns in each design by selecting the item that completed the pattern from five alternatives. The task ended when the participant obtained three consecutive incorrect responses.

Procedure

Participants completed two testing sessions on two different days. In the first session, participants completed the pure-tone hearing and language proficiency assessments, as well as several executive function tests that will not be further reported here. In addition, the participants completed a language background questionnaire in which they self-reported detailed information regarding their L1 and L2 language proficiency, AoA, and patterns of language use. In the second session, participants performed the experimental speech perception in noise task, while their electroencephalogram was recorded. Following the experimental task, participants completed three other tasks that are not reported here (see Giroud et al., 2020; Gilbert et al., 2021). For all tasks, participants were seated in a sound attenuated booth in front of a computer monitor. Participants first completed a practice block of the speech perception in noise task in English and French. Practice trials consisted of 41 sentences (22 English and 19 French), half high-constraint and half low-constraint sentences. Five sentences in each language were presented in quiet and the rest in noise. Participants then completed one list (i.e., 240 sentences) of the experimental task. Sentences were binaurally presented through EARLINK tube ear inserts (Neuroscan, El Paso, TX, United States) using Inquisit 4.0 (Millisecond Software, Washington). In the noise condition, stimuli were presented at a signal-to-noise ratio of + 1 dB as this gave a 30% error rate in the most challenging condition (i.e., low-constraint L2 sentences presented in noise) during pilot testing. During sentence presentation, a fixation cross was presented on the computer screen. After each sentence was presented, participants were prompted to repeat the final word of the preceding sentence 1,000 ms after the end of the sentence (i.e., when "Final Word?" appeared on the computer screen). Responses were manually scored as correct or incorrect by the experimenter. In addition to verbatim correct responses, responses were accepted as correct if the participant made a pluralization error that was semantically and syntactically correct within the context of the sentence or if participants included the determiner associated with the target word in the French sentences. Only correct trials were included in EEG analyses.

Electroencephalogram Data Acquisition and Analysis

Electrophysiological activity was recorded from a 64 Ag-AgCl active electrodes using the international 10/20 system of electrode placement (Biosemi, Amsterdam, NL) with a sampling rate of 2048 Hz. Additional facial electrodes were placed above and below the left eye and on the left and right canthi to record horizontal and vertical eye movements.

Processing of EEG data was conducted using BrainVision Analyzer 2.0.3 (Brain Products, Gilching, DE). Data were screened manually to remove visible artifacts and sections of the recording in between experimental blocks. All scalp electrodes were re-referenced offline to the average of electrodes placed on the left and right earlobes. A low-pass filter of 100 Hz and a high-pass filter of 0.01 Hz were applied, as well as a DC drift correction. Artifacts from vertical and horizontal eye movements were removed using the Ocular Correction Independent Components Analysis. Following ocular correction, the data were segmented into 1,500 ms intervals, with a 500 ms pre-stimulus baseline period before the onset of the sentence final word, and a 1,000 ms post-stimulus interval. Artifact rejection was semi-automatic, and segments were removed from the analysis if the absolute difference between two adjacent data points within a segment exceeded 50 microvolts, if the difference between the maximum and minimum amplitude within a segment exceeded 200 microvolts, or if the activity within a segment fell below 0.5 microvolts. An average of 26% of trials was removed for each participant. Following artifact rejection, each condition was segmented and baseline-corrected individually. Only correct trials were included; thus, a greater number of trials was excluded on average in the noise, low constraint, and L2 conditions, with the minimum number of trials in the L2 Low Constraint Noise condition (mean = 19, or 65% of trials). To obtain time-frequency representations of the data, we applied a Morlet transformation to the data between 5 and 40 Hz (35 steps), with a cycle parameter of 5. For each condition we then subtracted the evoked power from the total power of the transformed data to measure induced power. Time-frequency data from 7.5–12 Hz were exported for statistical analysis in 100 ms time windows from 100 to 700 ms post stimulus.

Statistical Analysis of the Time-Frequency Data

Statistical analyses of the induced time-frequency data consisted of a linear mixed-effects model with random effects for subjects using the lme4 package (version 1.1–19) of R (version 3.5.1). Based on the typical distribution of the auditory N400

(Connolly et al., 1992; Connolly and Phillips, 1994; D'Arcy et al., 2004; van den Brink et al., 2006) and to reduce our familywise Type I error rate (Luck and Gaspelin, 2017), alpha power was operationalized as the average power in the 7.5–12 Hz frequency range at electrodes CPz and Pz.

The analysis included contrast-coded fixed effects for Language (L1 = −0.5, L2 = 0.5), Semantic Constraint (high = −0.5, low = 0.5) and Listening Condition (quiet = −0.5, noise = 0.5) in a 2 × 2 × 2 factorial design. Additional continuous fixed effects were estimated for AoA, time window, and Task Accuracy of repeating the final word (mean values per participant per condition). Although no predictions were made with respect to Time, given the precise temporal resolution afforded by EEG we included time as a factor to examine whether any of the effects of interest interacted with time. Time was scaled such that the time windows (100–200 ms, 200–300 ms, ... 600–700 ms) were entered as values from 1 to 6. AoA and Time were allowed to interact with our other experimental factors listed above, whereas Task Accuracy was included as a separate fixed effect. Accuracy performance was standardized in the form of z-scores before inclusion in the model. Random effects included random intercepts for subjects. Random effects were limited to random intercepts per participant given that a) we estimated condition level averages as our dependent variable and b) the majority of our experimental factors have only two levels, which is not optimal for random slope estimation (Bolker, 2012). Models were fit using a restricted maximum likelihood estimation technique. A fixed effect was considered significant if the absolute value of the t-statistic was greater than or equal to 2.0 (Linck and Cunnings, 2015) and the p-values reported in **Supplementary Table 1** were estimated using sjPlot's tab_model function (version 2.6.1).

Statistical Analysis of Behavioral Accuracy

Condition-level accuracy on the speech-in-noise task was evaluated in a linear mixed-effects model with random intercepts for subjects using the lme4 package (version 1.1–19) of R (version 3.5.1). Similar to the analysis of the electrophysiological data, the analysis included contrast-coded fixed effects for Language (L1 = −0.5, L2 = 0.5), Semantic Constraint (high = −0.5, low = 0.5) and Listening Condition (quiet = −0.5, noise = 0.5), as well as AoA as a continuous fixed effect. Fixed effects were evaluated using the same criteria and packages as in the time-frequency analysis.

RESULTS

Verbal Fluency

Participants scored higher in L1 letter fluency (M = 36.65; SD = 9.71) compared to L2 letter fluency (M = 29.46; SD = 9.28; paired $t(47) = 4.67$, $p < 0.001$). Similarly, participants scored higher in L1 category fluency (M = 19.21; SD = 6.15) compared to L2 category fluency (M = 16.00; SD = 5.42; paired $t(46) = 2.48$, $p = 0.02$).

Animacy Judgment

Participants' reaction times (RTs) on the animacy judgment task were assessed in terms of the coefficient of variation, i.e., their standard deviation divided by their mean RT. As automatization in a language increases, the coefficient of variation decreases (Segalowitz and Segalowitz, 1993). The coefficient of variation in L1 (M = 0.37, SD = 0.20) was not significantly different from L2 (M = 0.40, SD = 0.22; $t(47) = -1.14$, $p = 0.26$), indicating a similar degree of automaticity across L1 and L2, despite greater verbal fluency in L1 compared to L2.

Role of Age of L2 Acquisition

In our sample, average age of L2 acquisition was 4.27 years (SD = 3.63) and ranged from 0 to 15 years. We evaluated the influence of age of acquisition on participants' proficiency by running a multivariate regression that evaluated the predictive power of AoA on L2 category fluency, L2 letter fluency, and the difference between the coefficient of variation in L2 and L1. Overall, the influence of AoA was not significant ($F(3,45) = 1.62$, $p = 0.20$), indicating that participants' L2 proficiency was not confounded with AoA.

Revised Speech Perception in Noise Test Behavioral Accuracy

All participants were more accurate on high constraint sentences compared to low constraint sentences (Beta Estimate = −10.55, CI [−13.54 −7.78], $p < 0.001$). Similarly, all participants were more accurate while perceiving speech in quiet compared to noise (Beta Estimate = −12.30, CI [−15.18 −9.42], $p < 0.001$). However, the decrease in accuracy for the noise compared to the quiet condition was greater for low than high constraint sentences (see **Figure 1A**; Beta Estimate = −16.50, CI [−22.26 −10.74], $p < 0.001$). Additionally, there was a Language by AoA interaction (see **Figure 1B**; Beta Estimate = −0.82, CI [−1.37 −0.28], $p = 0.003$) such that performance was overall less accurate in L2 compared to L1 for bilinguals with later ages of L2 acquisition.

Analysis of Induced Alpha Power

Results of the mixed-effect analyses are summarized in **Supplementary Table 1** and depicted in **Figure 2**. Hypotheses 1 and 2 were supported by main effects of Language (Beta Estimate = 6.57, CI [2.08 11.07], $p = 0.004$; higher alpha power in L2 than L1), and Listening Condition (Beta Estimate = 4.66, CI [0.18 9.15], $p = 0.042$; higher alpha power in noise than quiet). The results did not support hypothesis 3 given that there was no significant main effect of Semantic Constraint (Beta Estimate = −3.67, CI [−8.16 0.81], $p = 0.11$), or interactions involving Semantic Constraint (all ps > 0.14). Additional main effects included: Time (Beta Estimate = −0.69, CI [−1.27 −0.12], $p = 0.019$; decreased alpha power over time) and Task Accuracy (Beta Estimate = 0.92, CI [0.11 1.74], $p = 0.027$; lower alpha was associated with lower accuracy). In terms of hypothesis 4, the main effect of Listening Condition was moderated by a two-way interaction with AoA (Beta Estimate = −0.98, CI [−1.82 −0.14], $p = 0.022$) and further by a three-way interaction between

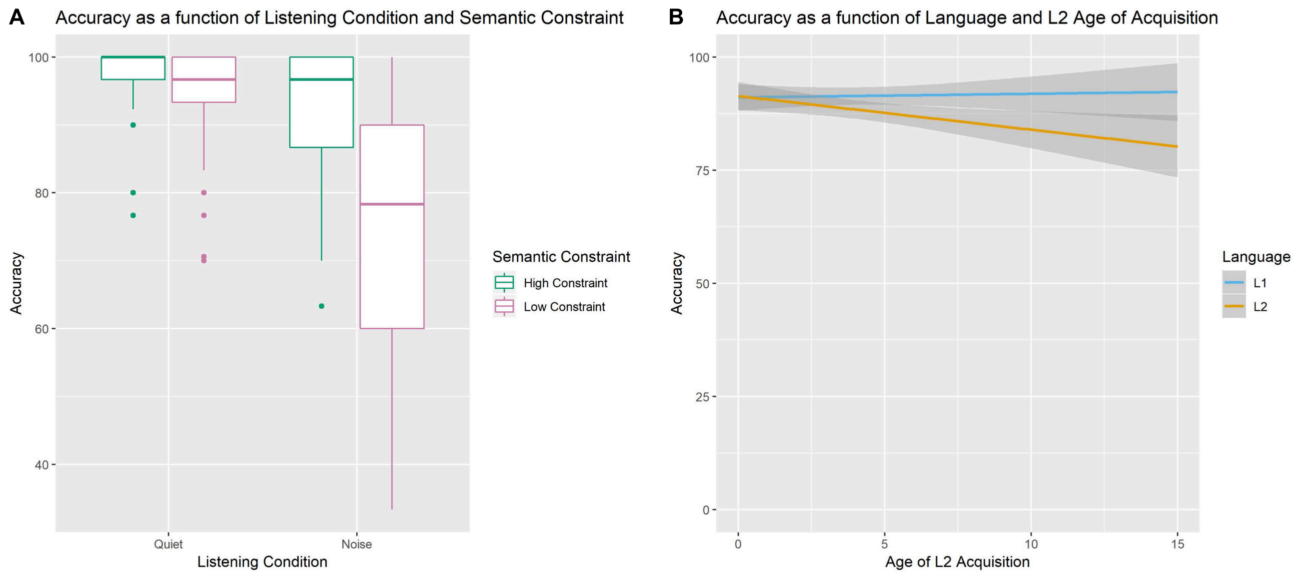

FIGURE 1 | Accuracy Performance on the SPIN task. Panel **(A)** displays an interaction between Listening Condition and Semantic Constraint such that the effect of Semantic Constraint is larger in noisy conditions. Panel **(B)** displays an interaction between AoA and Language such that accuracy in the L2 decreases as L2 AoA increases.

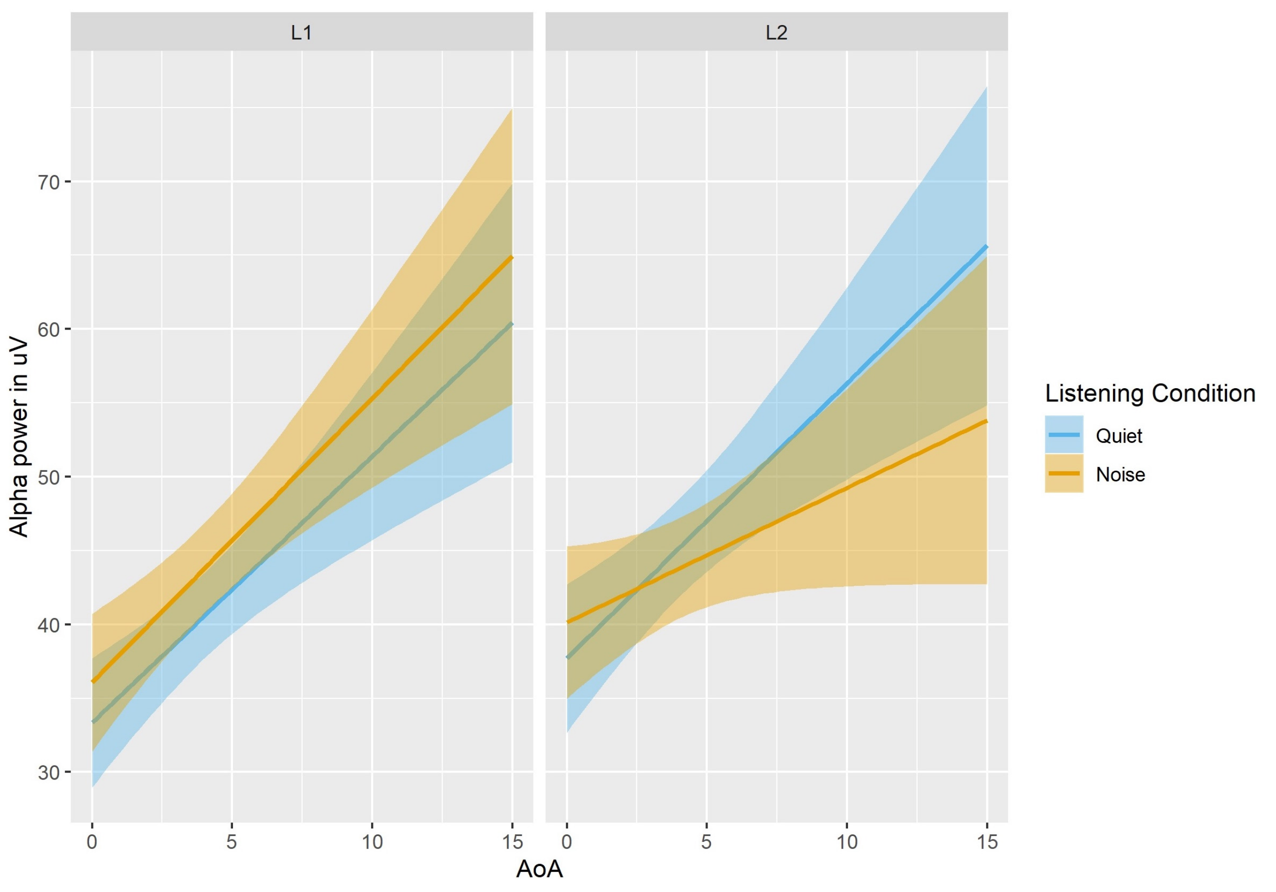

FIGURE 2 | Alpha power as a function of Language, Listening Condition and AoA. In Quiet, alpha power is positively correlated with AoA, for each language, with overall higher alpha for L2. In Noise, alpha power is still positively correlated with AoA, but alpha power is lower in the L2 than the L1 for later AoA.

Listening Condition, Language, and AoA (Beta Estimate = −1.84, CI [−3.52 −0.16], p = 0.032), showing that (1) later AoA was associated with increased alpha in both L1 and L2 overall, (2) later AoA was associated with increased alpha in L2 compared to L1 only in quiet, and (3) later AoA was associated with increased alpha in quiet compared to noise in the L2.

DISCUSSION

Our study examined speech-in-noise processing in bilinguals who varied in their L2 AoA. Participants identified the terminal word of sentences that varied in terms of semantic constraint and we examined behavioral performance and alpha power as a measure of attentional control. We hypothesized that we would observe (1) increased alpha power during speech comprehension in the more difficult noise condition compared to quiet, (2) increased alpha power during L2 as compared to L1 speech comprehension, indicating more effortful processing, and (3) increased alpha power for low compared to high constraint sentences, and (4) that the increase in alpha power for L2 processing would positively correlate with L2 AoA. Our findings partially support these hypotheses.

The direction of the main effects of Listening Condition and Language supported hypotheses 1 and 2 – there was an increase in alpha power when processing speech in noise compared to quiet and in L2 compared to L1. Hypothesis 4 predicted an interaction between Listening Condition, Language, and AoA such that increasing AoA was expected to be associated with increased alpha power in noise in the L2. Although we observed a significant 3-way interaction, the source of the interaction did not support our hypothesis. In fact, later AoA was associated with increased alpha in L2 compared to L1 in quiet only, and there was a decrease in alpha power in L2 noise compared to L2 quiet. This pattern of results is distinct from the super-additive pattern we had hypothesized based on Obleser et al. (2012). However, our finding is consistent with activation patterns in the inferior frontal gyrus observed by Kousaie et al. (2019) using a similar task and group of participants. Like Kousaie et al., we interpret this finding as indicating that the observed pattern of decreased alpha power in L2 noise compared to L2 quiet may reflect resource exhaustion in the most challenging condition. This interpretation is also consistent with the observed interaction between Language and Listening Condition showing an increase in alpha for the noise compared to the quiet condition in L1 only, and the main effect of Language showing greater overall alpha power in L2 compared to L1, suggesting that both the noise and quiet conditions in L2 recruited similarly greater attentional resources than listening in L1. The behavioral results also show a decrease in accuracy for noise compared to quiet conditions that is larger in L2 than L1, providing additional evidence that this condition is more effortful.

In the case of alpha power, our interpretation of the absence of an increase in alpha power during the most difficult listening condition being the result of an exhaustion of available resources is consistent with several studies that fail to find increases in alpha power under incomprehensible/impossible task conditions (e.g., Becker et al., 2013; Wisniewski et al., 2017). Although our SPIN task was not impossible, as demonstrated by participants' accuracy scores, it may be that the increase in alpha in response to task demands resembles a U-shaped function, wherein alpha power is low under easy and highly difficult conditions, and increases at medium processing loads. Given previous work that observed super additive effects of WM load and noise was conducted at the word level, it may be that the working memory tasks used in those studies never reached sufficient difficulty to observe a reduction in alpha power (Obleser et al., 2012; Wostmann et al., 2017). In contrast, our data are based on sentence-level processing in both a stronger and a weaker language, and consequently it is plausible that, particularly when L2 AoA is late, our task may have been sufficiently difficult to reach the point where additional alpha power was no longer beneficial. Further support for this interpretation comes from our behavioral results, which show decreases in performance in L2 with later AoA.

Although we demonstrated an association between alpha power and both noise and language in bilinguals, we did not observe an influence of semantic constraint on alpha power, thus not supporting hypothesis 3. This is inconsistent with previous studies that have found a decrease in alpha power for highly constraining sentences (e.g., Rommers et al., 2017; Wang et al., 2018), although these studies only examined processing in quiet. Despite the absence of an effect of constraint in the electrophysiological data, behaviorally we show that bilinguals benefit from semantic constraint in both languages, particularly in noise, and show improved behavioral performance in high constraint conditions. Our behavioral findings are consistent with the behavioral results from Coulter et al. (2020) with a partially overlapping sample of participants. However, Coulter et al. also showed an effect of semantic constraint on N400 amplitude, with larger amplitudes for low compared to high constraint sentences. In contrast, other previous work has found that bilinguals who learn their L2 after age 5 years do not benefit from semantic constraint in L2 noise (Kousaie et al., 2019); however, in that study the signal to noise ratio was lower than in the current study, thus further increasing the difficulty of speech processing and potentially attributing to the difference in findings. In the current study, we observe interactions with AoA, such that L2 speech-in-noise processing performance decreased at later AoAs (see **Figure 1B**), but these effects do not outweigh the benefits of semantic constraint on speech perception in noise in our highly proficient bilingual sample.

Further research will be needed to understand the mechanisms driving the effect of AoA during speech-in-noise processing, but one potential avenue for research could investigate the role of individual differences in phonetic perception in the L2, a skill that is known to be optimally sensitive during infancy (Werker et al., 1981). *Post hoc* correlations between the accuracy data on our SPIN task and participants' frequency following response (i.e., an electrophysiological measure of the fidelity of neural encoding of sound) to vowels, a task that was completed later in the testing session (see Giroud et al., 2020 for details) revealed a positive relationship between these two measures. This supports the hypothesis that AoA may be related to more efficient lower-level phonetic processing leading to improved speech processing in difficult listening conditions. Given that we observed a greater alpha response at earlier time windows, and that participants with earlier AoAs show reduced alpha power compared to participants with later AoAs, our results are congruent with an interpretation that emphasizes the role of both language experience and bottom-up processing in speech perception in noise in an L2.

More broadly, our higher-order interactions with Language, Listening Condition, and AoA suggest that alpha reflects inhibitory processing during attentional control in bilingual auditory language processing, as has been previously demonstrated in vision (e.g., Engel et al., 2001). These data support hypotheses positing that bilinguals use domain-general cognitive control systems to manage the cognitive challenges associated with L2 language processing (e.g., Green, 1998; Green and Abutalebi, 2013). Furthermore, the participants in this study varied with respect to their L1, with approximately half of the participants reporting English to be their L1 and half reporting French as their L1, suggesting that the observed effects are relevant to bilingual language processing and not specific to a particular L2, at least in terms of the languages used here.

CONCLUSION

The current data extend our understanding of alpha power to the bilingual context, showing that alpha power is sensitive to the attentional control demands associated with L2 speech comprehension, and that age of acquisition, beyond proficiency alone, predicts the degree of attentional control necessary for bilingual speech processing in noise. Future studies should build on our findings to examine, for example, whether experiential factors like AoA—which we have shown here to be associated with overall alpha power—are also associated with differences in the source of neural recruitment. These results represent an initial step toward broadening our understanding of naturalistic speech processing in ubiquitous conditions, such as in noisy environments and in a non-native language.

DATA AVAILABILITY STATEMENT

The dataset presented in this article is not readily available because participants did not provide consent for open access to their data. Requests to access the dataset should be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board of the Faculty of Medicine and Health Sciences, McGill University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AMG and SK: formal analysis, data curation, writing (original draft and editing). ACG: formal analysis, writing (review and editing). KC: data curation, writing (review and editing). SB, VG, DT, and DK: conceptualization, writing (review and editing), funding acquisition. NP: conceptualization, writing (review and editing), funding acquisition, supervision. All authors contributed to the article and approved the submitted version.

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REFERENCES

Aydelott, J., Dick, F., and Mills, D. L. (2006). Effects of acoustic distortion and semantic context on event-related potentials to spoken words. *Psychophysiology* 43, 454–464. doi: 10.1111/j.1469-8986.2006.00448.x

Becker, R., Pefkou, M., Michel, C. M., and Hervais-Adelman, A. G. (2013). Left temporal alpha-band activity reflects single word intelligibility. *Front. Syst. Neurosci.* 7:121. doi: 10.3389/fnsys.2013.00121

Bernstein, I. H., Bissonnette, V., Vyas, A., and Barclay, P. (1989). Semantic priming: subliminal perception or context? *Percept. Psychophys.* 45, 153–161. doi: 10.3758/BF03208050

Bilger, R. C., Nuetzel, J. M., Rabinowitz, W. M., and Rzeczkowski, C. (1984). Standardization of a test of speech perception in noise. *J. Speech Hear. Res.* 27, 32–48. doi: 10.1044/jshr.2701.32

Bolker, B. (2012). *Mixed Model Lab 1*. Available online at: https://ms.mcmaster.ca/~bolker/classes/uqam/mixedlab1.pdf (accessed January 6, 2022).

Bsharat-Maalouf, D., and Karawani, H. (2022). Bilinguals' speech perception in noise: perceptual and neural associations. *PLoS One* 17:e0264282. doi: 10.1371/journal.pone.0264282

Carey, D., Mercure, E., Pizzioli, F., and Aydelott, J. (2014). Auditory semantic processing in dichotic listening: effects of competing speech, ear of presentation, and sentential bias on N400s to spoken words in context. *Neuropsychologia* 65, 102–112. doi: 10.1016/j.neuropsychologia.2014.10.016

Chauvin, A., and Phillips, N. A. (in press). Bilinguals show proportionally greater benefit from visual speech cues and sentence context in their second compared to their first language. *Ear Hear.* doi: 10.1097/aud.0000000000001182

Coltheart, M. (1981). The MRC psycholinguistic database. *Q. J. Exp. Psychol. Sec. A* 33, 497–505. doi: 10.1080/14640748108400805

Connolly, J. F., and Phillips, N. A. (1994). Event-related potential components reflect phonological and semantic processing of the terminal word of spoken sentences. *J. Cogn. Neurosci.* 6, 256–266. doi: 10.1162/jocn.1994.6.3.256

Connolly, J. F., Phillips, N. A., Stewart, S. H., and Brake, W. G. (1992). Event-related potential sensitivity to acoustic and semantic properties of terminal words in sentences. *Brain Lang.* 43, 1–18. doi: 10.1016/0093-934x(92)90018-a

Coulter, K., Gilbert, A. C., Kousaie, S., Baum, S., Gracco, V. L., Klein, D., et al. (2020). Bilinguals benefit from semantic context while perceiving speech in noise in both of their languages: electrophysiological evidence from the N400 ERP. *Biling. Lang. Cogn.* 24, 344–357. doi: 10.1017/S1366728920000516

D'Arcy, R. C., Connolly, J. F., Service, E., Hawco, C. S., and Houlihan, M. E. (2004). Separating phonological and semantic processing in auditory sentence processing: a high-resolution event-related brain potential study. *Hum. Brain Mapp.* 22, 40–51. doi: 10.1002/hbm.20008

Davies, M. (2008). *The Corpus of Contemporary American English (COCA): 560 Million Words, 1990-Present*. Available online at: https://corpus.byu.edu/coca/ (accessed September 14, 2014).

Davis, M. H., Ford, M. A., Kherif, F., and Johnsrude, I. S. (2011). Does semantic context benefit speech understanding through "top-down" processes? Evidence from time-resolved sparse fMRI. *J. Cogn. Neurosci.* 23, 3914–3932. doi: 10.1162/jocn_a_00084

Engel, A. K., Fries, P., and Singer, W. (2001). Dynamic predictions: oscillations and synchrony in top–down processing. *Nat. Rev. Neurosci.* 2, 704–716. doi: 10.1038/35094565

Ferreira, G. C., Torres, E. M. O., Garcia, M. V., Santos, S. N., and Costa, M. J. (2019). Bilingualism and speech recognition in silence and noise in adults (Bilinguismo e reconhecimento de fala no silêncio e no ruído em adultos.). *Codas* 31:e20180217. doi: 10.1590/2317-1782/20192018217

Filippi, R., Leech, R., Thomas, M. S. C., Green, D. W., and Dick, F. (2012). A bilingual advantage in controlling language interference during sentence comprehension. *Biling. Lang. Cogn.* 15, 858–872. doi: 10.1017/S1366728911000708

Foxe, J. J., and Snyder, A. C. (2011). The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. *Front. Psychol.* 2:154. doi: 10.3389/fpsyg.2011.00154

Gilbert, A. C., Lee, J. G., Coulter, K., Wolpert, M. A., Kousaie, S., Gracco, V. L., et al. (2021). Spoken word segmentation in first and second language: when ERP and behavioral measures diverge [Original Research]. *Front. Psychol.* 12:705668. doi: 10.3389/fpsyg.2021.705668

Giroud, N., Baum, S. R., Gilbert, A. C., Phillips, N. A., and Gracco, V. (2020). Earlier age of second language learning induces more robust speech encoding in the auditory brainstem in adults, independent of amount of language exposure during early childhood. *Brain Lang.* 207:104815. doi: 10.1016/j.bandl.2020.104815

Golestani, N., Rosen, S., and Scott, S. K. (2009). Native-language benefit for understanding speech-in-noise: the contribution of semantics. *Biling. Lang. Cogn.* 12, 385–392. doi: 10.1017/s1366728909990150

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn.* 1, 67–81. doi: 10.1017/s1366728998000133

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Grosjean, F. (2008). *Studying Bilinguals*. Oxford: Oxford University Press.

Hervais-Adelman, A., Pefkou, M., and Golestani, N. (2014). Bilingual speech-in-noise: neural bases of semantic context use in the native language. *Brain Lang.* 132, 1–6. doi: 10.1016/j.bandl.2014.01.009

Jensen, O., and Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Front. Hum. Neurosci.* 4:186. doi: 10.3389/fnhum.2010.00186

Kalikow, D. N., Stevens, K. N., and Elliott, L. L. (1977). Development of a test of speech intelligibility in noise using sentence materials with controlled word predictability. *J. Acoust. Soc. Am.* 61, 1337–1351. doi: 10.1121/1.381436

Klimesch, W., Sauseng, P., and Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Res. Rev.* 53, 63–88. doi: 10.1016/j.brainresrev.2006.06.003

Kousaie, S., Baum, S., Phillips, N. A., Gracco, V., Titone, D., Chen, J. K., et al. (2019). Language learning experience and mastering the challenges of perceiving speech in noise. *Brain Lang.* 196:104645. doi: 10.1016/j.bandl.2019.104645

Kousaie, S., and Phillips, N. A. (2012). Conflict monitoring and resolution: are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Res.* 1446, 71–90. doi: 10.1016/j.brainres.2012.01.052

Kousaie, S., and Phillips, N. A. (2017). A behavioural and electrophysiological investigation of the effect of bilingualism on aging and cognitive control. *Neuropsychologia* 94, 23–35. doi: 10.1016/j.neuropsychologia.2016.11.013

Krizman, J., Bradlow, A. R., Lam, S. S.-Y., and Kraus, N. (2017). How bilinguals listen in noise: linguistic and non-linguistic factors. *Biling. Lang. Cogn.* 20, 834–843. doi: 10.1017/S1366728916000444

Kutas, M. (1997). Views on how the electrical activity that the brain generates reflects the functions of different language structures. *Psychophysiology* 34, 383–398. doi: 10.1111/j.1469-8986.1997.tb02382.x

Kutas, M., and Hillyard, S. A. (1980). Reading between the lines: event-related brain potentials during natural sentence processing. *Brain Lang.* 11, 354–373. doi: 10.1016/0093-934x(80)90133-9

Kutas, M., and Van Petten, C. K. (1994). "Psycholinguistics electrified: event-related brain potential investigations," in *Handbook of Psycholinguistics*, ed. M. A. Gernsbacher (San Diego, CA: Academic Press, Inc), 83–143.

Linck, J. A., and Cunnings, I. (2015). The utility and application of mixed-effects models in second language research. *Lang. Learn.* 65, 185–207. doi: 10.1111/lang.12117

Luck, S. J., and Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology* 54, 146–157. doi: 10.1111/psyp.12639

Mayo, L. H., Florentine, M., and Buus, S. (1997). Age of second-language acquisition and perception of speech in noise. *J. Speech Lang. Hear. Res.* 40, 686–693. doi: 10.1044/jslhr.4003.686

McMahon, C. M., Boisvert, I., de Lissa, P., Granger, L., Ibrahim, R., Lo, C. Y., et al. (2016). Monitoring alpha oscillations and pupil dilation across a performance-intensity function. *Front. Psychol.* 7:745. doi: 10.3389/fpsyg.2016.00745

New, B. (2006). "Lexique 3: une nouvelle base de données lexicales," in *Proceedings of the Actes de la Conférence Traitement Automatique des Langues Naturelles (TALN 2006)*, Louvain.

New, B., Pallier, C., Ferrand, L., and Matos, R. (2001). Une base de données lexicales du français contemporain sur internet: LEXIQUE. *L'Anné Psychol.* 101, 447–462. doi: 10.3406/psy.2001.1341

Obleser, J., and Kotz, S. A. (2011). Multiple brain signatures of integration in the comprehension of degraded speech. *Neuroimage* 55, 713–723. doi: 10.1016/j.neuroimage.2010.12.020

Obleser, J., Wöstmann, M., Hellbernd, N., Wilsch, A., and Maess, B. (2012). Adverse listening conditions and memory load drive a common α oscillatory network. *J. Neurosci.* 32, 12376–12383. doi: 10.1523/jneurosci.4908-11.2012

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., et al. (2016). Hearing impairment and cognitive energy: the framework for understanding effortful listening (FUEL). *Ear Hear.* 37, 5s–27s. doi: 10.1097/aud.0000000000000312

Rommers, J., Dickson, D. S., Norton, J. J. S., Wlotko, E. W., and Federmeier, K. D. (2017). Alpha and theta band dynamics related to sentential constraint and word expectancy. *Lang. Cogn. Neurosci.* 32, 576–589. doi: 10.1080/23273798.2016.1183799

Segalowitz, N., and Frenkiel-Fishman, S. (2005). Attention control and ability level in a complex cognitive skill: attention and second language proficiency. *Mem. Cogn.* 33, 644–653. doi: 10.3758/bf03195331

Segalowitz, N., and Segalowitz, S. J. (1993). Skilled performance, practice, and the differentiation of speed-up from automatization effects: evidence from second language word recognition. *Appl. Psycholinguist.* 14, 369–385. doi: 10.1017/s0142716400010845

Shi, L. F. (2010). Perception of acoustically degraded sentences in bilingual listeners who differ in age of english acquisition. *J. Speech Lang. Hear. Res.* 53, 821–835. doi: 10.1044/1092-4388(2010/09-0081)

Strauß, A., Kotz, S. A., and Obleser, J. (2013). Narrowed expectancies under degraded speech: revisiting the N400. *J. Cogn. Neurosci.* 25, 1383–1395. doi: 10.1162/jocn_a_00389

van den Brink, D., Brown, C. M., and Hagoort, P. (2006). The cascaded nature of lexical selection and integration in auditory sentence processing. *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 364–372. doi: 10.1037/0278-7393.32.3.364

Wang, L., Hagoort, P., and Jensen, O. (2018). Language prediction is reflected by coupling between frontal gamma and posterior alpha oscillations. *J. Cogn. Neurosci.* 30, 432–447. doi: 10.1162/jocn_a_01190

Wechsler, D. (2008). *WAIS-IV Technical and Interpretive Manual*. San Antonio, TX: The Psychological Corporation.

Werker, J. F., Gilbert, J. H., Humphrey, K., and Tees, R. C. (1981). Developmental aspects of cross-language speech perception. *Child Dev.* 52, 349–355. doi: 10.2307/1129249

Wilsch, A., and Obleser, J. (2016). What works in auditory working memory? A neural oscillations perspective. *Brain Res.* 1640(Pt B), 193–207. doi: 10.1016/j.brainres.2015.10.054

Winneke, A. H., and Phillips, N. A. (2011). Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception. *Psychol. Aging* 26, 427–438. doi: 10.1037/a0021683

Wisniewski, M. G., Thompson, E. R., and Iyer, N. (2017). Theta- and alpha-power enhancements in the electroencephalogram as an auditory delayed match-to-sample task becomes impossibly difficult. *Psychophysiology* 54, 1916–1928. doi: 10.1111/psyp.12968

Wostmann, M., Lim, S. J., and Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cereb. Cortex* 27, 3307–3317. doi: 10.1093/cercor/bhx074

Zekveld, A. A., Heslenfeld, D. J., Johnsrude, I. S., Versfeld, N. J., and Kramer, S. E. (2014). The eye as a window to the listening brain: neural correlates of pupil size as a measure of cognitive listening load. *Neuroimage* 101, 76–86. doi: 10.1016/j.neuroimage.2014.06.069

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Language Entropy Relates to Behavioral and Pupil Indices of Executive Control in Young Adult Bilinguals

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Introduction: It has been proposed that bilinguals' language use patterns are differentially associated with executive control. To further examine this, the present study relates the social diversity of bilingual language use to performance on a color-shape switching task (CSST) in a group of bilingual university students with diverse linguistic backgrounds. Crucially, this study used language entropy as a measure of bilinguals' language use patterns. This continuous measure reflects a spectrum of language use in a variety of social contexts, ranging from compartmentalized use to fully integrated use.

Methods: Language entropy for university and non-university contexts was calculated from questionnaire data on language use. Reaction times (RTs) were measured to calculate global RT and switching and mixing costs on the CSST, representing conflict monitoring, mental set shifting, and goal maintenance, respectively. In addition, this study innovatively recorded a potentially more sensitive measure of set shifting abilities, namely, pupil size during task performance.

Results: Higher university entropy was related to slower global RT. Neither university entropy nor non-university entropy were associated with switching costs as manifested in RTs. However, bilinguals with more compartmentalized language use in non-university contexts showed a larger difference in pupil dilation for switch trials in comparison with non-switch trials. Mixing costs in RTs were reduced for bilinguals with higher diversity of language use in non-university contexts. No such effects were found for university entropy.

Discussion: These results point to the social diversity of bilinguals' language use as being associated with executive control, but the direction of the effects may depend on social context (university vs. non-university). Importantly, the results also suggest that some of these effects may only be detected by using more sensitive measures, such as pupil dilation. The paper discusses theoretical and practical implications regarding the language entropy measure and the cognitive effects of bilingual experiences more generally, as well as how methodological choices can advance our understanding of these effects.

Keywords: bilingualism, executive control, language entropy, individual differences, pupillometry, generalized additive mixed modeling

INTRODUCTION

It has been theorized that the life experience of using more than one language contributes to enhanced domain-general executive control in bilinguals,[1] as they are constantly required to regulate the simultaneous activation of multiple languages in one mind (Kroll et al., 2012). However, defining "bilingualism" is perhaps an impossible feat (Surrain and Luk, 2019). There is now a general consensus that it is unattainable to accurately represent the dynamic, multifaceted, and complex nature of bilingualism by treating it as a binary construct (Bialystok, 2021, this special issue). Recent work examining bilingualism on a continuum has suggested that individual experiences place different demands on language control and domain-general cognitive systems, each differentially shaping language processing, cognitive functioning, and brain structure and function (DeLuca et al., 2019; Beatty-Martínez and Titone, 2021; Gullifer and Titone, 2021b). Despite recent attempts to unravel the complexity of bilingualism and its consequences for cognition, much remains unknown about how bilingual experiences may be responsible for these neurocognitive adaptations. Importantly, to capture these intricate effects, sensitive methodologies are required (Poarch and Krott, 2019). This study investigates how the social diversity of language use relates to behavioral and pupil indices of executive control in bilinguals.

Bilingual experiences comprise static factors such as age of acquisition (AoA) and number of languages ever learned as well as ongoing, dynamic experiences such as code-switching practices and current language use within and across contexts. These static and dynamic experiences likely interact in modulating cognitive performance in bilinguals, but recent years have seen a particular focus on the diversity of language use, rather than knowledge, in shaping neurocognitive adaptations in bilinguals (Abutalebi and Green, 2016). This idea was put forward by Green and Abutalebi (2013) in the Adaptive Control Hypothesis. Specifically, Green and Abutalebi identified three types of interactional contexts: a single-language context (SLC), a dual-language context (DLC), and a dense code-switching context (DCS). In the SLC, bilinguals use their languages for different purposes and in strictly separate contexts (e.g., communicating in the L1 at home and in the L2 in educational settings). In the DLC, bilinguals engage in highly integrated language contexts in which their languages may be used in a more balanced manner (e.g., speaking both the L1 and L2 at work, but with different people). Finally, in the DCS, language use is also highly integrated, but fewer restrictions are placed on when to use which language and with whom. According to the Adaptive Control Hypothesis, each context places different demands on language- and domain-general executive control in bilinguals, with the DLC being the most challenging for the executive control system.

Empirical work looking at the influence of interactional contexts on executive control has, for instance, found that Spanish-English bilinguals who reside in contexts in which languages are used separately (i.e., an SLC) showed greater reliance on reactive control, whereas bilinguals residing in contexts in which languages are used interchangeably (i.e., both in dual-language and dense code-switching contexts) mostly adopted proactive control strategies (Beatty-Martínez et al., 2020). Similarly, Hartanto and Yang (2016) classified bilinguals into SLC bilinguals and DLC bilinguals and found that DLC bilinguals showed lower switching costs than SLC bilinguals. In a follow-up study, the authors reported that DLC bilingualism predicted enhanced set shifting abilities and that DCS bilinguals were more likely to perform better on tasks requiring inhibitory control and goal maintenance (Hartanto and Yang, 2020). Likewise, Yow and Li (2015) found a relationship between enhanced goal maintenance (operationalized as mixing cost) and more balanced language use in bilinguals. Altogether, these findings suggest that demands that are placed on bilinguals by the environment differentially modulate cognitive adaptations, on an aggregated level and within bilingual groups.

Despite the empirical importance of investigating theoretical propositions in such aggregated groups, individual variation in bilingual language use is perhaps best captured using continuous measures (Luk and Bialystok, 2013). Bilinguals may not always find themselves in a purely SLC or DLC (cf. Lai and O'Brien, 2020), and on an individual level, some social settings may be characterized as DLCs and others as SLCs (e.g., two languages are spoken at home, but only one language is spoken at work). In this light, Gullifer and Titone (2020) proposed a novel continuous measure of the social diversity of language use: language entropy. Entropy is a concept adapted from information theory (Shannon, 1948) and is generally used to quantify the diversity or uncertainty of a phenomenon. Language entropy reflects a spectrum of language use across or between communicative contexts, and it draws on the concepts proposed in the Adaptive Control Hypothesis.[2] Crucially, language entropy is not restricted to

[1]Our paper uses the term "bilingualism" to represent the proficiency in more than one language, whether the proficiency is in two languages (bilingualism) or in three or more languages (multilingualism).

[2]It needs to be noted, however, that there is no one-to-one mapping of language entropy and the interactional contexts posited in the Adaptive Control Hypothesis, as language entropy does not differentiate between DLC and DCS. For example, language entropy is not able to distinguish a person frequently switching between two languages with one person in one context from a person perfectly balancing speaking two languages in one context with two different people. The resulting entropy values would be comparable.

a set number of languages, as its values range from 0 to log n (where n is the number of languages that entropy is computed over). It is calculated in such a way that it captures the inherent variability in bilingual language use, where the lowest values approximate compartmentalized language use (i.e., only one language is used in a context), and the highest value represents fully integrated language use (i.e., all languages are used equally). In fully compartmentalized contexts, one language is used much more than the other(s) and, as such, the predictability of which language to use is very high. In highly integrated contexts, the languages are used in a more balanced way and so the (appropriate) language to use is less predictable. It then follows that the degree of unpredictability is also affected by the number of languages a person speaks. That is, when all available languages are used in a fully integrated manner, the unpredictability of which language to use increases as the number of available languages increases. The extent to which the management of this unpredictability is needed is argued to drive neurocognitive adaptations, which consequently increase behavioral efficiency and optimize decision making (Gullifer and Titone, 2021a).

However, it is less clear how this continuous measure of the diversity in bilingual language use may be associated executive control. To reiterate, the Adaptive Control Hypothesis posits that, in contexts where the predictability of which language to use is low, bilinguals need to engage domain-general executive control processes to adapt to changing environmental demands (e.g., a change in interlocutor with whom another language needs to be spoken) to a larger extent than in high-predictability contexts. In other words, they must keep speaking the appropriate language without letting their other language(s) interfere (goal maintenance, also termed proactive control), scan the environment for changes (e.g., conflict monitoring), and switch to another language when this is required (mental set shifting, henceforth set shifting). Previously, higher language entropy has been associated with increased reliance on proactive control (Gullifer et al., 2018; Gullifer and Titone, 2021b), and with functional brain patterns related to enhanced conflict monitoring, set shifting, and goal maintenance (Li et al., 2021), underscoring the possible relationship between the diversity of language use and individual differences in executive control. Importantly, language entropy may reflect a distinct aspect of bilingual language use, as it has been shown by Kałamała et al. (2021) that other indices of bilingual language use, such as code-switching and language-mixing habits, only moderately correlated with language entropy.

In the bilingualism literature, conflict monitoring, set shifting, and goal maintenance have been frequently assessed using cued-switching paradigms (Lehtonen et al., 2018), such as the color-shape switching task (CSST). The cued-switching paradigm is difficult enough to result in large RT costs even in young adults (Monsell, 2003). Despite this, reaction times may not always be sensitive enough in capturing individual differences in certain groups. For example, young adults, a commonly studied demographic, showcase less individual variation in cognitive performance and, as such, in RTs, than other age groups (Hultsch et al., 2002). This may be due to the fact that young adults are at their cognitive performance peak (Park et al., 2002; Bialystok et al., 2012). Perhaps unsurprisingly then, behavioral effects of bilingualism have been found least consistently in young adults (Antoniou, 2019). It is therefore paramount that a measurement is used that is sensitive enough to yield relatively large effects and individual variation when studying young adults, while also capturing a form of processing that is expected to be modulated by bilingual experiences.

It is worth mentioning that cognitive effects of bilingualism have been found in brain indices in the absence of behavioral effects between bilingual and monolingual groups, as well as between bilingual groups with different characteristics (e.g., Bialystok, 2017; Lehtonen et al., 2018; DeLuca et al., 2020). Thus, to further increase sensitivity of the assessments, behavioral indices may be supplemented with a proxy of brain activity, such as pupil dilation. Pupil dilation in response to task demands is commonly thought to be modulated by phasic activity in the locus coeruleus-norepinephrine (LC-NE) system (Aston-Jones and Cohen, 2005; van der Wel and van Steenbergen, 2018). The LC-NE system receives information from the orbitofrontal cortex and the anterior cingulate cortex about task demands. In turn, the LC adjusts its activation patterns to ensure that behavioral responses are optimal (Aston-Jones and Cohen, 2005). As such, pupil dilation can serve as a window into processes related to task performance. An increase in pupil size has often been used as an index of higher resource allocation (i.e., increased cognitive effort and attention allocation to complete the task). This effect has been found in a variety of cognitive tasks (for a literature review, see van der Wel and van Steenbergen, 2018). For example, Rondeel et al. (2015) showed that switch trials elicited larger pupil dilation than non-switch trials in a number switch task. To date, there have been no inquiries regarding the cognitive effects of bilingualism on set shifting using pupil dilation as an outcome measure.

The current study's primary goal is to examine how the social diversity of bilingual language use, as measured by language entropy, relates to executive control in university students with diverse bilingual experiences, using behavioral measures and pupil dilation. The study was conducted in November and December 2020 at the University of Groningen, the Netherlands, when COVID-19 restrictions were in place. Specifically, the data were collected at a time when teaching took place fully online. The University of Groningen's student population consists mostly of native speakers of Dutch but also includes international students from all over the world (University of Groningen, 2020). This diverse student population is the result of many of the study programs at the University of Groningen being taught exclusively in English. The Dutch student population starts to formally learn English from a young age (the end of primary school or even earlier) and is regularly exposed to the language through media input, as Dutch television subtitles its foreign programs, for instance. At university, students may speak English in the classroom but Dutch or English or yet other languages with their fellow students during breaks. Their multilingual experience may extend to contexts outside of university, as the North of the

Netherlands is a highly multilingual region in itself (Schmeets and Cornips, 2021). In this part of the Netherlands, some speak a regional minority language such as Frisian (in the province of Fryslân) or a form of the Low Saxon dialect in addition to Dutch. In sum, the sample that was targeted in this study was linguistically diverse and likely to vary in how they used their languages across social contexts. This allowed us to assess the impact of inter-individual differences in the social diversity of bilingual language use on executive control.

In our study, we used a color-shape switching task (see method below) to measure conflict monitoring, set shifting, and goal maintenance. As described previously, bilinguals who mainly use their languages in separate contexts are not regularly required to monitor the interactional context for linguistic changes. However, bilinguals who use two or more languages within one context need to engage these precise executive control processes more often to appropriately regulate the activation of their languages, thereby possibly increasing their efficiency over time (Green and Abutalebi, 2013). Thus, we predicted bilingual individuals with higher language entropy to demonstrate enhanced conflict monitoring, set shifting, and goal maintenance abilities relative to those individuals whose language use is more compartmentalized. Crucially, the CSST was adapted to allow for simultaneous recording of pupil size over time, permitting an additional, and potentially more sensitive, measure of set shifting in addition to RTs. Behavioral versions of the CSST have been used regularly in this field (see meta-analysis by Lehtonen et al., 2018). However, to our knowledge, only one study has examined set shifting with simultaneous tracking of pupil size (Rondeel et al., 2015). Changes in pupil size occur very slowly and require slower-paced task designs than purely behavioral tasks (Mathôt, 2018; Winn et al., 2018). Therefore, our secondary objective was to validate whether our version of the CSST captured the expected additional effort of completing switch trials over non-switch trials, henceforth denoted as pupil switching cost, and whether a smaller pupil switching cost was related to higher language entropy. In the case of the CSST, we proposed that a smaller difference in pupil size between switch and non-switch trials would reflect enhanced set shifting efficiency. We explored the possibility that increased efficiency in set shifting is visible in the pupil data only, given that pupil size over time may be more sensitive in detecting individual differences than RTs in our young adult sample.

MATERIALS AND METHODS

General Procedure

Fifty-five young adults were recruited for this study at the University of Groningen, the Netherlands, and through posts on a Facebook page targeting research participants in Groningen. Participants enrolled in the study by filling out a short screening questionnaire at home, which simultaneously served to determine their eligibility to participate. Participants were excluded from participation when they reported having (1) reading or learning disorders; (2) uncorrected sight problems (e.g., color blindness); (3) current substance abuse; (4) past traumatic brain injury; and (5) a history of psychological or neurological disorders. Furthermore, participants belonging to a COVID-19 at-risk group (e.g., people with compromised immune systems and/or pulmonary problems) were not eligible to participate, as data were collected during the COVID-19 pandemic (November and December of 2020). Importantly, participants were not selected based on their language background, as the current study aimed to explore the impact of various bilingual experiences on executive control. Hence, our target demographic consisted of students being born in the Netherlands as well as international students. With most degree programs at the University of Groningen teaching (at least partially) in English, no subjects reported exclusive monolingual daily language use; all reported to be bilingual or multilingual and were proficient in English and at least one other language.

Eligible participants first provided written informed consent online. They were then asked to complete an online background questionnaire at home. They were subsequently invited to an experimental laboratory session. In this session, participants completed three eye-tracking tasks, of which the CSST was administered last. Prior to the CSST, participants completed a resting-state measurement and an anti-saccade task (the results of which are not reported here). Task instructions were given in English.

The entire experimental session took approximately 1 h and 45 min to complete, of which 45 min were spent on the CSST. Participants received a monetary compensation of €15 upon session completion and were debriefed on the goals of the study. The study protocol was approved by the Research Ethics Committee (CETO) of the Faculty of Arts at the University of Groningen (reference number: 69895095).

Participants

Complete data were collected for 44 participants (33 women), aged 18–30 years ($M = 22.75$, $SD = 2.78$). Demographic variables such as age, gender, educational attainment, and paternal and maternal educational attainment as a proxy of socio-economic status were extracted from the online background questionnaire. Nineteen out of 44 participants reported to have been born in the Netherlands. Sample characteristics, including language background indices, are listed in **Table 1**.

In total, participants reported 14 different first languages (L1s; first language based on reported age of onset of learning). Dutch was most frequent ($n = 18$), followed by English ($n = 6$), Italian, and German (both $n = 4$). The majority ($n = 32$) reported to speak English as their second language (L2). Participants reported speaking English with a generally high proficiency level (scale of 1–10: $M = 8.42$, $SD = 1.22$, $min = 6$, $max = 10$).

There were 10 participants who did not complete the study, either because they did not fill out the background questionnaire ($n = 1$), because of COVID-19 symptoms or COVID-19 restrictions ($n = 4$), technical difficulties ($n = 2$), or a lack of available lab facilities ($n = 3$). Additionally, it was impossible to calculate entropy scores for one participant due to missing data. This last participant's data were used in the analyses investigating the main effect of trial type in the CSST, however.

TABLE 1 | Participant demographics and language experience.

	Participants ($n = 44$)			
	M	***SD***	**min**	**max**
Demographics				
Gender		33 female; 11 male		
Age (years)	22.75	2.78	18	30
Educational attainment[1]	3.25	1.40	2	5
Paternal educational attainment[2]	3.89	1.03	1	5
Maternal educational attainment[1]	3.82	1.05	1	5
Language experience				
Number of known languages[3]	3.61	1.03	2	5
Age of Acquisition (AoA)				
L2 AoA (years)	6.42	3.45	0	19
L3 AoA ($n = 33$; years)	12.30	4.45	0	22
Proficiency				
L1 Speaking (1–10)	9.54	0.87	6	10
L2 Speaking (1–10)	7.79	1.97	1	10
L3 Speaking ($n = 33$; 1–10)	4.66	2.65	1	10
Exposure				
L1 Exposure (%)	42.32	24.60	5	85
L2 Exposure (%)	43.49	25.88	0	95
L3 Exposure ($n = 33$; %)	10.97	16.11	0	72
Code-switching habits		***n* (%)**		
No switching		21 (47.7%)		
Switches on sentence-by-sentence basis		7 (15.9%)		
Switches on word-by-word basis		16 (36.4%)		

[1]Scale of 1–6:1 = primary school, 2 = secondary school, 3 = intermediate vocational education/community college, 4 = University of Applied Sciences or equivalent, 5 = university, and 6 = PhD degree.
[2]Scale of 1–5: 1 = no secondary school diploma, 2 = secondary school diploma, 3 = some post-secondary education, 4 = post-secondary degree or diploma, or 5 = graduate/PhD degree or professional degree.
[3]Participants were able to indicate up to five languages in the language background questionnaire. Therefore, it is possible that they knew more than five languages.

Materials

Background Questionnaire

In order to obtain a detailed picture of participants' language background and usage patterns, a questionnaire was administered online to participants using Qualtrics (Qualtrics, Provo, UT). In addition to questions asking about standard demographic information, the questionnaire included questions from the LEAP-Q 3.0 (Marian et al., 2007) and the Language Social Background Questionnaire (Anderson et al., 2018). This was done to tailor the questionnaire to the University of Groningen context, specifically. For the purposes of the current study, we extracted data pertaining to language use in several contexts (for reading, for speaking, at home, at university, at work, and in social settings), global language exposure, AoA, and self-assessed language proficiency for the L1, L2, and L3. Please see our entry in the Open Science Framework (OSF; see section "Data Availability Statement") for the complete questionnaire.

Color-Shape Switching Task

To tap conflict monitoring, set shifting, and goal maintenance abilities, we used a CSST. In the CSST, participants are presented with colorful geometric figures and are asked to respond to the color (in our case, blue or orange) or the shape (in our case, a circle or a square) of the figure by means of a button-press. In so-called single blocks, participants are required to respond to a single criterion (i.e., only color or only shape). In the color task, participants decide by means of a button-press whether the figure is blue or orange, and in the shape task, participants press a button to indicate whether the figure is a circle or a square. In mixed blocks, a cue indicates to which criterion the participant should respond. These cues randomly alternate within blocks, resulting in switch trials (trials for which the criterion changes) and non-switch trials (trials for which the criterion is the same as for the previous trial).

Following Li et al. (2021), we extracted global RT, switching costs, and mixing costs as indices of executive control. Global RT is represented by the overall RT in the mixed blocks and has been used previously to relate language entropy to conflict monitoring (Li et al., 2021). Switching costs were calculated as the difference in RTs between switch trials and non-switch trials in the mixed blocks and were used as a proxy for set shifting (Prior and MacWhinney, 2010). Mixing costs were calculated by the difference in RTs between non-switch trials in the mixed blocks and single trials and have been considered to tap goal maintenance abilities (Marí-Beffa and Kirkham, 2014). As engaging in contexts where language use is more integrated requires a speaker to monitor the environment for linguistic changes, we expected that bilinguals with more integrated language use would have more efficient conflict monitoring abilities, as manifested in faster global RTs. Furthermore, we predicted that more integrated bilingual

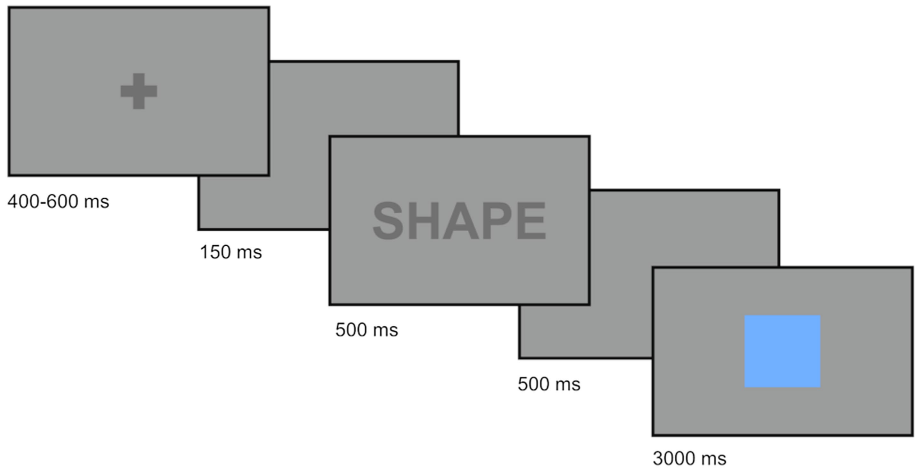

FIGURE 1 | Sample trial procedure for a mixed trial in the color-shape switching task.

language use would be associated with smaller switching and mixing costs in RTs, taking into account the findings by Li et al. (2021), Gullifer et al. (2018), and Gullifer and Titone (2021b).

Apparatus

Pupil size over time (in arbitrary units) was recorded using the Eyelink Portable Duo eye-tracking system (SR Research, Canada) at a sampling rate of 500 Hz. Data were only collected for the participants' dominant eye. The CSST was programmed using OpenSesame version 3.2.8 (Mathôt et al., 2012) and the PyGaze library (Dalmaijer et al., 2014) and was presented on a 17.3-inch laptop with a 1920 × 1080 resolution.

Stimuli

In the CSST, participants were presented with blue (RGB: 95, 167, and 252) and orange (RGB: 207, 152, and 24) squares and circles (square: 2.3° × 2.3°; circle: 2.3° diameter), which appeared one-by-one in the middle of the screen on a light gray background (RGB: 155, 155, and 155). Depending on the criterion, the participant had to either decide on the color or the shape of the stimulus by pressing a key. The cues, which only appeared in mixed blocks, were the words "SHAPE" or "COLOR" and appeared in dark gray (RGB: 112, 112, and 112) in Arial (font size: 72) in the middle of the screen.[3]

Experimental Procedure

Participants were seated approximately 60 cm from the eye-tracker. Distance to the eye-tracker was tracked online with a target sticker placed on the participant's forehead. The eye-tracking signal was calibrated and validated using a nine-point procedure before the start of the task. Manual drift correction took place before each experimental block.

Following Prior and MacWhinney (2010), the participants completed two single-task blocks of 36 items each (color and shape), followed by three mixed blocks of 48 trials each, and ended with two single-task blocks of 36 items each. The order of the single-task blocks, as well as the dedicated response keys, were counterbalanced across participants, resulting in four versions of the experiment. Responses were made pressing the "d" and "f" keys with the left hand and the "j" and "k" keys with the right hand. One hand always responded to the "color" criterion and the other always responded to the "shape" criterion. Experimental blocks were preceded by eight practice trials in single-task blocks, and 16 practice trials in mixed blocks. The practice blocks were repeated until the participant reached an accuracy of at least 80%, to ensure a correct understanding of the task. Participants received feedback on their performance during the practice trials only. In total, the experiment contained 144 single-task block trials (72 color and 72 shape task trials) and 144 mixed trials (72 switch and 72 non-switch trials).

Trials were presented as follows. First, the participants looked at a fixation cross at the center of the screen for 400–600 ms in order to trigger the start of the trial. In the single-task blocks, the stimulus appeared after a lag of 150 ms. Alternatively, in mixed blocks, a cue ("COLOR" or "SHAPE"; 500 ms) and an additional gap of 500 ms preceded the stimulus. The stimulus always remained on the screen for 3,000 ms to ensure a fixed trial length within blocks. Despite this, participants were instructed to respond as fast and as accurately as possible. In the mixed blocks, trials of the same type did not appear more than four times in a row. **Figure 1** schematically illustrates a mixed block trial.

Analysis

The data were preprocessed, analyzed, and plotted in R version 4.1.1 (R Core Team, 2021) using version 1.0.7 of the *dplyr*

[3]Whereas in previous versions of the CSST, graphic cues are used to circumvent possible linguistic effects (Yang et al., 2016); for the purpose of our experiment, it was vital to keep the luminosity of the cues constant across conditions. As such, we opted for words denoting the task (cf. Ramos et al., 2017).

TABLE 2 | Mean language entropy scores for reading, speaking, home, university, and social contexts.

Language entropy	Participants ($n = 44$)			
	M	*SD*	min	max
Reading	0.79	0.38	0	1.57
Speaking	0.74	0.47	0	1.58
Home	0.73	0.47	0	1.58
University	0.43	0.49	0	1.49
Social	0.95	0.37	0	1.58

package (Wickham et al., 2018). The full reproducible code is available in the OSF repository.

Calculating Language Entropy Scores

Following Gullifer and Titone (2020), language entropy scores were calculated from the self-reported language use data for the L1, L2, and L3 in each communicative context (at home, at university, in social domains, for reading, and for speaking; see **Table 2**), using the *languageEntropy* package (Gullifer and Titone, 2018). The usage data for the home, university, and social contexts were elicited using Likert scales, with the prompt "Please rate the amount of time you *actively use* the following language(s)/dialect(s) in [context] on a scale of 1–7 (1 = no usage at all, 7 = all the time)." Following Gullifer and Titone (2020), these scores were baselined by subtracting 1 from each response, such that a score of 0 represented "no usage at all." Subsequently, these scores were converted to proportions by dividing a language's score by the sum total of the scores in each context. For reading and speaking, language use was elicited by percentage of use (e.g., "When choosing a language/dialect to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language/dialect?"). All percentages added up to 100%. These percentages were converted to proportions, which were then used to calculate the entropy values per context for each participant. Language entropy was calculated using the entropy formula of Shannon (1948):

$$H = -\sum_{i=1}^{n} P_i \log_2 \left(P_i \right)$$

In this formula, the number of possible languages within the social context is represented by n, and P_i is the proportion of the use of language$_i$ in that context. A language entropy value of 0 indicates that only one language is used in a certain context. If a bilingual's language use is completely balanced, then the entropy value approximates 1 for two languages and 1.60 for three languages.

To reduce the complexity of the entropy data, we followed Gullifer and Titone (2020) and conducted a Principal Component Analysis (PCA). PCA is used to reduce the complexity of a given dataset by grouping correlated variables into a limited set of "principal components" reflecting the variance found in the data set (Abdi and Williams, 2010). We used varimax rotated components and selected our final number of components using a biplot and correlation matrices of the PC scores and individual entropy scores. This resulted in two PC components. Home, social, reading, and speaking entropy loaded into one component and explained 43.2% of the data. University entropy, with some cross-loading from social entropy, loaded into the second component and explained 26.7% of the data. The individual varimax component loadings are provided in the **Supplementary Table 1**. As a PCA can only be computed over complete cases, work entropy was not included in the PCA, as a considerable number of participants ($n = 13$, 29.5% of the sample) reported to be unemployed. Component scores for each participant were extracted and served as indices of university entropy and entropy anywhere else (non-university entropy) in the subsequent analyses. Recall from above that lower scores represent a more compartmentalized context, whereas higher scores represent a more integrated context, where the proportion of use of each language is more balanced.

Preprocessing

Behavioral Data

Since participants performed at ceiling level for all trial types (see Section "The Effect of Language Entropy on RTs"), we limited our analyses to RTs. Only RTs from correct responses were analyzed. Following recommendations for RT analysis (Luce, 1991; Whelan, 2008), responses <100 ms were excluded from the analysis (0.38% of the entire dataset). The data were subsetted per trial type to calculate global RT and switching costs (switch and non-switch trials) and mixing costs (non-switch and single-task trials). The processed datasets are available in the OSF repository.

Pupil Data

The pupil data collected during the CSST were preprocessed using version 0.0.1.2. of the *gazeR* package (Geller et al., 2020). To preprocess the data, we executed the following steps. First, we identified blinks in the signal and subsequently applied a smoothing function and interpolated the signal using a cubic spline. Then, we applied subtractive baseline correction (pupil size—baseline) for the 200 ms preceding the 150 ms gap in the trial. During the artifact rejection procedure, we excluded 3.98% of the data in the entire dataset in several steps. First, we removed trials that missed >25% of the data. Then, following recommendations by Mathôt et al. (2018), we rejected unlikely pupil values by visually inspecting a histogram of pupil values per participant. Any value that was clearly much higher or lower than the majority of the data was deleted. Lastly, we estimated the mean absolute deviation and removed observations for which the pupil size changed quicker than physiologically probable. As a next step, we aligned the event start time to the presentation of the cue. Finally, we downsampled the data to 50 Hz (i.e., time bins of 20 ms). For a complete discussion and accompanying code of the preprocessing procedure, we refer to our preprocessing script in the OSF repository and Geller et al. (2020).

Reaction Times

The RT data were analyzed using a trial-by-trial approach with generalized linear mixed-effects models using the *glmer* function from the *lme4* package (version 1.1-27.1; Bates et al., 2015). *p*-Values of the estimates were obtained *via t*-tests using the Satterthwaite approximations to degrees of freedom, using version 3.1-3 of the *lmerTest* package (Kuznetsova et al., 2017). Following recommendations for RT analysis (Lo and Andrews, 2015), instead of using linear mixed-effects models and log-transforming the RTs, we fitted generalized linear mixed-effects models with an Inverse Gaussian distribution paired with an "identity" link to approximate the distribution of our RT data. We added sum-to-zero orthogonal contrasts to the trial type variable to improve interpretation of the results (Baguley, 2012; Schad et al., 2020). For mixing cost, we coded single trials as −0.5 and non-switch trials as +0.5 (−SI + NS). For switching cost, we coded non-switch trials as −0.5 and switch trials as +0.5 (−NS + SW). As such, the effect of trial type is to be interpreted as the change in effect when moving from one trial type to the other.

To investigate the effect of the diversity of language use at university and in non-university contexts on global RT and switching and mixing costs, we fitted two hypothesis models (RTs for switch and non-switch trials and RTs for non-switch and single trials). RT was entered as the dependent variable, followed by an interaction between trial type (switch and non-switch, or non-switch and single) and university and non-university entropy, a fixed effect of trial number to account for autocorrelation in the data, and a random intercept for each participant. This resulted in the following basic model specification:

$$\begin{aligned} RT \sim & \left(\text{Trial Type} \times \text{University Entropy}\right) \\ & + \left(\text{Trial Type} \times \text{Non} - \text{university Entropy}\right) \\ & + \text{Trial Number} + \left(1|\text{Subject}\right) \end{aligned}$$

Trial number was scaled and centered around the mean in each model. Model comparisons using the *anova* function and the Akaike's Information Criterion (AIC) assessed whether the addition of random slopes of trial type or trial number per subject improved the fit of each hypothesis model. These random slopes were included in the model to account for the possibility that participants may show individual fatigue effect patterns (i.e., in some participants, RTs may increase as the number of completed trials increases).

Considering that more traditional bilingual language variables may explain variance in the data in addition to language use patterns (Gullifer and Titone, 2020), additional fixed effect predictors of L2 age of acquisition, L2 proficiency, and L2 exposure were added one-by-one to our hypothesis model. These predictors did not significantly contribute to the model fit for switching cost [L2 AoA: ($\chi^2(1) = 0.2302$, $p = 0.63$); L2 proficiency: ($\chi^2(1) = 0.6773$, $p = 0.41$); L2 exposure: ($\chi^2(1) = 0.1484$, $p = 0.70$)] or mixing cost [L2 AoA: ($\chi^2(1) = 0.8309$, $p = 0.36$); L2 proficiency: ($\chi^2(1) = 0.946$, $p = 0.33$)], or inclusion led to unresolvable model convergence issues (in the case of L2 exposure in the mixing cost analysis). Therefore, these predictors were not included in the final models. Model assumptions were checked with version 0.8.0 of the *performance* package (Lüdecke et al., 2021). We applied model criticism on the best fitting models by excluding all observations with absolute residuals larger than 2.5 SDs above the mean (1.99% of the observations for switching cost and 2.14% of the observations for mixing cost). No undue influence from outliers on the model estimates was identified. The final models (see **Table 3**) reflect the results on the basis of the trimmed datasets. The results were visualized using version 2.8.9 of the *sjPlot* package (Lüdecke, 2021).

Pupil Size Over Time

Pupil size over time was analyzed using Generalized Additive Mixed Models (GAMMs).[4] GAMMs are an extension of mixed-effects regression models (Sóskuthy, 2017). However, they differ in that they are able to model non-linear data using so-called "smooths" (Baayen et al., 2018; Wieling, 2018). These smooths are made by combining a set of basis functions in such a way that they fit the data (for more details, see Wieling, 2018, p. 91). GAMMs then apply a non-linearity penalty to prevent overfitting. This penalty is called wiggliness. This method is especially suitable for analyzing time-course data, as it can take into account autocorrelation and because the signal needs not be averaged over a prespecified epoch. For this reason, GAMMs have become quite popular in recent years for studying event-related potentials (Meulman et al., 2015), dynamic phonetic data (Wieling, 2018), and pupillometric data (van Rij et al., 2019; Boswijk et al., 2020).

GAMMs were fitted in R version 4.1.2 (R Core Team, 2021), using version 1.8-38 of the *mgcv* package (Wood, 2011). First, a base model was built to verify that our version of the CSST captured the additional attentional resources needed to respond to the more difficult switch trials. That is, to see whether switch trials resulted in larger pupil size over time than non-switch trials.[5] This model included a factor smooth modeling the pupil size over time per participant. Another factor smooth modeled the individual variation over time by trial type. We then investigated if gaze position (i.e., the *x* and *y*-coordinates on the screen), distance to the eye-tracker, and the effect of distance to the eye-tracker per participant needed to be added to the model by comparing AIC scores per model using the *CompareML* function in *mgcv*.

To test our hypotheses, two models were built that included an interaction between trial type with university entropy or non-university entropy. These models were based on the best models resulting from the analysis investigating the main trial type effect. The best fitting models resulting from these comparisons are presented in the Results section. Since the models' residuals were not normally distributed, all final models were refitted with a scaled-*t* distribution used for heavy-tailed data. The results were visualized using version 2.4 of the *itsadug* package

[4]For introductions and tutorials for GAMMs, please refer to Sóskuthy (2017), Wood (2017), and Wieling (2018).

[5]The current design of the CSST did not permit appropriate comparison of pupil size during single and non-switch trials. As such, we only target the difference in pupil size for switch- and non-switch trials.

TABLE 3 | Summary of the *glmer* models of the effect of language entropy on global RT and switching costs (RT) as well as the effect of language entropy on mixing costs (RT) reporting the explained variance and standard deviation (SD) for the random effects, and the model estimates, standard errors (SE), *t*-values, and *p*-values for the fixed effects.

	Global RT and Switching cost				Mixing cost			
Random effects								
Grouping	**Effect**	**Variance**	**SD**	**Correlation**	**Effect**	**Variance**	**SD**	**Correlation**
Participant	(Intercept)	9,793	98.960	–	(Intercept)	4,415	66.444	–
	Trial Type (-NS+SW)	2,413	49.126	0.41	Trial Type (-SI+NS)	4,888	69.912	0.60
	Trial Number	7,623	87.311	–	Trial Number	348.5	18.668	0.28 0.04
Residual		0.0002903	0.017	–	–	0.0002089	0.0145	–
Fixed effects								
Effect	**Estimate**	**SE**	***t*-value**	***p*-value**	**Estimate**	**SE**	***t*-value**	***p*-value**
(Intercept)	851.515	19.937	42.710	**<0.001*****	709.160	12.478	56.834	**<0.001*****
Trial Type (−NS+SW)	129.358	12.323	10.497	**<0.001*****	–	–	–	–
Trial Type (−SI+NS)	–	–	–	–	163.158	12.068	13.520	**<0.001*****
Trial Number	41.743	17.452	2.392	**0.017***	29.046	5.169	5.619	**<0.001*****
University Entropy	127.393	27.433	4.644	**<0.001*****	115.336	11.837	9.744	**<0.001*****
Non-university Entropy	−38.015	27.184	−1.398	0.162	−37.972	11.570	−3.282	**0.001****
Trial Type * University Entropy	19.874	19.607	1.014	0.311	23.557	14.206	1.658	0.097
Trial Type * Non-university Entropy	4.933	19.520	0.253	0.801	−41.526	14.454	−2.873	**0.004****

**p*<0.05; ***p*<0.01; ****p*<0.001. The values in bold reflect significance at at least the *p*<0.05 level.*

(van Rij et al., 2020). For a complete overview of our model-building procedure, see our entry in the OSF repository.

RESULTS

The Effect of Language Entropy on RTs

Mean RTs and accuracy rates per condition, followed by mean global RT, switching costs, and mixing costs in the CSST, are displayed in **Table 4**. The effects of university entropy and non-university entropy on global RT and switching costs, and on mixing costs are visualized in **Figures 2, 3**, respectively. Summaries of the final models, including random effects, are available in **Table 3**.

The model summary for switching cost showed a main effect of trial type (est = 129.358, $p < 0.001$), such that, overall, participants were slower to respond to switch trials in comparison to non-switch trials (i.e., showed a switching cost, as expected). In addition, university entropy modulated global RT (est = 127.393, $p < 0.001$), suggesting that those individuals with higher diversity of language use at university were generally slower in performing the mixed blocks. No main effect of non-university entropy was found, indicating that non-university entropy did not modulate global RT. Likewise, the interactions between trial type and neither entropy measure were not significant.

Similarly, for mixing cost, a main effect of trial type was found (est = 163.158, $p < 0.001$): participants responded significantly slower to non-switch trials in the mixed block in comparison with single trials (i.e., showed a mixing cost). The results also revealed a main effect of university entropy on RTs (est = 115.336, $p < 0.001$), such that participants who used their languages in a more integrated manner at university were slower in responding overall. The reverse

TABLE 4 | Mean RTs (ms) and accuracy, and EF measures derived from the CSST.

	Reaction time (ms) *M* (SD)	Accuracy *M* (SD)
Single-task trials	525.74 (225.23)	0.99 (0.11)
Non-switch trials (mixed block)	624.18 (366.88)	0.97 (0.17)
Switch trials (mixed block)	710.79 (409.77)	0.96 (0.20)
EF measures		
Global RT (mixed block)	667.24 (391.17)	
Switching cost	82.92 (505.65)	
Mixing cost	95.57 (426.66)	

was found for non-university entropy (est = −37.972, $p < 0.01$), indicating that those bilinguals with higher diversity of language use in contexts outside university were faster at responding overall. Finally, non-university entropy interacted with trial type (est = −41.526, $p < 0.01$), such that higher diversity of language use in contexts outside the university setting was related to a smaller mixing cost. No interaction effect was found between university entropy and trial type.

Pupil Dilation Results

The Main Effect of Switching on Pupil Size

The first GAMM modeled the main effect of trial type (switch trials versus non-switch trials) on pupil size over time. The results of this model, as well as the interaction models, can be found in **Table 5**. The average pupil size for switch trials was significantly larger than for non-switch trials (est = 19.591, $p < 0.001$). The model estimates do not tell us how pupil dilation developed over time. In order to evaluate the actual pattern

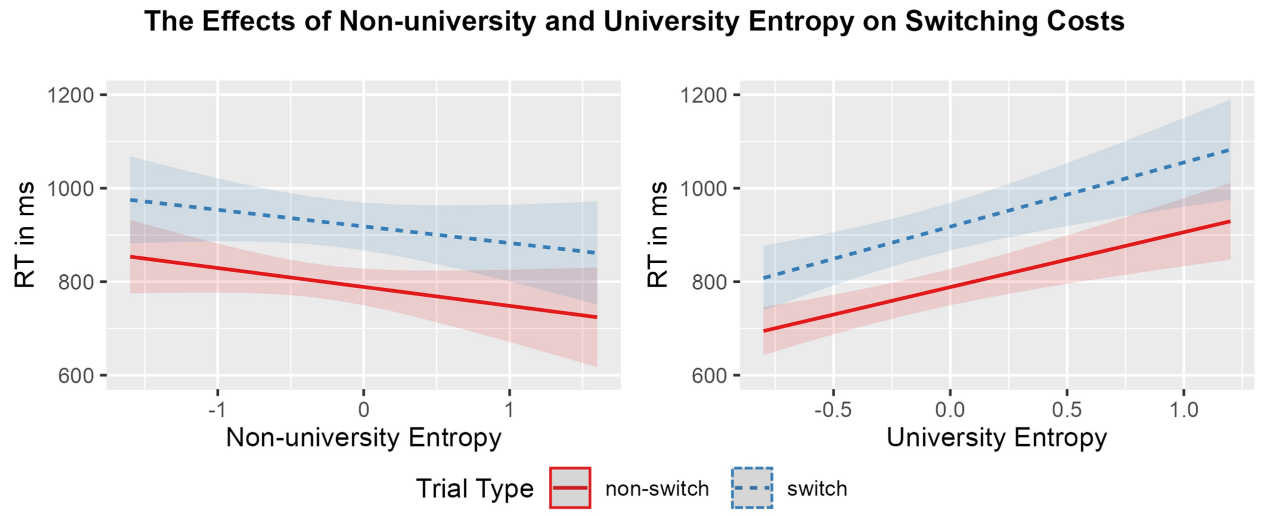

FIGURE 2 | Regression model plot of the interaction between non-university entropy (**left panel**) and university entropy (**right panel**) and trial type (blue striped: switch; red solid: non-switch) on RTs (ms). Shading represents the size of the confidence bands.

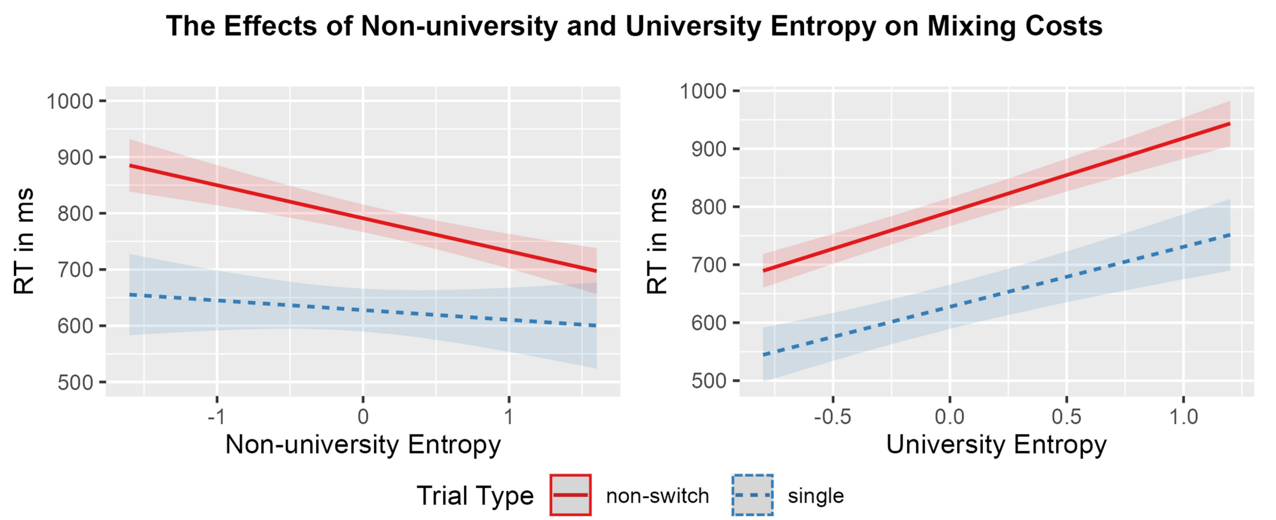

FIGURE 3 | Regression model plot of the interaction between non-university entropy (**left panel**) and university entropy (**right panel**) and trial type (blue striped: single; red solid: non-switch) on RTs (ms). Shading represents the size of the confidence bands.

of this non-linear effect during the trial, we plotted the change in pupil size over time for switch trials and non-switch trials in **Figure 4**. As can be seen in the plots, a pupil switching cost emerged immediately after the cue was shown. The difference between switch and non-switch trials became significant at 609 ms after the cue was shown; it peaked around 2,200 ms, and it remained significant for the remainder of the trial.

University Entropy and Pupil Switching Cost

The second model supplemented the original model by including a non-linear interaction with university entropy. The model summary can be found in **Table 5**. The main effect of trial type remained significant (est = 12.481, $p < 0.001$), meaning that the average pupil dilation for switch trials (the reference level) remained larger than for non-switch trials. **Figure 5** is a contour plot that models the difference in pupil size between the switch and non-switch trials over time, while taking into account an interaction with university entropy. Contour plots are useful in visualizing three-dimensional interactions, but it is difficult to quantify the size of the difference between switch and non-switch trials based on color alone. The solid lines in the contour plot, therefore, show us how big the difference in pupil size is between switch and non-switch trials. The dotted green and red lines represent the confidence intervals for each line. The pupil switching cost became significant slightly earlier

TABLE 5 | Summary of the generalized additive mixed models looking at the main effect of trial type, and the interaction of trial type with university and non-university entropy on pupil size.

	Base model				University entropy model				Non-university entropy			
	Estimate	**SE**	***t*-value**	**Pr(>|*t*|)**	**Estimate**	**SE**	***t*-value**	**Pr(>|*t*|)**	**Estimate**	**SE**	***t*-value**	**Pr(>|*t*|)**
Parametric coefficients												
(Intercept)	−7.450	5.859	−1.272	0.204	−10.278	5.261	−1.954	0.051	−7.601	5.214	−1.458	0.145
Trial TypeO−switch	19.591	4.651	4.212	**<0.001*****	–	–	–	–	–	–	–	–
Trial Type−switch	–	–	–	–	12.481	3.435	3.634	**<0.001*****	12.942	3.476	3.724	**<0.001*****
Smooth terms	**Edf**	**Ref. df**	***F*-value**	***p*-value**	**Edf**	**Ref. df**	***F*-value**	***p*-value**	**Edf**	**Ref. df**	***F*-value**	***p*-value**
s (Time)	8.959	8.964	28.907	**<0.001*****	–	–	–	–	–	–	–	–
s (Time):Trial TypeO−switch	4.167	4.643	6.673	**<0.001*****	–	–	–	–	–	–	–	–
te (Time, Entropy):Trial Type−non-switch	–	–	–	–	13.394	14.087	0.134	1.00	17.950	18.668	13.241	**<0.001*****
te (Time, Entropy):Trial Type−switch	–	–	–	–	10.996	11.609	1.112	0.349	18.406	19.024	12.381	**<0.001*****
s (Mean X, Mean Y)	28.262	28.960	92.206	**<0.001*****	28.011	28.929	67.604	**<0.001*****	27.979	28.924	63.134	**<0.001*****
s (Mean Distance)	5.486	5.994	3.807	**<0.001*****	5.941	6.465	2.196	**<0.05***	6.013	6.535	2.539	**<0.05***
s (Time, Subject)	358.916	395.000	27.324	**<0.001*****	346.851	387.000	28.140	**<0.001*****	344.579	385.000	28.371	**<0.001*****
s (Time, Subject):Trial TypeO−switch	345.950	395.000	4.346	**<0.001*****	316.401	387.000	3.712	**<0.001*****	304.308	385.000	1.620	**<0.001*****
s (Mean Distance, Subject)	165.455	390.000	2.673	**<0.001*****	142.311	383.000	2.064	**<0.001*****	141.529	381.000	2.103	**<0.001*****
		R^2 (adjusted): 0.0939				R^2 (adjusted): 0.122				R^2 (adjusted): 0.114		
		Explained deviance: 7.22%				Explained deviance: 9.5%				Explained deviance: 8.95%		

*We report parametric coefficients, effective degrees of freedom (Edf), reference degrees of freedom (Ref. df), F-values, and p-values for the tensor products, smooth terms, and random effects. The interaction between university entropy and trial type over time is displayed in two rows. The reason for this is that it can become problematic to have an ordered factor in the fixed effects structure if that same term is also in the model as a non-linear interaction. Also note that the language entropy×trial type interaction in rows 3 and 4 of the smooth terms represent university entropy and non-university entropy, depending on the model.*p<0.05;**p<0.01; ***p<0.001. The values in bold reflect significance at at least the p<0.05 level.*

for participants with higher university entropy scores. However, apart from this, there did not appear to be a clear interaction between pupil switching cost and university entropy.

Non-university Entropy and Pupil Switching Cost

The last model supplemented the base model by including a non-linear interaction with non-university entropy. The summary for this model is available in **Table 5**. The main effect of trial type (est = 12.941, $p < 0.001$) remained, meaning that the average pupil dilation for switch trials continued to be larger than for non-switch trials. To understand the model output, a contour plot was made showing the interaction between non-university entropy and pupil switching cost over time (**Figure 6**). Participants with lower non-university entropy scores (i.e., more compartmentalized language use) showed a larger pupil switching cost, whereas the difference in pupil size between switch and non-switch trials for participants with higher non-university entropy scores (i.e., more integrated language use) was much smaller. When looking at **Supplementary Figure 1**, we can deduce that there was no significant difference in pupil size between switch and non-switch trials for participants with the highest non-university entropy scores.

DISCUSSION

The primary goal of the present study was to examine the effect of the social diversity of language use, as measured by language entropy, on executive control in young adults with diverse bilingual experiences. This was done by administering a CSST, tapping conflict monitoring (global RT), mental set shifting (switching cost), and goal maintenance (mixing cost). We also recorded pupil size over time during the task and compared pupil size during switch and non-switch trials as an additional, and potentially more sensitive measure of set shifting. The social diversity of language use was calculated by looking at self-reported language use in several contexts (at home, speaking, reading, in social settings, and at university). These five contexts were reduced to two components using a PCA, namely, a university entropy component (language use at university) and a non-university entropy component (language use in all other contexts). Based on previous studies, we predicted that language entropy scores would modulate the performance on the CSST, such that individuals who engaged in more integrated language contexts (i.e., had higher entropy scores) would perform the task more efficiently. For RTs, higher university entropy scores were related to slower global RT. In addition, we found reduced mixing costs for individuals with higher non-university entropy scores but not reduced switching costs. However, in the pupillometric data, we found a smaller difference in pupil size between switch trials in comparison with non-switch trials (i.e., a smaller pupil switching cost) for participants with more integrated bilingual language use in non-university contexts. This study is, to the best of our knowledge, the first to provide evidence for the beneficial effects of the diversity of bilingual language use on executive control using pupillometry.

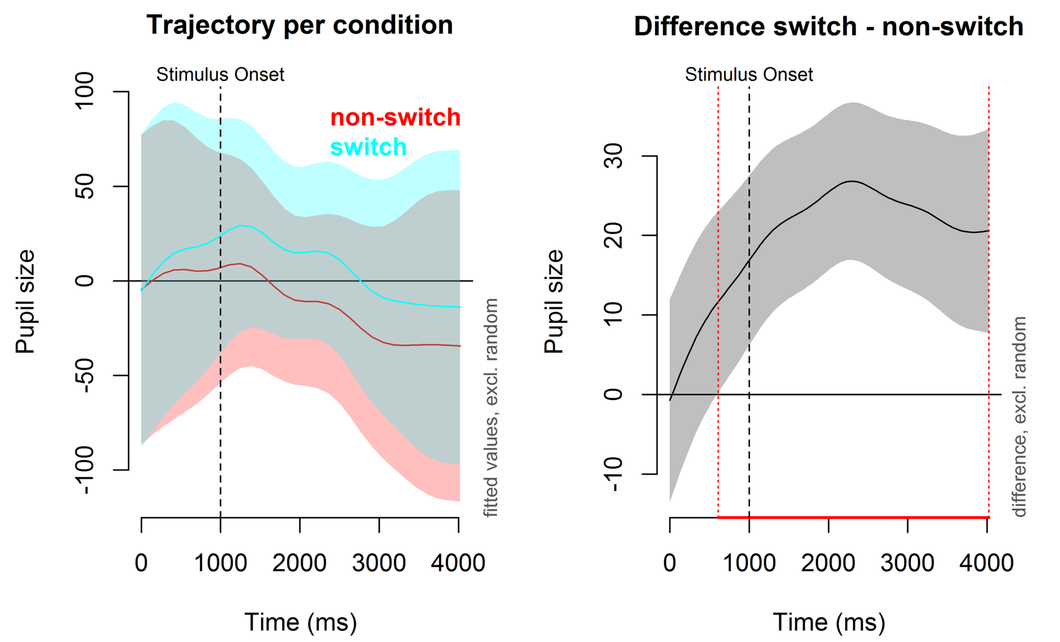

FIGURE 4 | Pupil dilation per trial type over time. **Left panel**: Pupil dilation (in arbitrary units) for switch trials (blue) and non-switch trials (red). Time (*x*-axis) starts at cue onset. The black dotted line at 1,000 ms represents the stimulus onset. **Right panel**: Pupil switching cost. The red dotted line represents the moment the difference in pupil size between switch and non-switch trials became significant.

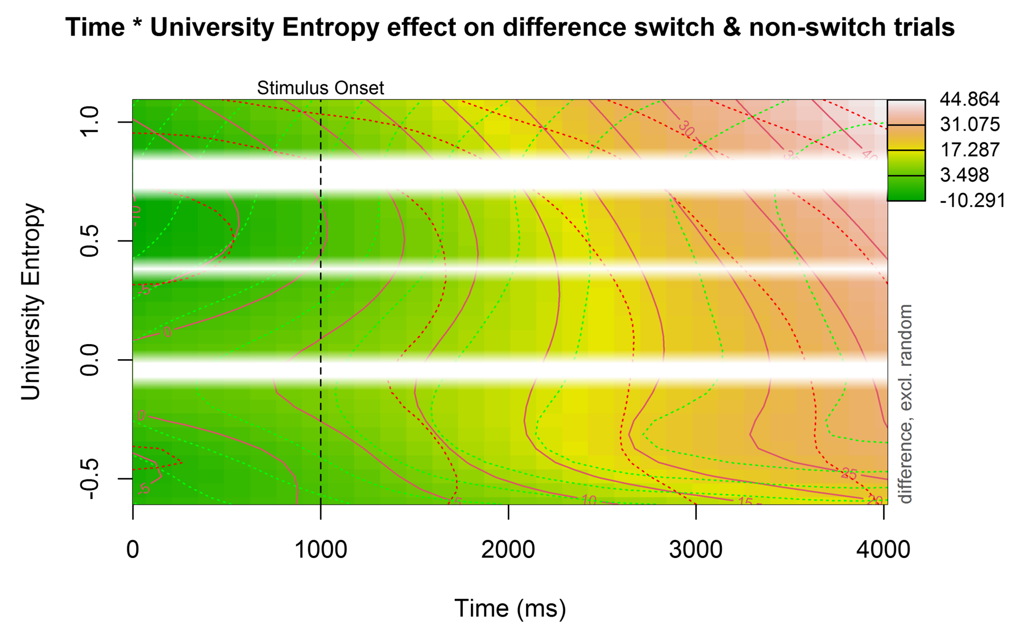

FIGURE 5 | Contour plot showing the interaction between university entropy, time, and the pupil switching cost (i.e., the difference in pupil size between switch and non-switch trials). Time is plotted on the *x*-axis, university entropy is plotted on the *y*-axis, and the pupil switching cost is indicated by color: darker green indicates a small or even reversed effect (where non-switch trials elicit a larger pupil dilation). The more red or even white the plot becomes, the larger the pupil switching cost. The white bars indicate missing data (i.e., non-existing entropy values in our dataset).

Language Entropy and Executive Control

Before discussing our primary outcomes, it is important to consider the suitability of the employed method to answer our main research question. In other words, we needed to establish whether the CSST captured robust switching and mixing costs. The pace of the CSST version used in the present

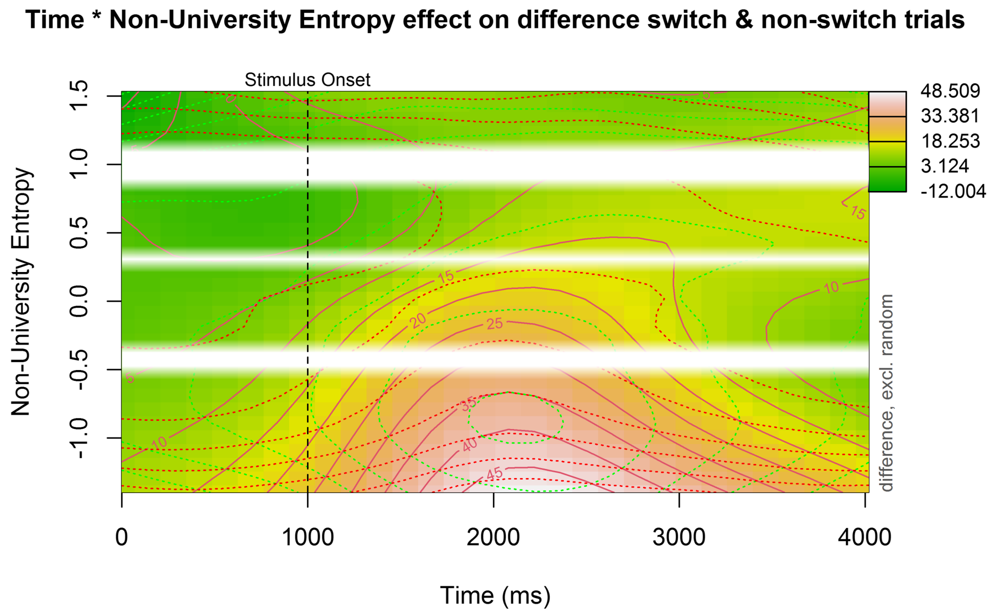

FIGURE 6 | Contour plot showing the interaction between non-university entropy, time, and the pupil switching cost. Time is plotted on the *x*-axis, non-university entropy is plotted on the *y*-axis, and the pupil switching cost is indicated by color: darker green indicates a smaller difference. The more red or even white the plot becomes, the larger the pupil switching cost. The white bars indicate missing data (i.e., non-existing entropy values in our dataset).

study was slower than in previous studies, which was required in order to let the task-induced pupil size return to baseline levels. We therefore took the main effects of trial type on RTs as a starting point for our analysis. The size of the switching and mixing costs was generally smaller than in previous studies using faster paced versions of the task (Prior and MacWhinney, 2010; Hartanto and Yang, 2016; Li et al., 2021). Despite the slower pacing, however, significant switching and mixing costs emerged in our behavioral data. Hence, we assumed that our version of the CSST was able to tap into behavioral indices of conflict monitoring, set shifting, and goal maintenance abilities.

Regarding effects of language entropy on the behavioral measure (RT) of the CSST, our results showed that higher university entropy was associated with slower overall RTs in the mixed blocks (i.e., global RT), contrary to our expectations. These results suggest that those bilinguals with more integrated language use at university showed poorer conflict monitoring skills. Surprisingly, we observed an opposite pattern for the non-university entropy scores, such that bilinguals with higher entropy outside of university were faster at responding in the mixed blocks, albeit not significantly so. These results suggest that the diversity of language use in separate communicative contexts (in our case, university and non-university contexts) may differentially affect executive control. However, we believe there are several potential alternative explanations for these findings. First, our data were collected during the COVID-19 pandemic, when most teaching had been online for several months. Paired with the observation that a number of participants had moved to the Netherlands during the pandemic, it is fair to conclude that these participants only had minimal exposure to university as a social context. Even participants who had been studying at the University of Groningen for more than a year had not taken in-person classes in the 9 months preceding their participation in the current study. Additionally, the quality and quantity of participation in online classes are generally not found to be as high as in-person education (e.g., Meeter et al., 2020). While it is possible that language entropy is not as reliable in assessing bilingual language use in all social contexts, we deem it unlikely that these unexpected results can be attributed to the language entropy measure itself, considering the circumstances. As with any tool, the quality of the measure depends on the quality of the data it is fed. Comparing the university entropy scores to the other examined contexts, we observed a considerable disparity between university and non-university contexts. This was further supported by our PCA that resulted in two clear components with only minimal cross-loading from the other contexts to university entropy. Altogether, this raises the question if the university context was accurately represented as an interactional setting in our study, and consequently, if our outcomes are reliable in this respect.

Regarding the relationship between language entropy and set shifting (as measured by switching cost), there were no significant interactions between either entropy component (university and non-university) and switching cost in the behavioral data. The results are therefore not in line with our prediction that people with higher entropy scores would show a reduced switching cost. These results are not consistent with previous work by Hartanto and Yang (2016) either, who found that DLC bilinguals (i.e., bilinguals with more diverse language use) had significantly lower switching costs than SLC bilinguals. Moreover, our behavioral results do not align with those presented by Li et al. (2021), who found a reduced switching cost for individuals with higher entropy scores. We speculate that the absence of this interaction for switching cost in our study could be caused by the timing of our adapted CSST, as it included a lag of 1,000 ms between the cue onset and stimulus onset to accommodate for the relatively slow pupillary trajectories. Even though our paradigm captured a significant main switching effect, the effect was relatively small (82.9 ms), as compared to 144 ms for bilinguals in Prior and MacWhinney (2010), 199 ms for DLC bilinguals in Hartanto and Yang (2016), and 185 ms in Li et al. (2021). This may be indicative of lower task difficulty, corroborated by the near-ceiling accuracy scores in our task. As such, it could be the case that the relatively small switching effect was not substantial enough to also capture intricate interaction effects, especially if one keeps in mind that there is less individual variation in the RTs of young adults (Hultsch et al., 2002).

Turning to the effects of language entropy on goal maintenance (as measured by mixing cost), no significant interaction was found between university entropy and trial type. Again, we attribute this finding to the possibility that university was not a representative social context during the COVID-19 pandemic. However, we did find a significant interaction between non-university entropy and trial type, such that higher entropy scores were associated with a smaller mixing cost, reflecting enhanced goal maintenance. Interpreted within the Adaptive Control Hypothesis framework (Green and Abutalebi, 2013), our results show that individuals who use their languages in a more integrated manner, and thus encounter situations in which it is less predictable which language will be used, are more efficient in dealing with such ambiguity. These results are in line with our predictions and earlier work demonstrating a relationship between enhanced goal maintenance and more balanced language use (Yow and Li, 2015).

Language Entropy and Pupil Switching Cost

Our secondary objective was to verify if our version of the CSST, which was adapted for recording pupil size over time, captured the expected additional effort of completing switch trials over non-switch trials, and whether a smaller pupil switching cost was related to higher language entropy. As the CSST had not previously been conducted with pupillometry, the focus of our initial analysis was on the main effect of trial type (switch vs. non-switch trials). As expected, we observed that switch trials induced significantly larger pupillary responses than non-switch trials, thus corroborating the main effect of trial type found in the behavioral data. This suggests that our version of the CSST was able to capture the increased attention that was required for completing the switch trials, and as such, we treated the pupil switching cost as an additional measure of set shifting in our study.

As a next step, we related the language entropy measures to the difference in pupil size for switch and non-switch trials (i.e., pupil switching cost). No interaction effect was found for university entropy and trial type in the pupil data. Several potential reasons for this have been described above. However, the analysis did reveal an interaction effect between non-university entropy and trial type: while a significant pupil switching cost emerged in participants with lower entropy scores, higher entropy scores were associated with smaller, non-significant, and pupil switching costs. This suggests that bilinguals with a higher diversity of language use in non-university contexts showed increased set shifting efficiency. Importantly, this effect was not captured in the RT data. This showcases the benefit of supplementing behavioral data with more sensitive indices, such as pupillometric data, when assessing the cognitive effects of individual bilingual experiences.

The fact that we found a bilingual experience effect that was absent in more traditional behavioral measures is not uncommon in the bilingualism literature (e.g., Bialystok, 2017; Lehtonen et al., 2018; DeLuca et al., 2020). However, it has to be noted that Li et al. (2021) did find a relationship between higher language entropy and a smaller switching cost (but not global RT and mixing cost) in RTs and functional brain patterns relating to executive control. To reiterate, we attribute this discrepancy between earlier work and our study to the faster pacing of the CSST in their study, making it more sensitive in detecting small individual differences in behavioral set shifting than our adapted CSST. Our result also highlights that differences with respect to methodological choices in task design can partly explain mixed results in the bilingualism literature (see Yang et al., 2016, for cued-switching paradigms, specifically).

Limitations and Future Directions

While the present study presented novel results as to the effects of language entropy on executive control, it was subject to several limitations. First, our study set out to investigate one index of bilingual language use, namely, language entropy. For the current calculation of language entropy, we did not take into account individual differences in the amount of time spent in the communicative contexts. A more accurate picture of the diversity of bilingual language use could be obtained if entropy scores were weighted with the amount of time spent in each social context, as was first done in Kałamała et al. (2020, 2021) and subsequently in Li et al. (2021). This way, one can control for the disparity in engagement in the various contexts. This could be a more appropriate approach, as the diversity of language use in contexts in which an individual spends more time likely has a larger effect on domain-general executive control (Abutalebi and Green, 2016). Moreover, to obtain a more complete image of bilingual language use patterns and their effects on executive control, variables quantifying language switching and mixing behaviors should be considered in conjunction with language entropy (e.g., Kałamała et al., 2021). This would simultaneously enable future research to test the full set of predictions made by the ACH. The second limitation relates to our adapted CSST task. Despite its ability to capture behavioral switching and mixing costs, we propose it can be improved in two ways. First, in its current form, it does not allow for a direct comparison of pupil size during trials in the single blocks and non-switch trials in the mixed blocks to obtain pupil indices of goal maintenance. One way this can be approached in the future is to alter the trial procedure, such that the cue (i.e., "COLOR" or "SHAPE") is presented in mixed blocks as well as in single blocks. This way, trials are comparable in nature and length across single and mixed blocks, which would enable the investigation of a "pupil mixing cost." Second, the relatively long lag between cue onset and stimulus onset may explain the lack of an interaction effect between entropy and switching cost in the RT data in our study. This lag was initially introduced to accommodate for expected slow changes in pupil size. However, in the pupillometry analyses, we found that larger pupil dilation for switch trials occurred almost immediately after cue onset, and even that this difference became significant before the stimulus onset. This result strongly suggests that pupillometry is an appropriate way to measure an increase in effort exerted during switch trials. However, it is also likely that the slower pace of our CSST made the task easier to complete, which would explain the generally smaller switching and mixing costs in the RT data, as compared to other studies (Prior and MacWhinney, 2010; Hartanto and Yang, 2016; Li et al., 2021). To capture the behavioral effects better while still measuring pupil dilation patterns over time, we recommend a faster paced design in future studies. Such a design will shorten the task and also increase task demands, possibly leading to an optimal sensitivity in capturing behavioral and pupil size effects.

A final and obvious limitation to discuss is the fact that this study was conducted during the COVID-19 pandemic. Our results currently point toward the possibility that the diversity of language use in separate social contexts (university and non-university contexts) is differentially associated with executive control. This suggests that language use varying per social context may be a key variable in neurocognitive adaptations resulting from bilingual experiences. It could be argued that there is a difference between the two components in terms of voluntarity of language use. While language use in non-university contexts may be more of a choice, students at the University of Groningen are often required to speak English during class, and so it is more predictable when which language to use at university than in other contexts. However, as discussed above, we question the validity of the university entropy component in our study due to the circumstances imposed on the university system during the pandemic. It is therefore difficult to speculate if the contradictory results can indeed be explained as such. Hence, we recommend that future work replicates this study when restrictions regarding in-person teaching have been lifted.

CONCLUSION

In conclusion, our study's findings provide further evidence for the relationship between the social diversity of bilingual language use, as measured by language entropy, and executive control. We demonstrated reduced switching and mixing costs, reflecting enhanced set shifting and goal maintenance abilities, for bilinguals with a higher diversity of language use relative to lower diversity in non-university contexts. No such relationship was found for university contexts, but higher university entropy was associated with weaker conflict monitoring. This potentially illustrates that the effect of the diversity of language use differs per social context. Alternatively, it is possible that university simply was not a valid social context during the COVID-19 pandemic. As such, replication of this study is warranted. We also showed that our adapted CSST effectively captured switching and mixing cost in the RTs. The pupillometry data were able to capture effects that were not visible in the behavioral data. These findings additionally highlight the utility of pupillometry as a sufficiently sensitive tool to assess the effects of individual bilingual experiences on executive control.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: Open Science Framework repository, https://osf.io/3xjsq/?view_only=e88ee7956d4b4a038bba3cbe59aa871c.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Research Ethics Committee (CETO) of the Faculty of Arts of the University of Groningen. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FvdB, JB, and MK conceived the study idea. FvdB and JB developed the methodology. FvdB programmed the experiments. FvdB, JB, and TT carried out the experiments, analyzed the data, and drafted the manuscript. All authors discussed and interpreted the results of the study, critically revised the article, and have read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.864763/full#supplementary-material

REFERENCES

Abdi, H., and Williams, L. J. (2010). Principal component analysis. *Wiley Interdiscip. Rev. Comput. Stat.* 2, 433–459. doi: 10.1002/wics.101

Abutalebi, J., and Green, D. W. (2016). Neuroimaging of language control in bilinguals: neural adaptation and reserve. *Biling. Lang. Cogn.* 19, 689–698. doi: 10.1017/S1366728916000225

Anderson, J. A. E., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Antoniou, M. (2019). The advantages of bilingualism debate. *Annu. Rev. Linguist.* 5, 395–415. doi: 10.1146/annurev-linguistics-011718-011820

Aston-Jones, G., and Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annu. Rev. Neurosci.* 28, 403–450. doi: 10.1146/annurev.neuro.28.061604.135709

Baayen, R. H., van Rij, J., de Cat, C., and Wood, S. (2018). "Autocorrelated errors in experimental data in the language sciences: some solutions offered by generalized additive mixed models," in *Mixed-Effects Regression Models in Linguistics Quantitative Methods in the Humanities and Social Sciences*. eds. D. Speelman, K. Heylen and D. Geeraerts (Cham: Springer International Publishing), 49–69.

Baguley, T. (2012). *Serious Stats: A Guide to Advanced Statistics for the Behavioral Sciences* Macmillan International Higher Education (England, Houndmills).

Bates, D., Mächler, M., Bolker, B., and Walker, S. (2015). Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67, 1–48. doi: 10.18637/jss.v067.i01

Beatty-Martínez, A. L., Navarro-Torres, C. A., Dussias, P. E., Bajo, M. T., Guzzardo Tamargo, R. E., and Kroll, J. F. (2020). Interactional context mediates the consequences of bilingualism for language and cognition. *J. Exp. Psychol. Learn. Mem. Cogn.* 46, 1022–1047. doi: 10.1037/xlm0000770

Beatty-Martínez, A. L., and Titone, D. A. (2021). The quest for signals in noise: leveraging experiential variation to identify bilingual phenotypes. *Language* 6:168. doi: 10.3390/languages6040168

Bialystok, E. (2017). The bilingual adaptation: how minds accommodate experience. *Psychol. Bull.* 143, 233–262. doi: 10.1037/bul0000099

Bialystok, E. (2021). Bilingualism as a slice of Swiss cheese. *Front. Psychol.* 12:769323. doi: 10.3389/fpsyg.2021.769323

Bialystok, E., Craik, F. I. M., and Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends Cogn. Sci.* 16, 240–250. doi: 10.1016/j.tics.2012.03.001

Boswijk, V., Loerts, H., and Hilton, N. H. (2020). Salience is in the eye of the beholder: increased pupil size reflects acoustically salient variables. *Ampersand* 7:100061. doi: 10.1016/j.amper.2020.100061

Dalmaijer, E. S., Mathôt, S., and Van der Stigchel, S. (2014). PyGaze: an open-source, cross-platform toolbox for minimal-effort programming of eyetracking experiments. *Behav. Res. Methods* 46, 913–921. doi: 10.3758/s13428-013-0422-2

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U. S. A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage* 204:116222. doi: 10.1016/j.neuroimage.2019.116222

Geller, J., Winn, M. B., Mahr, T., and Mirman, D. (2020). GazeR: a package for processing gaze position and pupil size data. *Behav. Res.* 52, 2232–2255. doi: 10.3758/s13428-020-01374-8

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Gullifer, J. W., and Titone, D. (2018). Compute language entropy with {languageEntropy}.

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/.neuropsychologia.2018.04.037

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Biling. Lang. Cogn.* 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., and Titone, D. (2021a). Bilingualism: a neurocognitive exercise in managing uncertainty. *Neurobiol. Lang.* 2, 464–486. doi: 10.1162/nol_a_00044

Gullifer, J. W., and Titone, D. (2021b). Engaging proactive control: influences of diverse language experiences using insights from machine learning. *J. Exp. Psychol. Gen.* 150, 414–430. doi: 10.1037/xge0000933

Hartanto, A., and Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages: a diffusion-model analysis of the effects of interactional context on switch costs. *Cognition* 150, 10–19. doi: 10.1016/j.cognition.2016.01.016

Hartanto, A., and Yang, H. (2020). The role of bilingual interactional contexts in predicting interindividual variability in executive functions: a latent variable analysis. *J. Exp. Psychol. Gen.* 149, 609–633. doi: 10.1037/xge0000672

Hultsch, D. F., MacDonald, S. W. S., and Dixon, R. A. (2002). Variability in reaction time performance of younger and older adults. *J. Gerontol. Ser. B* 57, P101–P115. doi: 10.1093/geronb/57.2.P101

Kałamała, P., Senderecka, M., and Wodniecka, Z. (2021). On the multidimensionality of bilingualism and the unique role of language use. *Biling. Lang. Cogn.* 1–13. doi: 10.1017/S1366728921001073

Kałamała, P., Szewczyk, J., Chuderski, A., Senderecka, M., and Wodniecka, Z. (2020). Patterns of bilingual language use and response inhibition: a test of the adaptive control hypothesis. *Cognition* 204:104373. doi: 10.1016/j.cognition.2020.104373

Kroll, J. F., Dussias, P. E., Bogulski, C. A., and Valdés Kroff, J. R. (2012). "Chapter seven – juggling two languages in one mind: what bilinguals tell us about language processing and its consequences for cognition," in *Psychology of Learning and Motivation*. ed. B. H. Ross (Cambridge, MA: Academic Press), 229–262.

Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2017). lmerTest package: tests in linear mixed effects models. *J. Stat. Softw.* 82, 1–26. doi: 10.18637/jss.v082.i13

Lai, G., and O'Brien, B. A. (2020). Examining language switching and cognitive control Through the adaptive control hypothesis. *Front. Psychol.* 11:1171. doi: 10.3389/fpsyg.2020.01171

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* 144, 394–425. doi: 10.1037/bul0000142

Li, X., Ng, K. K., Wong, J. J. Y., Lee, J. W., Zhou, J. H., and Yow, W. Q. (2021). Bilingual language entropy influences executive functions through functional connectivity and signal variability. *Brain Lang.* 222:105026. doi: 10.1016/j.bandl.2021.105026

Lo, S., and Andrews, S. (2015). To transform or not to transform: using generalized linear mixed models to analyse reaction time data. *Front. Psychol.* 6:1171. doi: 10.3389/fpsyg.2015.01171

Luce, R. D. (1991). *Response Times: Their Role in Inferring Elementary Mental Organization*. New York: Oxford University Press.

Lüdecke, D. (2021). sjPlot: Data Visualization for Statistics in Social Science. Available at: https://CRAN.R-project.org/package=sjPlot (Accessed December 13, 2021).

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., and Makowski, D. (2021). Performance: an R package for assessment, comparison and testing of statistical models. *J. Open Source Softw.* 6:3139. doi: 10.21105/joss.03139

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: interaction between language proficiency and usage. *J. Cogn. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The language experience and proficiency questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Marí-Beffa, P., and Kirkham, A. (2014). "The mixing cost as a measure of cognitive control," in *Task Switching and Cognitive Control* eds. J. A. Grange and G. A. Houghton (New York: Oxford University Press). 74–100.

Mathôt, S. (2018). Pupillometry: psychology, physiology, and function. *J. Cogn.* 1, 16–23. doi: 10.5334/joc.18

Mathôt, S., Fabius, J., Van Heusden, E., and Van der Stigchel, S. (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behav. Res. Methods* 50, 94–106. doi: 10.3758/s13428-017-1007-2

Mathôt, S., Schreij, D., and Theeuwes, J. (2012). OpenSesame: an open-source, graphical experiment builder for the social sciences. *Behav. Res. Methods* 44, 314–324. doi: 10.3758/s13428-011-0168-7

Meeter, M., Bele, T., Hartogh, C.den, Bakker, T., Vries, R. E.de, and Plak, S. (2020). College students' motivation and study results after COVID-19 stay-at-home orders. PsyArXiv [preprint]. doi:10.31234/osf.Io/kn6v9

Meulman, N., Wieling, M., Sprenger, S. A., Stowe, L. A., and Schmid, M. S. (2015). Age effects in L2 grammar processing as revealed by ERPs and how (not) to study them. *PLoS One* 10:e0143328. doi: 10.1371/journal.pone.0143328

Monsell, S. (2003). Task switching. *Trends Cogn. Sci.* 7, 134–140. doi: 10.1016/S1364-6613(03)00028-7

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., and Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychol. Aging* 17, 299–320. doi: 10.1037/0882-7974.17.2.299

Poarch, G. J., and Krott, A. (2019). A bilingual advantage? An appeal for a change in perspective and recommendations for future research. *Behav. Sci.* 9. doi: 10.3390/bs9090095

Prior, A., and MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism* 13, 253–262. doi: 10.1017/S1366728909990526

R Core Team (2021). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/ (Accessed December 13, 2021).

Ramos, S., Fernández García, Y., Antón, E., Casaponsa, A., and Duñabeitia, J. A. (2017). Does learning a language in the elderly enhance switching ability? *J. Neurolinguistics* 43, 39–48. doi: 10.1016/j.jneuroling.2016.09.001

Rondeel, E. W. M., van Steenbergen, H., Holland, R. W., and van Knippenberg, A. (2015). A closer look at cognitive control: differences in resource allocation during updating, inhibition and switching as revealed by pupillometry. *Front. Hum. Neurosci.* 9:494. doi: 10.3389/fnhum.2015.00494

Schad, D. J., Vasishth, S., Hohenstein, S., and Kliegl, R. (2020). How to capitalize on a priori contrasts in linear (mixed) models: a tutorial. *J. Mem. Lang.* 110:104038. doi: 10.1016/j.jml.2019.104038

Schmeets, H., and Cornips, L. (2021). Talen en dialecten in Nederland. *Centraal Bureau voor de Statistiek*. Available at: https://www.cbs.nl/nl-nl/longread/statistische-trends/2021/talen-en-dialecten-in-nederland?onepage=true (Accessed January 21, 2022).

Shannon, C. E. (1948). A mathematical theory of communication. *Bell Syst. Tech. J.* 27, 379–423. doi: 10.1002/j.1538-7305.1948.tb01338.x

Sóskuthy, M. (2017). Generalised additive mixed models for dynamic analysis in linguistics: a practical introduction. ArXiv170305339 Stat. Available at: http://arxiv.org/abs/1703.05339 (Accessed October 1, 2021).

Surrain, S., and Luk, G. (2019). Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005-2015. *Bilingualism* 22, 401–415. doi: 10.1017/S1366728917000682

University of Groningen (2020). Key figures. University of Groningen. Available at: https://www.rug.nl/about-ug/profile/facts-and-figures/ (Accessed December 20, 2021).

van der Wel, P., and van Steenbergen, H. (2018). Pupil dilation as an index of effort in cognitive control tasks: a review. *Psychon. Bull. Rev.* 25, 2005–2015. doi: 10.3758/s13423-018-1432-y

van Rij, J., Hendriks, P., van Rijn, H., Baayen, R. H., and Wood, S. N. (2019). Analyzing the time course of Pupillometric data. *Trends Hear.* 23:233121651983248. doi: 10.1177/2331216519832483

van Rij, J., Wieling, M., Baayen, R. H., and Rijn, H.van (2020). Itsadug: Interpreting Time Series and Autocorrelated Data Using GAMMs.

Whelan, R. (2008). Effective analysis of reaction time data. *Psychol. Rec.* 58, 475–482. doi: 10.1007/BF03395630

Wickham, H., François, R., Henry, L., and Müller, K. (2018). Dplyr: a grammar of data manipulation. Available at: https://CRAN.R-project.org/package=dplyr (Accessed December 13, 2021).

Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *J. Phon.* 70, 86–116. doi: 10.1016/j.wocn.2018.03.002

Winn, M. B., Wendt, D., Koelewijn, T., and Kuchinsky, S. E. (2018). Best practices and advice for using pupillometry to measure listening effort: an introduction for those who want to get started. *Trends Hear.* 22:233121651880086. doi: 10.1177/2331216518800869

Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *J. R. Stat. Soc. Ser. B Stat Methodol.* 73, 3–36. doi: 10.1111/j.1467-9868.2010.00749.x

Wood, S. N. (2017). *Generalized Additive Models: An Introduction With R. 2nd Edn*. Boca Raton: CRC Press/Taylor & Francis Group.

Yang, H., Hartanto, A., and Yang, S. (2016). The complex nature of bilinguals' language usage modulates task-switching outcomes. *Front. Psychol.* 7:560. doi: 10.3389/fpsyg.2016.00560

Yow, W. Q., and Li, X. (2015). Balanced bilingualism and early age of second language acquisition as the underlying mechanisms of a bilingual executive control advantage: why variations in bilingual experiences matter. *Front. Psychol.* 6:164. doi: 10.3389/fpsyg.2015.00164

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Individual and Sociolinguistic Differences in Language Background Predict Stroop Performance

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To examine how differences in language experience and sociolinguistic context impact cognitive control, 146 Spanish-English bilingual participants were tested on a non-linguistic Stroop arrows task. Dimensions of language experience included a continuum of L2 proficiency, exposure, age of L2 acquisition, and English receptive vocabulary, along with cognitive non-verbal reasoning. Sociolinguistic context varied with more exposure to Spanish for participants in Southern California (SoCal) than in the Midwest. The task involved perceptual stimulus-stimulus conflict within stimulus features (e.g., right-pointing arrow on the left side of a display). Reaction times to trials where arrow location and direction matched (congruent), mismatched (incongruent), or arrow location was centered (neutral) were used to calculate Stroop (incongruent-congruent), facilitation (neutral-congruent), and inhibition (incongruent-neutral) effects. When examining performance on a continuum of bilingual language experience, individual differences in linguistic background (i.e., L2 proficiency and exposure, receptive vocabulary) and cognitive abilities (i.e., non-verbal reasoning abilities) predicted more efficient performance on the Stroop task. Across sociolinguistic contexts, findings revealed better performance via smaller Stroop and facilitation effects in the Midwest than in SoCal, and no group difference on the inhibition effect. We conclude that research on the cognitive consequences of bilingualism must consider a continuum of language experiences and must be situated in broader naturalistic contexts that take into account the sociolinguistic environments of language use.

Keywords: bilingualism, proficiency, age of acquisition, dominance, Stroop, cognitive control, inhibition, facilitation

INTRODUCTION

Bilingual language experience may impact cognitive control (e.g., Luk et al., 2011; Lehtonen et al., 2018; Van den Noort et al., 2019; but see Paap et al., 2019; Beatty-Martínez et al., 2020). The debate on the cognitive consequences of bilingualism has been complicated by difficulties conceptualizing bilingualism due to variability in language background factors such as proficiency, exposure, sociolinguistic context of language use, and age of acquisition. One valuable approach to conceptualizing bilingualism has been a shift to assessing bilingualism on a continuum of these variables, instead of the bilingual-monolingual categorical distinctions (e.g., Luk and Bialystok, 2013; Kaushanskaya and Prior, 2015; Poarch and Krott, 2019; Kroll et al., 2021). The purpose of the current study was to examine whether individual differences and sociolinguistic context mediated cognitive control performance in individuals who varied in bilingual experience.

Cognitive control is the ability to regulate, plan, and execute goal-oriented behaviors (Braver, 2012) and involves the interplay between multiple executive functions (i.e., attention, cognitive flexibility, inhibitory control, working memory). Cognitive control is an important aspect of bilingual language processing (e.g., Green and Abutalebi, 2013), given that bilinguals navigate and manage two language systems that are active in parallel (e.g., Marian and Spivey, 2003; Starreveld et al., 2014). In fact, cognitive control correlates with bilinguals' language use in the presence of conflicting crosslinguistic responses (e.g., Blumenfeld and Marian, 2013; Giezen et al., 2015; Singh and Mishra, 2016; Freeman et al., 2017) and is engaged during L2 processing (e.g., Darcy et al., 2015; Grant et al., 2015). Thus, bilingual experiences and contexts may promote cognitive control abilities due to the constant practice of monitoring and inhibiting language.

Van den Noort et al. (2019) cite 46 studies in the past 20 years that investigated bilingual vs. monolingual performance on tasks measuring cognitive control. The results demonstrate a bilingual advantage in 54% of studies, with 17% of studies revealing null effects. To account for differences in findings, research is beginning to examine how variability in bilingual experiences shapes cognitive control (e.g., Beatty-Martínez et al., 2020; Bonfieni et al., 2020). To accomplish this goal, multiple dimensions of bilingualism should be considered while targeting theoretically motivated aspects of cognitive control (e.g., Bonfieni et al., 2020). To examine contributions of proficiency, exposure, and age of acquisition to cognitive performance, variability along these dimensions can be leveraged within and across groups.

In the current study, we focused on how individual differences in language experience, proficiency, and cognition shaped cognitive control abilities in individuals with bilingual experience across sociolinguistic contexts. Specifically, we tested participants in the Midwest and in Southern California (SoCal) areas of the United States, thus varying the constellations of individual differences that contribute to each sociolinguistic context. Individual differences measures included linguistic variables, such as self-reported L2 proficiency and exposure, age of L2 acquisition, and receptive vocabulary, along with a cognitive measure of non-verbal intelligence, the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). We used a non-linguistic Stroop arrows task that may be particularly sensitive to bilingual experience (Blumenfeld and Marian, 2014; Xia et al., 2021; but see Lehtonen et al., 2018; Paap et al., 2019).

The non-linguistic Stroop arrows task has been implemented across a number of studies to examine cognitive control abilities in bilinguals (e.g., Bialystok et al., 2008; Martin-Rhee and Bialystok, 2008; Bialystok and DePape, 2009; Blumenfeld and Marian, 2011, 2014; Giezen et al., 2015; Freeman et al., 2017). Participants identify arrow direction (left or right) when it appears on the left or right side on the visual display. Perceptual conflict results when the arrow direction and location do not correspond, such that a right-pointing arrow appears on the left side, or a left-pointing arrow appears on the right side of the visual display. Participants must resolve this perceptual conflict arising between the two dimensions of the stimulus on the display (location vs. direction of arrows) in order to respond appropriately. This type of conflict resolution has been termed stimulus-stimulus conflict, as the locus of the interference is within the stimulus (Kornblum et al., 1999). In addition, conflict occurs between stimulus dimensions and participant responses on Stroop-type tasks. For example, when a left-pointing arrow appears on the right side of a display, participants may initially be tempted to make a left-hand response, a response that must be inhibited together with the location dimension of the stimulus. Thus, Stroop tasks combine stimulus-stimulus and stimulus-response conflict (Kornblum et al., 1999).

Informed by the Dimensional Overlap Model (Kornblum et al., 1999), conflict between related stimulus dimensions (i.e., stimulus-stimulus: arrow direction left or right and arrow location left or right) is resolved at the same perceptual level as the related color-word Stroop task; in contrast, the traditional Simon task (Simon and Rudell, 1967) creates a conflict between a stimulus dimension and an unrelated manual response (i.e., stimulus-response: arrow direction up or down and button press left or right). Bilinguals have been shown to make more efficient responses on the Stroop than the Simon task, while monolinguals perform the same across the two tasks (Blumenfeld and Marian, 2014; Xia et al., 2021). Stroop arrows performance has also been found to correlate with bilingual language processing across a number of studies (Blumenfeld and Marian, 2011, 2013; Mercier et al., 2014; Giezen et al., 2015; Freeman et al., 2017). Specifically, the Stroop task with stimulus-stimulus conflict (e.g., inhibiting arrow location to identify arrow direction) may be more reflective of bilingual language experience (e.g., inhibiting one language while using the other).

Three related but separable Stroop processing effects were examined in the current study. The Stroop effect (i.e., inhibition and facilitation effects in combination, captured by incongruent minus congruent trials) has been found to correlate with speech and language processing in bilinguals (e.g., Blumenfeld and Marian, 2013; Giezen et al., 2015; Freeman et al., 2017). We maintain this overall effect in the current analyses, acknowledging that it may capture broader aspects of bilingual processing than its two subcomponents. Further, the Stroop facilitation effect was derived from response times on neutral minus congruent trials. This effect captures to what extent converging stimulus dimensions on congruent trials would facilitate responses relative to neutral trials. Here, neutral trials serve as a baseline where one of the stimulus dimensions is neutral (arrow location), meaning it never diverges from or converges with the other dimension (arrow direction). Finally, the Stroop inhibition effect was derived from responses on neutral minus incongruent trials. This effect captures to what extent conflicting stimulus dimensions on incongruent trials (arrow direction, arrow location) would trigger interference and the need to inhibit the arrow location dimension to respond correctly.

While some theoretical frameworks assign a shared mechanism to Stroop facilitation and inhibition and predict that the two effects track together (e.g., Botvinick et al., 2001), the two effects have been shown to be separable in studies where their timecourse was examined (e.g., Coderre et al., 2013; Parris, 2014). Critically, on a non-verbal Stroop arrows task, Hernández et al. (2010) found that Catalan-Spanish bilinguals showed larger Stroop facilitation but smaller Stroop inhibition effects relative to Spanish monolinguals. The authors took these findings as evidence that potential cognitive consequences of bilingualism may extend beyond inhibitory control to monitoring and making use of facilitatory information (also see Roelofs et al., 2006). In the current study, we examined performance on the Stroop arrows task across individuals with bilingual experience across two sociolinguistic contexts (Midwest and SoCal) to further specify how individual differences related to linguistic (i.e., proficiency, exposure, and age of L2 acquisition) and cognitive (non-verbal intelligence) factors shaped cognitive control abilities.

Linguistic Background and Cognitive Control

Various dimensions of bilingualism have been observed to meaningfully characterize bilingual experience as it relates to cognitive control. First, *language proficiency* has been shown to mediate cognitive control abilities in adults. For example, Luque and Morgan-Short (2021) linked L2 proficiency with cognitive control performance for reactive inhibition and speed of processing on a letter-automatic continuous performance (AX-CPT) task, with higher L2 proficiency related to better inhibitory control. However, there was no relation between L2 proficiency and performance on an Eriksen flanker arrows task. In contrast, Xie (2018) found a relation between L2 proficiency and conflict monitoring on a flanker arrows task. Participants with higher L2 proficiency demonstrated faster reaction times than participants with lower L2 proficiency (for similar findings on language dominance metrics, see Goral et al., 2015; Robinson Anthony and Blumenfeld, 2019; but see Paap et al., 2019 for null findings). Based on these differences in findings examining the influence of L2 proficiency on cognitive control abilities, more research is necessary to characterize how L2 proficiency, along with other individual differences in participants' language background and experience, shape cognitive control abilities.

One such additional individual differences variable that has been shown to influence cognitive control is L2 *age of acquisition* (AoA). Tao et al. (2011) found that Chinese-English bilingual adults outperformed their monolingual counterparts on a Simon-like (vertical arrows with a cueing component) task. Bilinguals with a late L2 AoA demonstrated greater conflict resolution skills, while early L2 AoA bilinguals demonstrated greater monitoring skills indexed by faster response times. Moreover, Luk et al. (2011) found that early bilinguals outperformed both later bilinguals and monolinguals on a flanker arrows task. It was anticipated in these studies that bilinguals would demonstrate better cognitive control; however, results suggested that a gradient of age of active bilingualism (derived from L2 AoA and age at testing) was a better predictor of cognitive control performance. Sabourin and Vinerte (2019) relatedly found that simultaneous French-English bilingual adults, but not early or late sequential bilingual adults, outperformed their monolingual peers on an arrow congruency task. Taken together, findings suggest that the timing and/or length of bilingual experiences (e.g., L2 AoA), as well as L2 proficiency, should be examined as predictors of cognitive control. The current investigation builds on previous findings to identify how *multiple* dimensions of bilingualism map onto specific aspects of cognitive control, while varying sociolinguistic contexts.

Sociolinguistic Context and Cognitive Control

The adaptive control hypothesis posits that bilinguals respond adaptively to the demands on language use within their sociolinguistic environments (Green and Abutalebi, 2013). Indeed, a number of studies suggest that cognitive control is shaped by bilinguals' contexts, such as whether they are exposed to primarily single language use vs. dual language use environments (Green and Wei, 2014; Green, 2018; Beatty-Martínez et al., 2020; Beatty-Martínez and Titone, 2021; Khodos and Moskovsky, 2021; Zhang et al., 2021). Here, we consider sociolinguistic context as a constellation of variables that constitute bilingual experience, such as L2 proficiency, exposure, and age of L2 acquisition. For example, in Beatty-Martínez et al. (2020) and Khodos and Moskovsky (2021), participants from different sociolinguistic contexts were distinguished from each other by their age of L2 acquisition and language exposure patterns.

Participants in Blumenfeld and Marian (2014) were tested on the non-linguistic Stroop arrows task and Simon task in the Midwest and SoCal sociolinguistic contexts. SoCal participants were in a sociolinguistic context where both languages were more regularly used, and they had learned Spanish earlier and reported higher Spanish proficiency than Midwest participants. SoCal residents live near the US-Mexican border, where many bilinguals are part of a binational bicultural context that frequently includes use of both languages (e.g., Cole, 2011). More balanced use of English and Spanish may have allowed SoCal participants to keep their two languages active simultaneously, while participants in the Midwest were exposed to Spanish less frequently. The observed distinction between the Midwest and SoCal contexts is also reflected in census data from the two communities. The SoCal area has a larger proportion of speakers of a language other than English (37.3%) and Spanish (21.4%), relative to the Midwest (language other than English: 17.2%; Spanish: 6.2%; census data extracted from mla.org language map). Sociolinguistic differences between the Midwest and SoCal participants in Blumenfeld and Marian likely contributed to the Midwest participants demonstrating better performance on the Stroop task relative to the Simon task, compared to smaller differences between Stroop and Simon performance in SoCal participants. SoCal participants were living in a context with a higher proportion of Spanish speakers who may have kept both languages available and relied less on stimulus-stimulus inhibition indexed by the Stroop task (i.e., non-target language inhibition). In the current study, we further examined the possibility that individual differences across dimensions of linguistic experience predicted inhibitory control performance within and across the same sociolinguistic contexts (the Midwest and SoCal).

The Present Study

In the current investigation, we aimed to identify the individual differences in participants' linguistic and cognitive backgrounds across sociolinguistic contexts (Midwest and SoCal) that led to more efficient performance on the non-linguistic Stroop arrows task (e.g., Blumenfeld and Marian, 2011, 2014; Giezen et al., 2015; Freeman et al., 2017). Individual differences information in participants' language background and experience was obtained from the *Language Experience and Proficiency Questionnaire* (LEAP-Q, Marian et al., 2007), including linguistic factors of L2 proficiency and exposure and age of L2 acquisition (L2 AoA). For a more nuanced understanding, we considered participants on a bilingual continuum of L2 proficiency and exposure, as well as L2 AoA. We also administered the Peabody Picture Vocabulary Test-3 (Dunn and Dunn, 1997) to index receptive vocabulary in English (the L2 for all of our participants).

Beyond aspects of bilinguals' linguistic environments, a cognitive measure of non-verbal intelligence was considered, the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), since it has been shown to potentially contribute to performance in cognitive control. Evidence for a relation between non-verbal intelligence and interference resolution indexed by Stroop-like tasks has been mixed, with significant correlations identified in Chen et al. (2019) and Paap et al. (2020), but not in Mercier et al. (2014) or Paap et al. (2018). Non-verbal intelligence may therefore have the potential to contribute to variability whenever the influence of bilingual experience on cognitive control is examined. Non-verbal intelligence was included to better understand how it contributed to Stroop performance. Based on previous findings, we formulated the following predictions concerning Stroop performance and individual differences related to Stroop effects:

First, based on previous research using the Stroop arrows task (e.g., Bialystok et al., 2008; Martin-Rhee and Bialystok, 2008; Bialystok and DePape, 2009; Blumenfeld and Marian, 2011, 2014; Giezen et al., 2015; Freeman et al., 2017; Lehtonen et al., 2018; Xia et al., 2021), it was predicted that (a) all participants would show robust *Stroop effects* (i.e., be faster to respond to congruent than incongruent trials), *inhibition effects* (i.e., be faster to respond to neutral than incongruent trials), and *facilitation effects* (i.e., be faster to respond to congruent than neutral trials); and (b) when the dichotomous sociolinguistic context contrast was considered, no or small group differences would emerge across trial types (congruent, incongruent, and neutral).

Second, based on previous literature examining dimensions of bilingualism (e.g., Luk et al., 2011; Tao et al., 2011; Goral et al., 2015; Robinson Anthony and Blumenfeld, 2019; Luque and Morgan-Short, 2021) and cognitive abilities (e.g., Chen et al., 2019; Paap et al., 2020), we predicted that, *continuous* variables of L2 proficiency, exposure, acquisition age, receptive vocabulary, and non-verbal reasoning would shape performance on the non-linguistic Stroop arrows task. Specifically, we expected that (a) participants with greater self-reported L2 proficiency and exposure (composite variable), an earlier L2 AoA, and higher L2 proficiency (indexed by higher PPVT receptive vocabulary standard score) would demonstrate smaller Stroop, facilitation, and inhibition effects (e.g., Goral et al., 2015; Xie, 2018; Robinson Anthony and Blumenfeld, 2019; Luque and Morgan-Short, 2021).We also predicted that (b) participants with higher non-verbal reasoning abilities would demonstrate smaller Stroop, facilitation, and inhibition effects (e.g., Chen et al., 2019; Paap et al., 2020).

Third, based on previous findings that participants in SoCal are more proficient in and more frequently exposed to both languages than the Midwest participants (Blumenfeld and Marian, 2014), we predicted that differences across the two sociolinguistic contexts (Midwest and SoCal) in L2 proficiency and exposure and L2 acquisition would be linked to variation in performance on the Stroop task. Participants living in a sociolinguistic context in which both languages are regularly used, such as near the US-Mexican border in SoCal, may be less likely to rely on stimulus-stimulus inhibition on the Stroop task. Therefore, we expected that more efficient cognitive control would emerge in Midwest participants, where the two languages are relatively more separated, and that performance would be tied to bilingual experience.

MATERIALS AND METHODS

Participants

Participants included 146 Spanish-English heritage bilinguals. These participants were included from a larger sample of 235 bilinguals based on availability of self-reported language experience and proficiency variables in their L1 and L2 on the *Language Experience and Proficiency Questionnaire* (LEAP-Q) (Marian et al., 2007). Of the bilinguals, 64 were tested in the Midwest and 82 were tested in SoCal. All participants were native Spanish speakers who acquired English around the age of 5. Participants completed the LEAP-Q to capture self-reported L1 and L2 proficiency, current language exposure, and age of acquisition (AoA). Participants also performed the Peabody Picture Vocabulary Test-Third Edition (PPVT; Dunn and Dunn, 1997) to examine English receptive vocabulary skills, as well as the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) to index non-verbal cognitive reasoning across participant sociolinguistic contexts and language groups, as well as. See **Table 1** for linguistic and cognitive characteristics of the participant sample, de-aggregated by sociolinguistic context (Midwest and SoCal).

Materials

Non-linguistic Stroop Arrows Task

The non-linguistic Stroop task (e.g., Bialystok et al., 2008; Martin-Rhee and Bialystok, 2008; Bialystok and DePape, 2009; Blumenfeld and Marian, 2011, 2014; Giezen et al., 2015;

TABLE 1 | Participants' language and cognitive background information.

	Midwest bilinguals mean (SD) $n = 64$	SoCal bilinguals mean (SD) $n = 82$	*P*-value
Age	23.27 (4.83)	22.72 (3.84)	0.12
Age of L2 (English) acquisition	5.95 (2.58)	5.12 (2.71)	0.06
Years of active bilingualism (age at testing-age of reported L2 fluency)	12.98 (4.88)	14.33 (5.33)	0.12
Current exposure to L2	64.94% (18.33)	55.11% (18.36)	0.001
Self-reported L1 proficiency (1–10 scale)	9.01 (1.01)	8.59 (1.24)	0.07
Self-reported L2 proficiency (1–10 scale)	9.12 (1.00)	9.13 (1.08)	0.96
L2 proficiency/exposure composite (z-score)	1.84 (1.54)	1.21 (1.38)	0.01
English receptive vocabulary (PPVT) standard score	109.13 (12.34)	100.50 (11.95)	<0.001
WASI matrix reasoning	28.33 (3.67)	26.54 (3.47)	0.01

Freeman et al., 2017) measured cognitive control abilities through the Stroop, facilitation, and inhibition effects. Congruent trials included arrows in which the location and direction corresponded. Incongruent trials contained arrows in which the location and direction did not correspond. Neutral trials comprised of arrows in the center of the visual display, pointing left or right (see **Figure 1** for example congruent, incongruent, and neutral trials). The Stroop effect is defined as difference scores between incongruent and congruent trials, capturing the overall facilitation/inhibition effect. A smaller Stroop effect reflects participants' ability to ignore irrelevant stimulus dimensions, thus incurring neither inhibition nor facilitation effects during the task. The facilitation effect is defined as difference scores between neutral and congruent trials, capturing participants' ability to derive facilitative benefit from congruent stimulus dimensions. The inhibition effect is defined as difference scores between incongruent and neutral trials, capturing participants' ability to resolve interference between incongruent stimulus dimensions.

In this retrospective study of the non-linguistic Stroop arrows task, three stimulus presentation platforms were employed in our labs at the time of testing across the Midwest and SoCal, including Matlab PsychToolbox (Brainard, 1997) ($n = 64$), ExperimentBuilder (SR Research Experiment Builder, 2011) ($n = 60$), and SuperLab (Cedrus Corporation, 2007) ($n = 22$). These stimulus presentation software packages are well-recognized platforms with excellent temporal resolution for chronometric data collection. The change of platform does not appear to have impacted the results; rather, the consistency across the platforms demonstrated the generalizability of the observed effects. The task consisted of 220 trials, including 20 practice trials (12 congruent, 4 incongruent, and 4 neutral). Black arrows were presented on a visual display pointing to the left, right, or center. The experimental trials contained 120 congruent, 40 incongruent, and 40 neutral trials. The congruent trials contained 60 trials with a leftward-facing arrow on the left side of the visual display and 60 with a right-ward facing arrow on the right side of the visual display. The incongruent trials contained 20 trials with a leftward-facing arrow on the right side of the visual display and 20 trials with a right-facing arrow on the left side of the visual display. The neutral trials contained 20 trials with a leftward-facing arrow in the center of the visual display and 20 trials with a rightward-facing arrow in the center of the visual display. The ratio of incongruent to congruent trials as well as neutral to congruent trials was 1:3.

Procedure

All data were collected in a quiet room during in-person participation sessions in laboratory settings. Participants completed the non-linguistic Stroop arrows task (e.g., Blumenfeld and Marian, 2014; Giezen et al., 2015; Freeman et al., 2017), the Language Experience and Proficiency Questionnaire (LEAP-Q, Marian et al., 2007), the Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999), and the Peabody Picture Vocabulary Test-Third Edition (PPVT, Dunn and Dunn, 1997).

On the non-linguistic Stroop arrows task, participants were instructed to ignore the location of the arrow on the visual display and respond on the keyboard using the left "Shift" key or right "Shift" key to indicate the direction of the arrow (left or right) as quickly and accurately as possible. For Matlab and Superlab versions of the script ($n = 86$), each trial began with a central fixation cross for 500 ms, followed by the stimulus display for 700 ms, and a blank screen for 800 ms. For the Experiment Builder script ($n = 60$), the blank screen was presented for 500 ms, followed by a 1,200 ms window where the stimulus was visible and responses could be made. As responses on the arrows Stroop task are typically made within the first 500 ms of stimulus presentation (e.g., Blumenfeld and Marian, 2014), and since response windows across the scripts were highly comparable at 1,500 and 1,200 ms, respectively, task version was not expected to influence performance. Trials were presented in a fixed pseudo-randomized order. Reaction times were measured from the onset of the stimulus display (arrow).

Coding and Analysis

Reaction times and accuracy to congruent, incongruent, and neutral trials were analyzed. Reaction times below 200 ms and reaction times below or above 2.5 standard deviations from the mean were discarded. In addition, incorrect responses were not included within the reaction time analyses. Given that multiple sociolinguistic contexts were involved, and given our primary interest in examining Stroop, facilitation, and inhibition effects, we chose to adjust (i.e., standardize) reaction times to factor out any differences across participants in overall processing speed. Reaction times were first log-transformed (Baayen and Milin, 2010) and then standardized with sociolinguistic context (Midwest and SoCal) as a fixed factor. To standardize reaction times, we divided participants' reaction times for each trial by

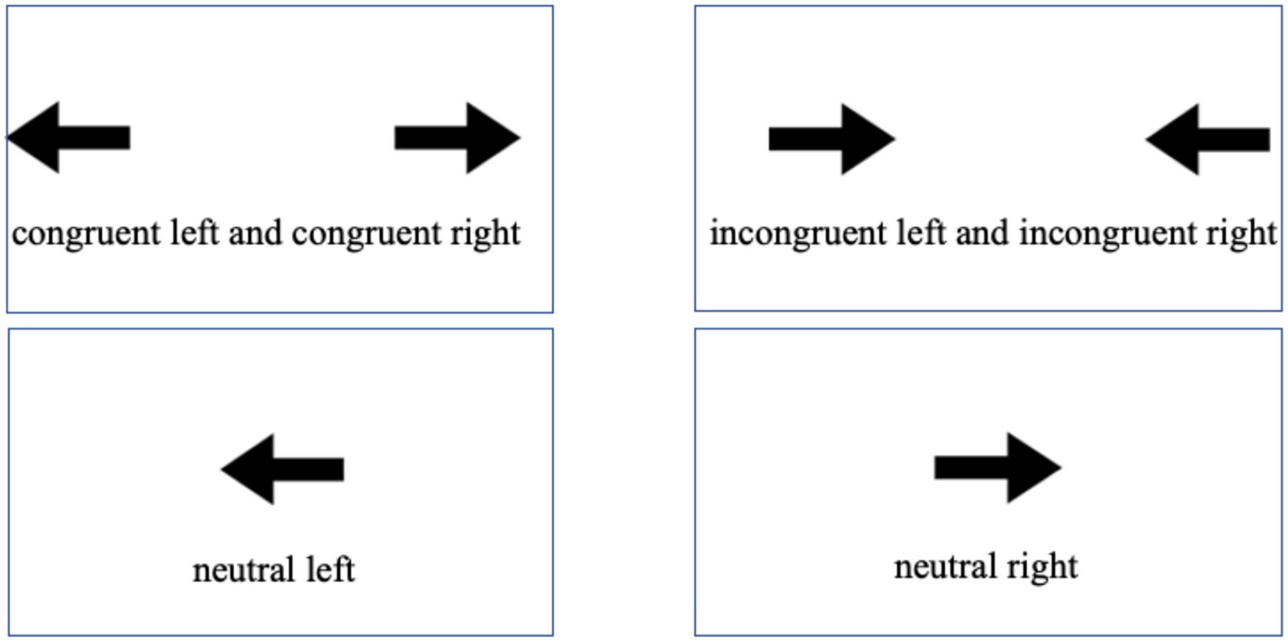

FIGURE 1 | Congruent, incongruent, and neutral stimuli on the non-linguistic Stroop arrows task.

their overall reaction time within that condition (congruent, incongruent, or neutral). To compare participants' performance across congruent, incongruent, and neutral trials, linear mixed effects regression models were employed using the lme4 package in R (Bates et al., 2011). Error terms, random intercepts, and slopes included trial type and subjects.

We computed Stroop, facilitation, and inhibition effects based on log-transformed and standardized reaction times to congruent, incongruent, and neutral trials. Next, we conducted linear regression analyses to examine the influence of individual differences measures on Stroop, facilitation, and inhibition effects. Within our sample of 146 bilinguals, individual difference measures of interest included (1) sociolinguistic context (Midwest and SoCal), (2) self-reported L2 proficiency and exposure (a composite variable including L2 understanding, listening, and reading proficiency and current L2 exposure from the LEAP-Q), (3) age of L2 acquisition (AoA), (4) objective L2 proficiency, indexed by performance on the PPVT, and (5) WASI scores. Proficiency and exposure were combined given their robust correlation in the current sample ($r^2 = 0.80$) as well as in previous research (Marian et al., 2007).

Forward stepwise linear regressions (Gareth et al., 2013) in R (R Core Team, 2020) were used to identify potential predictors of the Stroop, facilitation, and inhibition effects (individually) with the following candidate individual difference variables: L2 proficiency/exposure, L2 AoA, PPVT, and WASI. At each step, variables were chosen according to their contribution to the models' R^2 values. The stopping rule that limited the size of the final model was based off the lowest RMSE and MAE values, which are the prediction errors of each model. The lower the RMSE and MAE values, the better the model. For each effect, the best model contained one variable. Therefore, we examined the effect of the individual difference variables individually across Stroop, facilitation, and inhibition effects.

RESULTS

Overall reaction times to congruent, incongruent, and neutral trials, as well as Stroop, facilitation, and inhibition effects, were reported in initial models with a categorical variable of context (Midwest and SoCal). This was followed by analyses to examine the modulating role of linguistic dimensions of bilingualism and cognitive individual differences measures on Stroop performance and to elucidate the source of sociolinguistic context (Midwest and SoCal) effects. The continuous individual differences measures included L2 proficiency/exposure, L2 AoA, L2 English receptive vocabulary (PPVT), and non-verbal reasoning (WASI). Raw accuracy rates to congruent, incongruent, and neutral trials were also reported.

Overall Reaction Times in the Non-linguistic Stroop Arrows Task

A linear mixed effects regression model was used to analyze log-transformed standardized reaction times (RTs) to congruent, incongruent, and neutral trials with sociolinguistic context (Midwest and SoCal) as a fixed factor. Error terms, random intercepts, and slopes included trial type and subjects, see **Table 2** for model statistics. Overall, RTs differed as expected across congruent, incongruent, and neutral trial conditions. Participants were fastest on congruent trials (log-transformed and standardized, $M = 0.989$, $SE = 0.0002$), slowest on incongruent trials ($M = 1.017$, $SE = 0.0003$), and slower on

TABLE 2 | Linear mixed effects regression model for overall reaction times to congruent, incongruent, and neutral trials on the non-linguistic Stroop arrows task by sociolinguistic context.

Overall RT	B estimate	Std. error	Df	*t*-value	*p*-value
(Intercept) Congruent	0.9891	0.0004	202.10	2,751.961	<0.001
Incongruent	0.0280	0.0008	199.40	35.550	<0.001
Neutral	0.0084	0.0006	202.20	15.064	<0.001
Sociolinguistic context	−0.0009	0.0008	201.50	−1.209	0.023
Incongruent: sociolinguistic context	0.0048	0.0017	198.30	2.921	0.004
Neutral: sociolinguistic context	0.0061	0.0012	200.80	5.135	<0.001
Random effects estimates	**Name**	**Variance**	**Std. dev.**	**Correlation**	**Correlation**
Subject	(Intercept) Congruent	0.0000	0.004179		
	Incongruent	0.0001	0.009416	−0.89	
	Neutral	0.0000	0.005387	−0.96	0.81
Type	(Intercept)	0.0000	0		
Residual		0.0010	0.031164		

neutral ($M = 0.997$, $SE = 0.0003$) than congruent trials (all *p*s < 0.001, see **Table 2**).[1]

There were interactions between trial type and sociolinguistic context. Participants from SoCal ($M = 0.988$, $SE = 0.0003$) were marginally faster than participants from the Midwest ($M = 0.989$, $SE = 0.0002$) on congruent trials, B = −0.0008, SE = 0.0004, $t = -1.943$, $p = 0.052$. Yet for incongruent and neutral trials, participants from the Midwest were faster than participants from SoCal (incongruent trials: Midwest $M = 1.015$, $SE = 0.0006$; SoCal $M = 1.018$, $SE = 0.0003$; B = 0.0051, SE = 0.0007, $t = 5.833$, $p < 0.001$; neutral trials: Midwest $M = 0.994$, $SE = 0.0006$; SoCal $M = 0.999$, $SE = 0.0004$; B = 0.0040, SE = 0.0007, $t = 6.898$, $p < 0.001$).

Influence of Sociolinguistic Context on Stroop, Facilitation, and Inhibition Effects

For the **Stroop effect**, there was a main effect of sociolinguistic context, B = 0.0047, SE = 0.0020, $t = 2.325$, $p = 0.021$. Participants from the Midwest demonstrated a smaller Stroop effect than participants from SoCal (see **Figure 2**). For the **facilitation effect**, there was a main effect of sociolinguistic context, B = 0.0053, SE = 0.0014, $t = 3.746$, $p < 0.001$. Participants from the Midwest had a smaller facilitation effect than participants from SoCal. For the **inhibition effect**, there was no main effect of sociolinguistic context, B = −0.0005, SE = 0.0014, $t = -0.333$, $p = 0.739$.

To better understand how individual differences in language experience, proficiency, and cognition may have driven the observed sociolinguistic context differences, follow-up analyses on Stroop, facilitation, and inhibition effects included individual differences measures. See **Table 1** for means and group differences across individual differences measures. Individual differences measures were entered as independent variables, and Stroop, facilitation, and inhibition effects (derived from congruent, incongruent, and neutral trials) were entered as dependent measures. See **Table 4** for a summary of main effects and interactions for sociolinguistic context and individual differences.

Influence of Individual Differences on the Stroop Effect

Midwest bilinguals had higher L2 (English) proficiency and exposure than SoCal bilinguals (see **Table 1**). Accounting for L2 proficiency and exposure by entering the composite L2 proficiency/exposure variable into the **Stroop effect** model, a main effect of sociolinguistic context remained, B = 0.005, SE = 0.0021, $t = 2.168$, $p = 0.032$. Participants from the Midwest demonstrated a smaller Stroop effect than participants from SoCal, suggesting that the sociolinguistic context effect continued to be present when accounting for bilinguals' proficiency and exposure. Moreover, bilinguals in the current sample had similar L2 AoAs across sociolinguistic contexts. When L2 AoA as a continuous measure was entered into the sociolinguistic context model, the previously-reported main effect of sociolinguistic context remained, B = 0.0081, SE = 0.0031, $t = 2.601$, $p = 0.010$, also suggesting that the location-based difference in the Stroop effect model did not change when considering L2 AoA. When examining PPVT performance as an index of L2 proficiency within the sociolinguistic context model for the Stroop effect, similar to proficiency/exposure and AoA, the main effect of sociolinguistic context survived, B = 0.0048, SE = 0.0020, $t = 2.322$, $p = 0.022$, suggesting that sociolinguistic context continued to be a predictor of the Stroop effect. Finally, when WASI scores were entered into the model, the main effect of sociolinguistic context became marginal, B = 0.0038, SE = 0.0001, $t = 1.933$, $p = 0.055$. There was also a main effect of WASI score, B = −0.0020, SE = 0.0009, $t = -2.117$, $p = 0.031$, suggesting that as WASI scores increased, the Stroop effect decreased. This pattern was led by SoCal bilinguals, as demonstrated by the interaction between WASI score and sociolinguistic context, B = −0.0046, SE = 0.0019, $t = -2.412$, p

[1] When script type was entered into the model as a covariate (1,200 ms response window; 1,500 ms response window, see Procedure), no main effect of script type or interaction between script type and trial types emerged (all ps > 0.1), confirming that script type did not influence performance.

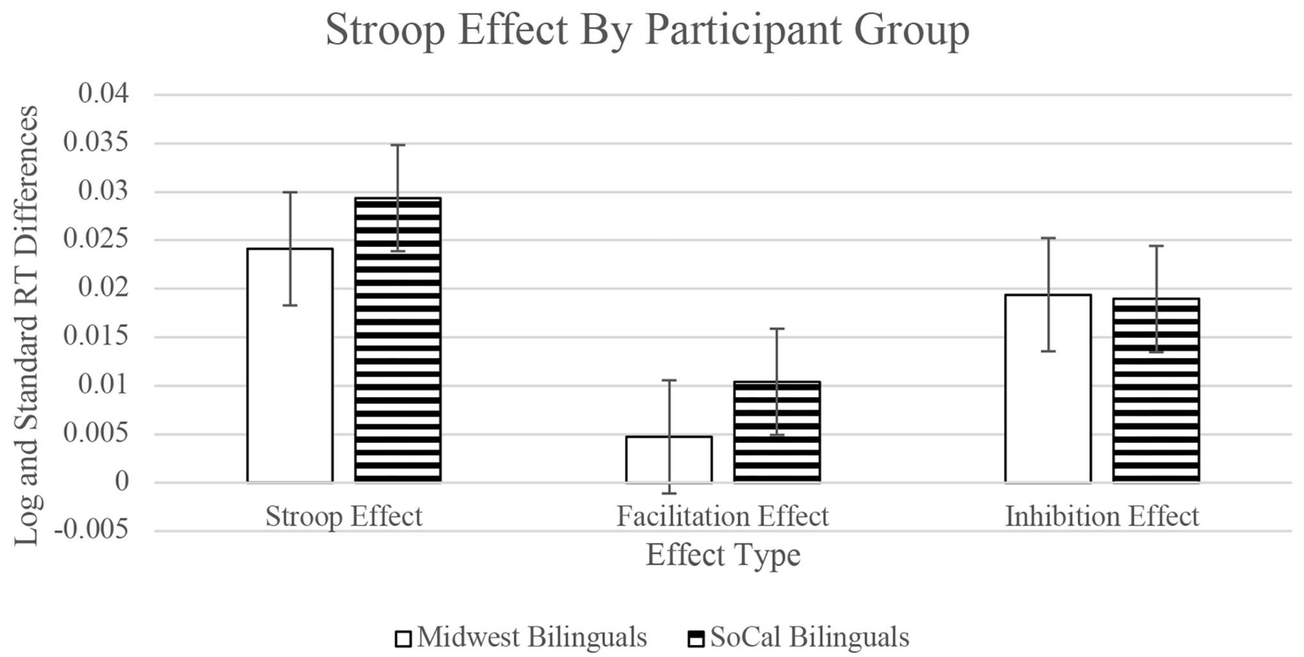

FIGURE 2 | Stroop, facilitation, and inhibition effects across sociolinguistic contexts (Midwest and SoCal). Error bars represent 1 standard error. RT = reaction times.

= 0.012. Therefore, higher non-verbal intelligence was associated with a smaller Stroop effect for SoCal bilinguals only, B = −0.0040, SE = 0.0013, $t = -3.076$, $p = 0.003$ (see **Figure 3**).

Influence of Individual Differences on the Facilitation Effect

When examining L2 proficiency/exposure within the **facilitation effect** model, the main effect of sociolinguistic context remained, B = 0.045, SE = 0.001, $t = 3.172$, $p = 0.002$, in addition to a main effect of L2 proficiency/exposure, B = −0.001, SE = 0.0006, $t = -2.590$, $p = 0.010$. Participants in the Midwest had a smaller facilitation effect than participants in SoCal. As L2 proficiency/exposure increased, the facilitation effect decreased. For L2 AoA, the main effect of sociolinguistic context also was maintained, B = 0.0058, SE = 0.0021, $t = 2.766$, $p = 0.006$, demonstrating that L2 AoA did not drive differences in sociolinguistic context. For PPVT scores, there were main effects of sociolinguistic context, B = 0.0046, SE = 0.0014, $t = 3.305$, $p = 0.001$, PPVT score, B = −0.001, SE = 0.0007, $t = -2.302$, $p = 0.023$, and a marginal interaction of sociolinguistic context and PPVT score, B = 0.0029, SE = 0.0015, $t = 1.949$, $p = 0.053$. Sociolinguistic context continued to be a predictor of the facilitation effect. As PPVT scores increased, the facilitation effect decreased, a pattern led by the Midwest bilinguals, B = 0.0054, SE = 0.0013, $t = 4.126$, $p < 0.001$. Therefore, as receptive L2 vocabulary increased, the facilitation effect became smaller for Midwest bilinguals only (see **Figure 4**). Finally, for WASI scores, there were main effects of sociolinguistic context, B = 0.0048, SE = 0.0014, $t = 3.402$, $p < 0.001$, and WASI score, B = −0.001, SE = 0.0007, $t = -2.060$, $p = 0.041$. Sociolinguistic context continued to be a predictor of the facilitation effect when accounting for non-verbal intelligence. In addition, as WASI score increased, the facilitation effect decreased, suggesting that higher levels of non-verbal intelligence resulted in a smaller facilitation effect.

Influence of Individual Differences on the Inhibition Effect

When examining L2 proficiency/exposure as a predictor of the **inhibition effect**, the main effect of sociolinguistic context was insignificant, B = −0.0000, SE = 0.0010, $t = -0.002$, $p = 0.998$, as was the location effect for L2 AoA, B = 0.0022, SE = 0.0022, $t = 0.838$, $p = 0.403$; PPVT score, B = 0.0001, SE = 0.0017, $t = 0.078$, $p = 0.9377$; and WASI, B = −0.0009, SE = 0.0017, $t = -0.558$, $p = 0.577$. However, there was a main effect of PPVT score, B = 0.0020, SE = 0.0086, $t = 2.405$, $p = 0.017$, and an interaction of sociolinguistic context and PPVT score, B = −0.060, SE = 0.0017, $t = -3.356$, $p = 0.001$. As the PPVT score increased, the inhibition effect increased, a pattern led by the Midwest bilinguals B = 0.0054, SE = 0.0013, $t = 4.126$, $p < 0.001$. Therefore, for Midwest bilinguals, higher receptive vocabulary resulted in larger inhibition effects (see **Figure 5**). In addition, for WASI scores, an interaction emerged between WASI performance and sociolinguistic context, B = −0.0040, SE = 0.0016, $t = -2.419$, $p = 0.017$, suggesting that for SoCal bilinguals only, as WASI score increased, the inhibition effect decreased, B = −0.0024, SE = 0.0011, $t = -2.225$, $p = 0.029$. Thus, as non-verbal intelligence increased, the inhibition effect decreased for SoCal participants (see **Figure 6**).

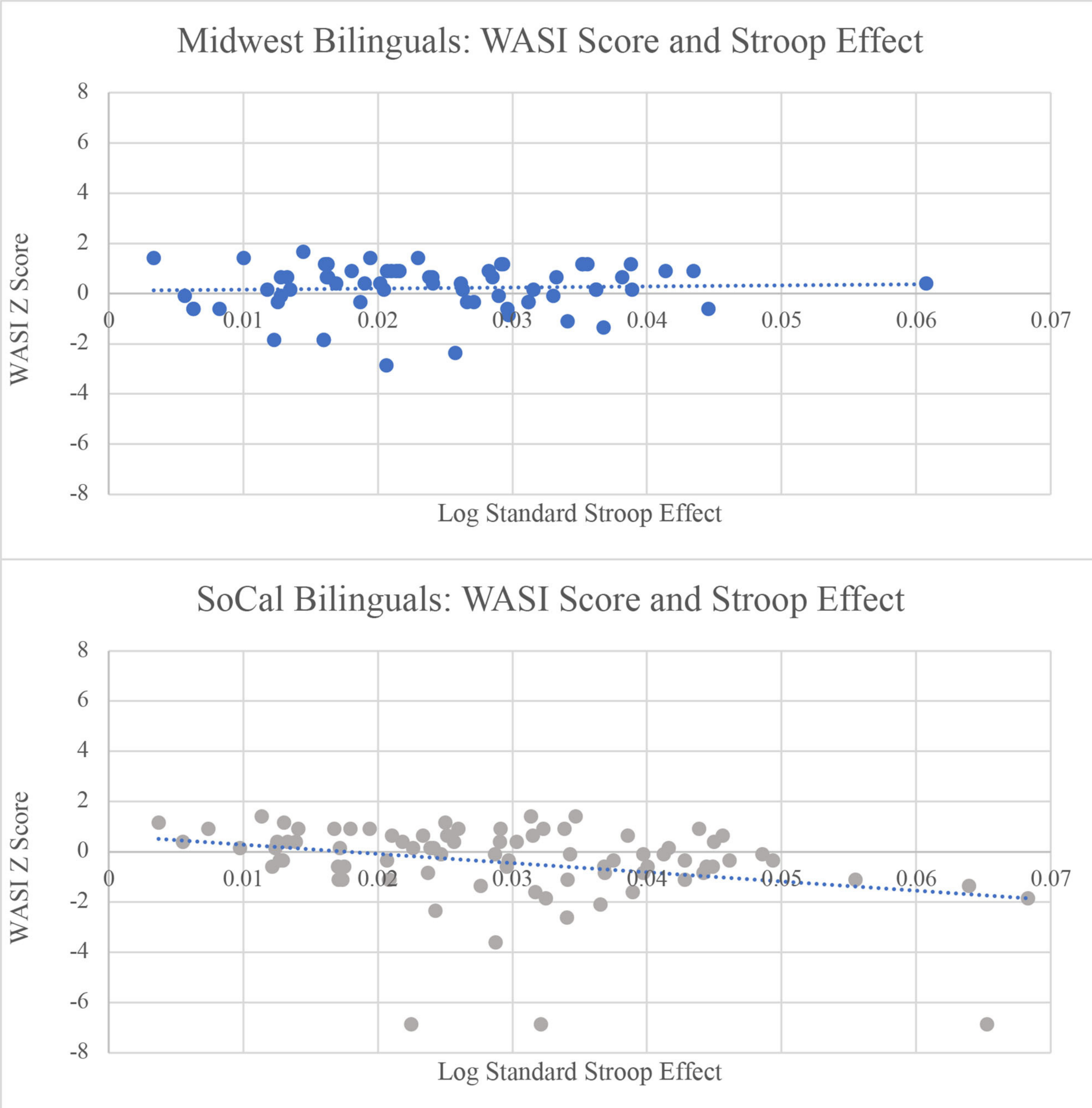

FIGURE 3 | As WASI score increased, the Stroop effect decreased for SoCal bilinguals. This relation was not significant for Midwest bilinguals. RT = reaction time; WASI = Wechsler Abbreviated Scale of Intelligence matrix reasoning score.

Overall Accuracy on the Non-linguistic Stroop Arrows Task

Finally, accuracy rates were analyzed across participants. A generalized linear mixed effects regression model was employed for log-transformed accuracy rates to congruent, incongruent, and neutral trials with the same fixed factors, error terms, random intercepts, and slopes as the reaction time model. The model failed to converge, and accuracy rates were overall high; we thus report means and standard errors across participant groups and conditions and limit analyses to reaction times (see **Table 3**).

DISCUSSION

In the current study, we examined performance on the non-linguistic Stroop arrows task across a sample of Spanish-English bilinguals on a continuum L2 (English) experience in the Midwest and in Southern California (SoCal). Participants in

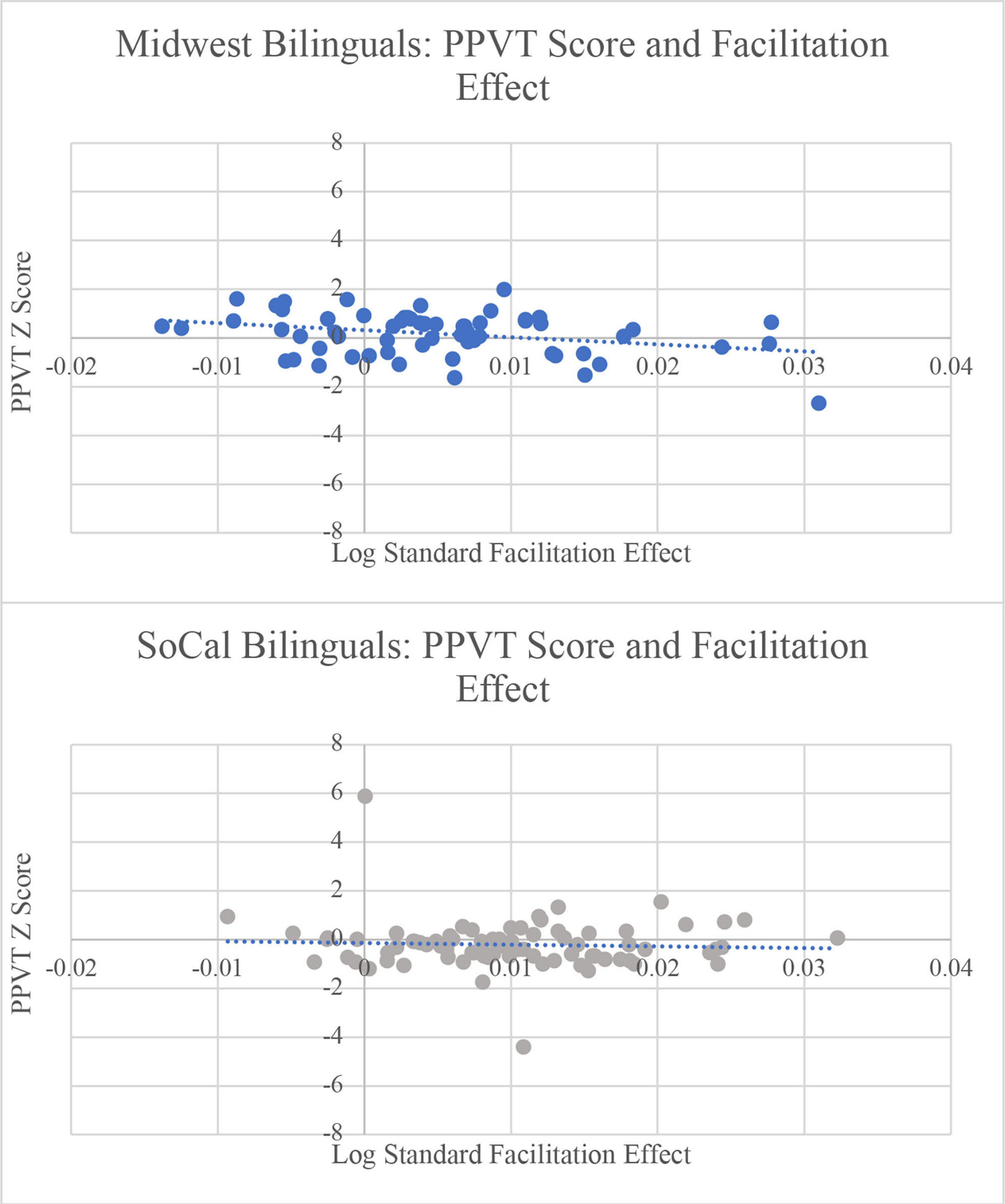

FIGURE 4 | As PPVT/English receptive vocabulary score increased, the facilitation effect decreased for Midwest bilinguals. The relation was not significant for SoCal bilinguals. RT = reaction times; PPVT = Peabody Picture Vocabulary Test.

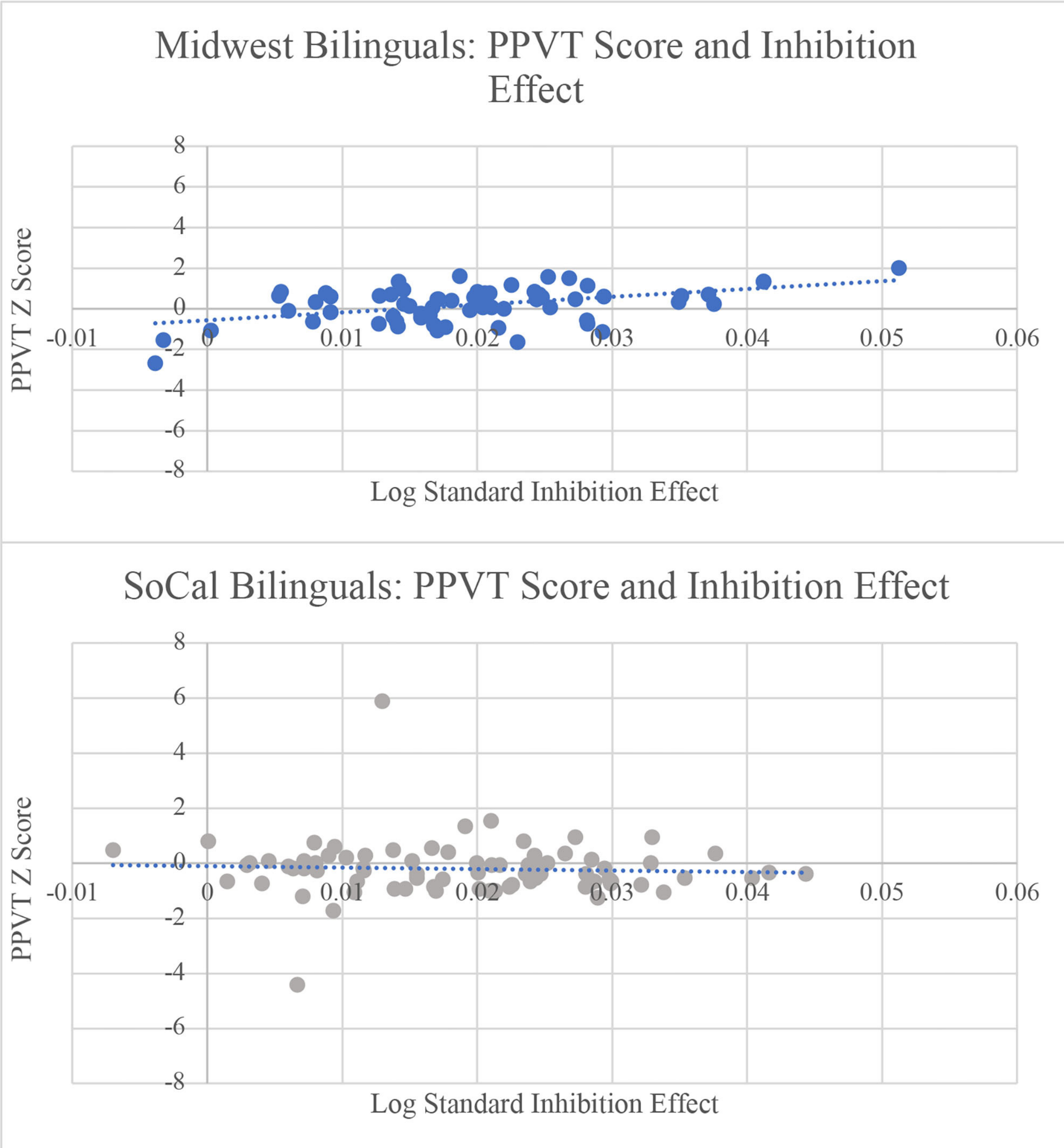

FIGURE 5 | As PPVT score increased, the inhibition effect increased for Midwest bilinguals. This relation was not significant for SoCal bilinguals. RT = reaction times; PPVT = Peabody Picture Vocabulary Test.

these two groups were all Spanish heritage speakers immersed in English but differed in that the Midwestern participants reported greater exposure to their L2 (English) and were objectively more proficient in it, as reflected by PPVT scores. While Midwest bilinguals demonstrated smaller Stroop and facilitation effects than SoCal bilinguals, there was no difference in the inhibition effect across sociolinguistic contexts. Further, dimensions of bilingual experience, including self-reported L2 proficiency and exposure, receptive vocabulary, but not L2 AoA mediated Stroop performance, in addition to cognitive non-verbal reasoning. These mediating factors explain differences in location. The current results align with previous findings that cognitive control

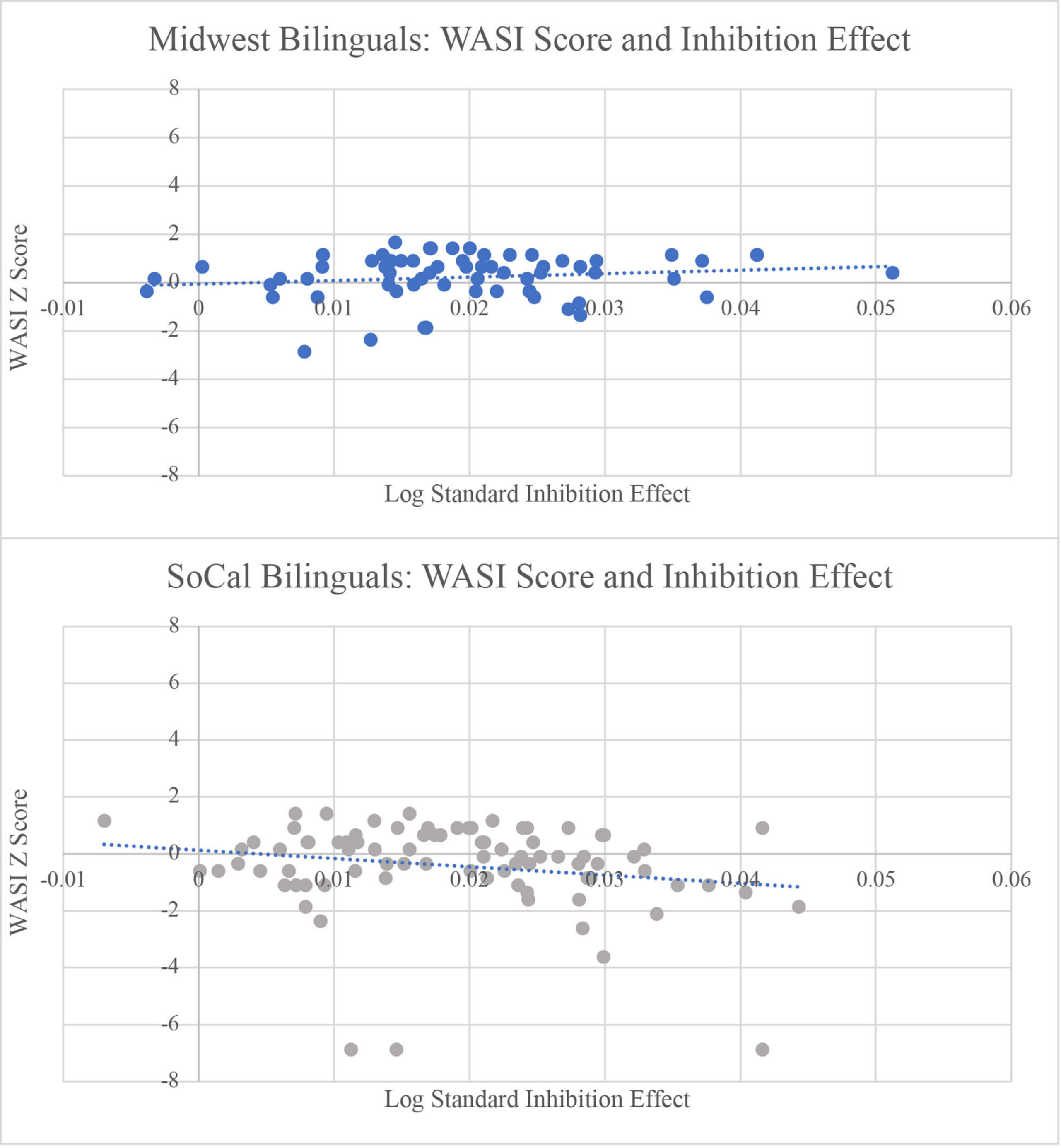

FIGURE 6 | As WASI score increased, the inhibition effect decreased for SoCal bilinguals. This relation was not significant for Midwest bilinguals. RT = reaction times; WASI = Wechsler Abbreviated Scale of Intelligence matrix reasoning score.

indexed by the Stroop task may be shaped by bilingual experience (Blumenfeld and Marian, 2014; Lehtonen et al., 2018; Xia et al., 2021, but see Paap et al., 2019) and cognitive factors (Chen et al., 2019; Paap et al., 2020).

The smaller Stroop effect in the Midwest participants was driven by a smaller facilitation effect compared to SoCal participants. This sociolinguistic context effect suggests that Midwest participants focused more exclusively on the relevant (arrow direction) instead of the irrelevant (arrow location) stimulus dimension that can facilitate or interfere with a correct response on the Stroop task. Further examining this overall effect, slightly faster responses on congruent trials and a

TABLE 3 | Overall accuracy on the non-linguistic Stroop arrows task by trial type (congruent, incongruent, and neutral).

Trial type	Midwest bilinguals mean% (SD)	SoCal bilinguals mean% (SD)
Congruent	99.30 (1.67)	98.88 (1.50)
Incongruent	92.14 (9.40)	91.17 (7.39)
Neutral	98.88 (3.14)	98.51 (2.68)
Overall accuracy	96.78 (4.20)	96.18 (3.09)

TABLE 4 | Summary of main effects of sociolinguistic context (A = Main effects of sociolinguistic context) and how they are modulated by individual differences measures (B = Individual differences across Spanish-English bilinguals).

	Stroop effect (incongruent–congruent)	Facilitation effect (neutral–congruent)	Inhibition effect (neutral-incongruent)
A			
Sociolinguistic context	**Midwest** < SoCal	**Midwest** < SoCal	Not significant
B			
Self-reported L2 proficiency and exposure	**Sociolinguistic context+**	**Sociolinguistic context+**↑Proficiency/Exposure, ↓Facilitation	
Age of L2 acquisition	**Sociolinguistic context+**	**Sociolinguistic context+**	
PPVT	**Sociolinguistic context+**	**Sociolinguistic context+** *↑PPVT, ↓facilitation (led by Midwest)*	*↑PPVT, ↑inhibition (led by Midwest)*
WASI	**Sociolinguistic context+** (marginal) ↑WASI,↓Stroop *SoCal only: ↑WASI,↓Stroop*	**Sociolinguistic context+** *↑WASI, ↓facilitation*	*SoCal only: ↑WASI, ↓inhibition*

A. smaller effects = better performance. < less than, > greater than for categorical contrasts.
B. +main effect remains, –main effect disappears, ↑increased, ↓decreased for continuous contrasts.
Main effects of sociolinguistic context (in bold) and main effects/interactions with individual differences measures (in italics).

larger facilitation effect were revealed in the SoCal participants. Midwest participants, on the other hand, demonstrated faster responses on neutral and incongruent trials. It thus appears that, at the group level, the Midwest and SoCal participants contrast in how they engaged cognitive control to perform on the Stroop task. The remaining Discussion further examines how individual difference factors (i.e., dimensions of bilingualism and cognitive abilities) and sociolinguistic context influence each of the Stroop, facilitation, and inhibition effects, as well as how sociolinguistic context may shape cognitive control more broadly.

Influence of Individual Differences Measures on the Stroop Effect

We examined Stroop task performance with bilinguals on a continuum of L2 proficiency/exposure, L2 AoA, L2 proficiency via receptive vocabulary (PPVT scores), and non-verbal cognitive reasoning. In doing so, we considered whether and how continuous aspects of bilingualism and cognition could account for variability in Stroop performance. A smaller Stroop effect was observed in Midwest than SoCal participants. While none of the individual difference measures could fully account for the sociolinguistic context effect, it was modulated by WASI. For the SoCal participants only, as WASI score increased, the Stroop effect decreased, suggesting that better non-verbal cognitive reasoning abilities led to more efficient Stroop performance. This finding aligns with Chen et al. (2019) and Paap et al. (2020) who found a similar relation between Stroop performance and non-verbal cognitive reasoning. When looking across testing sites, Midwest participants had higher WASI scores than SoCal participants ($p = 0.01$), a difference likely accounted for by a combination of admission selectivity and university rankings at the two testing sites, as well as socioeconomic factors that may come into play in tuition rates across the universities (see Von Stumm and Plomin, 2015 for performance differences on cognitive tests across different socioeconomic samples). Therefore, within and between Midwest-SoCal settings, the Stroop effect was modulated by WASI.

Influence of Individual Differences Measures on the Facilitation Effect

For the facilitation effect, increased L2 proficiency/exposure, higher PPVT scores, and better non-verbal reasoning were related to smaller facilitation effects. The facilitation effect decreased as L2 proficiency/exposure increased, a pattern that was found across locations and provides an explanation for the smaller facilitation effect in the Midwest context where L2 proficiency/exposure composite scores were significantly higher than in SoCal. In addition, L2 exposure was at 65% for Midwest participants and 55% for SoCal participants. PPVT scores could also account for the smaller facilitation effect in Midwest than SoCal bilinguals. For the Midwest participants only, the facilitation effect decreased as PPVT scores increased, aligning with previous findings that Stroop performance becomes more efficient with higher L2 proficiency (Xie, 2018; Luque and Morgan-Short, 2021). Indeed, we can note that the Midwest participants had higher PPVT scores ($M = 109$) than SoCal participants ($M = 101$) (see **Table 2**).

Moreover, increasing WASI scores were associated with a smaller facilitation effect, explaining the smaller facilitation effect in Midwest participants who also had somewhat higher WASI scores. Thus, greater L2 immersion, increased L2 proficiency, as well as increased cognitive skills are likely related to an increased ability to proactively monitor and attend to relevant information (e.g., bilinguals' language in current use; the direction of the Stroop arrow in the current task) while ignoring irrelevant information (e.g., the language not currently in use; the facilitating arrow location on congruent trials).

Higher L2 proficiency/exposure, PPVT, and WASI scores were related to less reliance on the irrelevant stimulus dimension to facilitate responses to congruent (relative to neutral) trials. The current Stroop task consisted of 60% congruent, 20%

incongruent, and 20% neutral trials, a ratio where it has been suggested that participants may engage a strategy that permits them to benefit from the facilitation provided by the irrelevant stimulus dimension on congruent trials (e.g., Gonthier et al., 2016). In theory, such a strategy would yield a greater facilitation effect. It is possible that individuals with higher L2 proficiency/exposure, PPVT, and WASI scores have more internal resources at their disposal because of greater cognitive capacity (Chen et al., 2019) and greater ease in maintaining the target language during L2 processing (Green, 1998). Therefore, individuals with these linguistic and cognitive profiles may focus on the relevant stimulus dimension on the Stroop task more consistently and thus rely less on facilitation cues during congruent trials. Relatedly, based on language profiles in the current study, Midwestern participants may operate more routinely in single-language contexts where information from the other (irrelevant) language must not be monitored. Individuals who routinely monitor input across two languages may also be more likely to monitor irrelevant information on non-linguistic tasks (Sabourin and Vinerte, 2019), resulting in larger facilitation effects for participants in SoCal. It is noteworthy that the current findings for SoCal bilinguals align with Hernández et al. (2010) in which Catalan-Spanish bilinguals demonstrated a larger facilitation effect relative to Spanish monolinguals. It is possible that the relatively integrated language contexts in Barcelona and SoCal may result in more continuous monitoring of information across languages and stimulus dimensions. Thus, linguistic factors (e.g., dimensions of bilingual experience; see Xie, 2018; Robinson Anthony and Blumenfeld, 2019; Luque and Morgan-Short, 2021) and cognitive factors (e.g., non-verbal intelligence; see Paap et al., 2018) may operate together to determine the facilitation effect.

Influence of Individual Differences Measures on the Inhibition Effect

While there was no difference in the inhibition effect across locations, the inhibition effect was differentially modulated across sociolinguistic contexts by PPVT and WASI scores. Within Midwest participants, the inhibition effect became larger with increased PPVT scores. It is possible that the language profiles within the Midwestern context that tended toward greater L2 immersion and proficiency would rely less on inhibiting the non-target language, yielding larger inhibition effects in the non-linguistic domain. As a counterpoint to this pattern, Gullifer and Titone (2021) found that individuals in more linguistically diverse environments relied more on proactive control on an AX-CPT task (see Bice and Kroll, 2019, for similar findings). Based on these previous findings, participants in SoCal more successfully anticipate and inhibit incongruent information. This was found to be the case primarily in individuals with higher non-verbal reasoning scores, suggesting a cognitive component in the inhibitory control performance of the SoCal participants. In general, SoCal participants, relative to Midwest participants, demonstrated faster responses on congruent trials and overall slower responses on neutral and incongruent trials. SoCal participants may thus have engaged a monitoring strategy to respond to neutral and incongruent trials and to adaptively inhibit irrelevant stimulus dimensions.

The combined results across the Stroop, facilitation, and inhibition effects suggest that a constellation of linguistic and cognitive individual differences could explain the nature of sociolinguistic context contrasts. Therefore, examining the full sociolinguistic contexts where linguistic and cognitive factors co-exist can provide a more accurate understanding of how linguistic and cognitive individual differences operate together to determine performance.

Influence of Sociolinguistic Context on Cognitive Control

Here, we sought to examine how participant differences across sociolinguistic contexts were shaped by the above-identified dimensions. In general terms, the influence of sociolinguistic context in our current study may be explained within the framework of the adaptive control hypothesis (Green and Abutalebi, 2013). Sociolinguistic contexts with varying demands on language interaction, such as contexts of competitive vs. cooperative language use (Beatty-Martínez and Titone, 2021), shape cognitive control performance in bilinguals. Given the language background information collected from participants in the current study, it is likely that the participants in SoCal functioned in a more integrated (cooperative) and linguistically diverse language context where both languages were used frequently, while the environment for participants in the Midwest reflected a potentially less integrated and potentially more competitive language environment in which the majority language was used more. The contrast between cooperative and competitive language environments made in Beatty-Martínez et al. (2020) focused on L2 immersion in the US (a competitive and varied context) vs. L1 immersion in Puerto Rico (a cooperative and integrated context). In the current investigation, we further home in on variability of L2 immersion contexts within the US. The Midwest bilinguals lived in a relatively more competitive (separated) language context than the SoCal bilinguals, who lived in a relatively more cooperative (integrated) language context.

Similar to the current study, the SoCal sample in Blumenfeld and Marian (2014) reported higher Spanish exposure than the Midwestern participants. Across Midwest and SoCal contexts, Blumenfeld and Marian compared performance on the Stroop arrows task to performance on a Simon task that did not include stimulus-stimulus inhibition (i.e., the need to inhibit an overlapping stimulus dimension of *right-left* location while making a *right-left* arrow direction judgment on the Stroop task). Better performance on the Stroop task, compared to the Simon task, emerged more robustly in participants who had been tested in the Midwest than those tested in SoCal. As in the current study, it is possible that the SoCal bilinguals were more likely to be in a cooperative L2 language immersion context in which their two languages were active simultaneously than participants in the Midwest. Therefore, SoCal participants may have relied less on linguistic stimulus-stimulus inhibition (e.g., inhibiting Spanish when using English) and found less opportunity to practice this suppression mechanism in their daily language use. The current findings align with recent work identifying distinctions in cognitive control between bilingual contexts where languages are used competitively (i.e., mostly separately) vs. cooperatively (Green and Wei, 2014; Green, 2018; Beatty-Martínez et al., 2020; Khodos and Moskovsky, 2021).

Investigations of the adaptive control hypothesis do not all converge on sociolinguistic contexts supporting cognitive control. Kałamała et al. (2020) found no relation between the degree of dual language context (e.g., believed to positively influence cognitive control) and inhibitory control (including latent variable and single measure outcomes on color/word Stroop, antisaccade, go/no go, and stop signal tasks; see Paap et al., 2019 for similar null findings). We take these studies to suggest that other yet unspecified factors likely contribute to shaping performance across bilingual populations. Testing for and establishing contrasts across multiple bilingual populations provides a valuable methodological avenue where the confluence of linguistic (dimensions of bilingualism) and cognitive (e.g., non-verbal intelligence) factors can be examined together to determine cognitive control performance. Future research is needed to describe how sociolinguistic contexts (e.g., extent of L2 immersion, Zhang et al., 2021) impact cognitive control (e.g., Gullifer et al., 2018; Ooi et al., 2018; Pot et al., 2018; Gullifer and Titone, 2020).

Limitations and Future Directions

As others have suggested (e.g., Poarch and van Hell, 2019; Beatty-Martínez et al., 2020; Bonfieni et al., 2020), the cognitive control tasks employed when cognitive consequences of bilingualism are examined must incorporate the types of conflict (e.g., stimulus-stimulus inhibition) that reflect bilingual language experiences (e.g., inhibiting one language to use the other). Admittedly, the Stroop arrows task is a single measure of a very specific type of cognitive control. If it is indeed the stimulus-stimulus conflict nature of the Stroop task that simulates bilingual experience (Blumenfeld and Marian, 2014; Xia et al., 2021), then other tasks with these features might be employed to trace the dynamics of stimulus-stimulus inhibition from the linguistic into the non-linguistic domain. Further, future studies may include important sociolinguistic variables such as more nuanced metrics of long-term L2 immersion and cooperative vs. competitive use of language, social networks, and language attitudes. Considering the social and sociolinguistic aspects of bilingualism together with cognitive consequences is in its relative infancy as an approach (e.g., Guerrero and Luk, 2021). Yet, for a more accurate and comprehensive understanding of the cognitive consequences of bilingualism, a concurrence of linguistic and cognitive factors on a continuum of bilingualism (i.e., beyond categorical distinctions) must be examined.

CONCLUSIONS

Here, we examined how cognitive performance on the non-linguistic Stroop arrows task was shaped by linguistic and cognitive factors across participants with various language experiences living in two sociolinguistic contexts. The differences in overall Stroop and facilitation effects, as well as the modulation of inhibition effects across the two sociolinguistic contexts, were driven by individual differences across a set of linguistic variables that together formed a multidimensional continuum of bilingualism. Specifically, the sociolinguistic context distinctions in Stroop performance could be explained by a constellation of individual differences in L2 experience and cognitive abilities. The individual differences that modulated Stroop, facilitation, and inhibition effects within and across language contexts included higher L2 proficiency and exposure (associated with smaller facilitation effects), higher L2 PPVT scores (associated with smaller facilitation and larger inhibition effects), as well as higher nonverbal reasoning scores (associated with smaller Stroop, facilitation, and inhibition effects). These findings suggest that as bilingual experience and cognitive skills increased, so did participants' ability to attend to relevant stimulus information (i.e., arrow direction) and ignore irrelevant stimulus information (i.e., arrow location) on the Stroop arrows task. The patterns identified in these individual differences measures illustrate that bilingual experiences and cognitive performance jointly shape cognitive control.

Findings also suggest that linguistic factors can differ between the sociolinguistic contexts of the Midwest and SoCal bilinguals. In the current sample, participants from SoCal likely lived in a relatively more cooperative (integrated) language context in which both languages were used more regularly, while participants from the Midwest likely lived in a relatively more competitive (separated) linguistic environment. This language context distinction, along with individual differences variables, likely drove the sociolinguistic context effects in Stroop performance. The current work adds to a growing body of evidence that the language environments must be taken into consideration to understand how bilingual experience shapes cognitive control, and that the exact manner in which linguistic and cognitive variables shape cognitive control can vary across settings. The sociolinguistic context differences in the current study confirm our conclusion that not just bilingualism, but sociolinguistic environment, may shape cognitive control. The current study contributes to a call to examine the cognitive consequences of bilingualism in broader and more naturalistic contexts that take into account the sociolinguistic contexts of language use.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Northwestern University's Institutional Review Board and San Diego State University's Institutional Review

Board. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MF is responsible for data coding and analysis. All authors are responsible for data acquisition, interpretation of the data, drafting the work and revising it critically for intellectual content, and final approval of the version to be published.

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REFERENCES

Baayen, R. H., and Milin, P. (2010). Analyzing reaction times. *Int. J. Psychol. Res.* 3, 12–28. doi: 10.21500/20112084.807

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., et al. (2011). Package 'lme4'. *Linear Mixed-Effects Models Using S4 Classes. R package version, 1*.

Beatty-Martínez, A. L., Navarro-Torres, C. A., Dussias, P. E., Bajo, M. T., Guzzardo Tamargo, R. E., and Kroll, J. F. (2020). Interactional context mediates the consequences of bilingualism for language and cognition. *J. Exp. Psychol. Learn. Memory Cogn.* 46, 1022. doi: 10.1037/xlm0000770

Beatty-Martínez, A. L., and Titone, D. A. (2021). The quest for signals in noise: leveraging experiential variation to identify bilingual phenotypes. *Languages* 6, 168. doi: 10.3390/languages6040168

Bialystok, E., Craik, F., and Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *J. Exp. Psychol. Learn. Memory Cogn.* 34, 859. doi: 10.1037/0278-7393.34.4.859

Bialystok, E., and DePape, A. M. (2009). Musical expertise, bilingualism, and executive functioning. *J. Exp. Psychol. Hum. Perception Perform.* 35, 565. doi: 10.1037/a0012735

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196, 104644. doi: 10.1016/j.bandl.2019.104644

Blumenfeld, H. K., and Marian, V. (2011). Bilingualism influences inhibitory control in auditory comprehension. *Cognition* 118, 245–257. doi: 10.1016/j.cognition.2010.10.012

Blumenfeld, H. K., and Marian, V. (2013). Parallel language activation and cognitive control during spoken word recognition in bilinguals. *J. Cogn. Psychol.* 25, 547–567. doi: 10.1080/20445911.2013.812093

Blumenfeld, H. K., and Marian, V. (2014). Cognitive control in bilinguals: advantages in Stimulus–Stimulus inhibition. *Bilingualism* 17, 610–629. doi: 10.1017/S1366728913000564

Bonfieni, M., Branigan, H. P., Pickering, M. J., and Sorace, A. (2020). Cognitive control in bilinguals: effects of language experience and individual variability. *Bilingualism: Language and Cognition* 23, 219–230. doi: 10.1017/S1366728918001086

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., and Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychol. Rev.* 108, 624–652. doi: 10.1037/0033-295X.108.3.624

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision* 10, 433–436. doi: 10.1163/156856897X00357

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends Cogn. Sci.* 16, 106–113. doi: 10.1016/j.tics.2011.12.010

Cedrus Corporation (2007). *Super Lab 4.5*. San Pedro: Cedrus Corporation.

Chen, Y., Spagna, A., Wu, T., Kim, T. H., Wu, Q., Chen, C., et al. (2019). Testing a cognitive control model of human intelligence. *Sci. Rep.* 9, 1–17. doi: 10.1038/s41598-019-39685-2

Coderre, E. L., VAN, Heuven, W. J., and Conklin, K. (2013). The timing and magnitude of Stroop interference and facilitation in monolinguals and bilinguals. *Bilingualism* 16, 420–441. doi: 10.1017/S1366728912000405

Cole, D. (2011). A linguistic journey to the border. *J. Appl. Lang. Stud.* 5, 77–92. Available online at: http://urn.fi/URN:NBN:fi:jyu-2011070411113

Darcy, I., Park, H., and Yang, C. L. (2015). Individual differences in L2 acquisition of English phonology: the relation between cognitive abilities and phonological processing. *Learn. Individ. Differ.* 40, 63–72. doi: 10.1016/j.lindif.2015.04.005

Dunn, L., and Dunn, L. (1997). *Peabody Picture Vocabulary Test*. 3rd Edn. Circle Pines, MN: American Guidance Service.

Freeman, M. R., Blumenfeld, H. K., and Marian, V. (2017). Cross-linguistic phonotactic competition and cognitive control in bilinguals. *J. Cogn. Psychol.* 29, 783–794. doi: 10.1080/20445911.2017.1321553

Gareth, J., Daniela, W., Trevor, H., and Robert, T. (2013). *An Introduction to Statistical Learning: With Applications in R. Springer*.

Giezen, M. R., Blumenfeld, H. K., Shook, A., Marian, V., and Emmorey, K. (2015). Parallel language activation and inhibitory control in bimodal bilinguals. *Cognition* 141, 9–25. doi: 10.1016/j.cognition.2015.04.009

Gonthier, C., Braver, T. S., and Bugg, J. M. (2016). Dissociating proactive and reactive control in the Stroop task. *Memory Cogn.* 44, 778–788. doi: 10.3758/s13421-016-0591-1

Goral, M., Campanelli, L., and Spiro, A. (2015). Language dominance and inhibition abilities in bilingual older adults. *Bilingualism* 18, 79–89. doi: 10.1017/S1366728913000126

Grant, A. M., Fang, S. Y., and Li, P. (2015). Second language lexical development and cognitive control: a longitudinal fMRI study. *Brain Lang.* 144, 35–47. doi: 10.1016/j.bandl.2015.03.010

Green, D. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism* 1, 67–81. doi: 10.1017/S1366728998000133

Green, D. W. (2018). Language control and code-switching. *Languages* 3, 8. doi: 10.3390/languages3020008

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Green, D. W., and Wei, L. (2014). A control process model of code-switching. *Lang. Cogn. Neurosci.* 29, 499–511. doi: 10.1080/23273798.2014.882515

Guerrero, S. L., and Luk, G. (2021). "Synergetic themes in cognitive and sociocultural bilingualism research," in *A Transdisciplinary Lens for Bilingual Education: Bridging Cognitive, Sociocultural, and Sociolinguistic Approaches to Enhance Student Learning*, eds E. Bauer, L. Sánchez, Y. Wang, and A. Vaughan (New York, NY: Routledge).

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism* 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., and Titone, D. (2021). Engaging proactive control: Influences of diverse language experiences using insights from machine learning. *J. Exp. Psychol. Gen.* 150, 414–430. doi: 10.1037/xge0000933

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., and Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism Lang. Cogn.* 13, 315–325. doi: 10.1017/S1366728909990010

Kałamała, P., Szewczyk, J., Chuderski, A., Senderecka, M., and Wodniecka, Z. (2020). Patterns of bilingual language use and response inhibition: a test of the adaptive control hypothesis. *Cognition* 204, 104373. doi: 10.1016/j.cognition.2020.104373

Kaushanskaya, M., and Prior, A. (2015). Variability in the effects of bilingualism on cognition: it is not just about cognition, it is also about bilingualism. *Bilingualism Lang. Cogn.* 18, 27–28. doi: 10.1017/S1366728914000510

Khodos, I., and Moskovsky, C. (2021). Dimensions of bilingualism promoting cognitive control: impacts of language context and onset age of active bilingualism on mixing and switching costs. *Linguistic Approaches Bilingualism* 11, 739–752. doi: 10.1075/lab.19064.kho

Kornblum, S., Stevens, G. T., Whipple, A., and Requin, J. (1999). The effects of irrelevant stimuli: 1. The time course of stimulus–stimulus and stimulus–response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *J. Exp. Psychol. Hum. Percept. Perform.* 25, 688–714. doi: 10.1037/0096-1523.25.3.688

Kroll, J. F., Takahesu Tabori, A., and Navarro-Torres, C. (2021). Capturing the variation in language experience to understand language processing and learning. *Lang. Interact. Acquis.* 12, 82–109. doi: 10.1075/lia.20018.kro

Lehtonen, M., Soveri, A., Laine, A., Järvenp,ää, J., De Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* 144, 394. doi: 10.1037/bul0000142

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *J. Cogn. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Luk, G., De Sa, E., and Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism Lang. Cognit.* 14, 588–595. doi: 10.1017/S1366728911000010

Luque, A., and Morgan-Short, K. (2021). The relationship between cognitive control and second language proficiency. *J. Neurolinguistics* 57, 100956. doi: 10.1016/j.jneuroling.2020.100956

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Marian, V., and Spivey, M. (2003). Competing activation in bilingual language processing: within-and between-language competition. *Bilingualism Lang. Cognit.* 6, 97–115. doi: 10.1017/S1366728903001068

Martin-Rhee, M. M., and Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism: language and cognition* 11, 81–93. doi: 10.1017/S1366728907003227

Mercier, J., Pivneva, I., and Titone, D. (2014). Individual differences in inhibitory control relate to bilingual spoken word processing. *Bilingualism Lang. Cognit.* 17, 89117. doi: 10.1017/S1366728913000084

Ooi, S. H., Goh, W. D., Sorace, A., and Bak, T. H. (2018). From bilingualism to bilingualisms: bilingual experience in Edinburgh and Singapore affects attentional control differently. *Bilingualism Lang. Cognit.* 21, 867–879. doi: 10.1017/S1366728918000020

Paap, K. R., Anders-Jefferson, R., Mason, L., Alvarado, K., and Zimiga, B. (2018). Bilingual advantages in inhibition or selective attention: more challenges. *Front. Psychol.* 9, 1409. doi: 10.3389/fpsyg.2018.01409

Paap, K. R., Anders-Jefferson, R., Mikulinsky, R., Masuda, S., and Mason, L. (2019). On the encapsulation of bilingual language control. *J. Mem. Lang.* 105, 76972. doi: 10.1016/j.jml.2018.12.001

Paap, K. R., Anders-Jefferson, R., Zimiga, B., Mason, L., and Mikulinsky, R. (2020). Interference scores have inadequate concurrent and convergent validity: should we stop using the flanker, Simon, and spatial Stroop tasks? *Cognit. Res. Principles Implications* 5, 1–27. doi: 10.1186/s41235-020-0207-y

Parris, B.A. (2014). Task conflict in the Stroop task: when Stroop interference decreases as Stroop facilitation increases in a low task conflict context. *Front. Psychol.* 5, 1182. doi: 10.3389/fpsyg.2014.01182

Poarch, G. J., and Krott, A. (2019). A bilingual advantage? An appeal for a change in perspective and recommendations for future research. *Behav. Sci.* 9, 95. doi: 10.3390/bs9090095

Poarch, G. J., and van Hell, J. G. (2019). "Does performance on executive function tasks correlate? Evidence from child trilinguals, bilinguals, and second language learners," in *Bilingualism, Executive Function, and Beyond: Questions and Insights*, eds I. A. Sekerina, L. Spradlin, and V. Valian (Amsterdam: John Benjamins Publishing Company), 223–236.

Pot, A., Keijzer, M., and De Bot, K. (2018). Intensity of multilingual language use predicts cognitive performance in some multilingual older adults. *Brain Sci.* 8, 92. doi: 10.3390/brainsci8050092

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/ (accessed April 25, 2022).

Robinson Anthony, J. J., and Blumenfeld, H. K. (2019). Language dominance predicts cognate effects and inhibitory control in young adult bilinguals. *Bilingualism Lang. Cogn.* 22, 1068–1084. doi: 10.1017/S1366728918001013

Roelofs, A., van Turennout, M., and Coles, M. G. H. (2006). Anterior cingulate cortex activity can be independent of response conflict in Stroop-like tasks. *Proc. Nat. Acad. Sci.* 103, 1388413889. doi: 10.1073/pnas.0606265103

Sabourin, L., and Vinerte, S. (2019). Cognitive control among immersed bilinguals: considering differences in linguistic and non-linguistic processing. *Bilingualism Lang. Cognit.* 22, 590–605. doi: 10.1017/S1366728918000524

Simon, J. R., and Rudell, A. P. (1967). Auditory SR compatibility: the effect of an irrelevant cue on information processing. *J. Appl. Psychol.* 51, 300. doi: 10.1037/h0020586

Singh, J. P., and Mishra, R. K. (2016). Effect of bilingualism on anticipatory oculomotor control. *Int. J. Bilingualism* 20, 550–562. doi: 10.1177/1367006915572398

SR Research Experiment Builder (2011). *SR Research Experiment Builder 1.10.165 [Computer software]*. Mississauga, ON: SR Research Ltd.

Starreveld, P. A., De Groot, A. M., Rossmark, B. M., and Van Hell, J. G. (2014). Parallel language activation during word processing in bilinguals: evidence from word production in sentence context. *Bilingualism Lang. Cognit.* 17, 258–276. doi: 10.1017/S1366728913000308

Tao, L., Marzecov,á, A., Taft, M., Asanowicz, D., and Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Front. Psychol.* 2, 123. doi: 10.3389/fpsyg.2011.00123

Van den Noort, M., Struys, E., Bosch, P., Jaswetz, L., Perriard, B., Yeo, S., et al. (2019). Does the bilingual advantage in cognitive control exist and if so, what are its modulating factors? A systematic review. *Behav. Sci.* 9, 27. doi: 10.3390/bs9030027

Von Stumm, S., and Plomin, R. (2015). Socioeconomic status and the growth of intelligence from infancy through adolescence. *Intelligence* 48, 30–36. doi: 10.1016/j.intell.2014.10.002

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence (WASI)*. San Antonio, TX: Psychological Corporation.

Xia, L., Bak, T. H., Sorace, A., and Vega-Mendoza, M. (2021). Interference suppression in bilingualism: stimulus-stimulus vs. stimulus-response conflict. *Bilingualism Lang. Cognit.* 25, 1–13. doi: 10.1017/S1366728921000304

Xie, Z. (2018). The influence of second language (L2) proficiency on cognitive control among young adult unbalanced Chinese-English bilinguals. *Front. Psychol.* 9, 412. doi: 10.3389/fpsyg.2018.00412

Zhang, H., Diaz, M. T., Guo, T., and Kroll, J. F. (2021). Language immersion and language training: two paths to enhanced language regulation and cognitive control. *Brain Lang.* 223, 105043. doi: 10.1016/j.bandl.2021.105043

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What Is a Language? Who Is Bilingual? Perceptions Underlying Self-Assessment in Studies of Bilingualism

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Research on the cognitive consequences of bilingualism typically proceeds by labeling participants as "monolingual" or "bilingual" and comparing performance on some measures across these groups. It is well-known that this approach has led to inconsistent results. However, the approach assumes that there are clear criteria to designate individuals as monolingual or bilingual, and more fundamentally, to determine whether a communication system counts as a unique language. Both of these assumptions may not be correct. The problem is particularly acute when participants are asked to classify themselves or simply report how many languages they speak. Participants' responses to these questions are shaped by their personal perceptions of the criteria for making these judgments. This study investigated the perceptions underlying judgments of bilingualism by asking 528 participants to judge the extent to which a description of a fictional linguistic system constitutes a unique language and the extent to which a description of a fictional individual's linguistic competence qualifies that person as bilingual. The results show a range of responses for both concepts, indicating substantial ambiguity for these terms. Moreover, participants were asked to self-classify as monolingual or bilingual, and these decisions were not related to more objective information regarding the degree of bilingual experience obtained from a detailed questionnaire. These results are consistent with the notion that bilingualism is not categorical and that specific language experiences are important in determining the criteria for being bilingual. The results impact interpretations of research investigating group differences on the cognitive effects of bilingualism.

Keywords: language, dialect, written language, bilingual experience, degree of bilingualism

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INTRODUCTION

Most of the research investigating the cognitive and brain consequences of bilingualism relies on assigning participants to language groups. Some studies comparing groups based on these categorical designations have reported that bilinguals performed more accurately or faster than monolinguals on various cognitive tasks and measures, especially those related to executive functioning, whereas other studies found no differences between groups (summary in Antoniou, 2019). Both conclusions have been supported by meta-analyses that either confirm the reliability of the group difference (Adesope et al., 2010; Grundy and Timmer, 2017; van den Noort et al., 2019; Grundy, 2020; Ware et al., 2020; Monnier et al., 2021) or fail to reject the null hypothesis (de Bruin et al., 2015; Lehtonen et al., 2018; Donnelly et al., 2019; Lowe et al., 2021). One factor contributing to these conflicting results is the definition of "bilingualism" and how participants are assigned to groups in various studies (for discussion see Bak, 2016; Bialystok, 2016). As discussed by Luk and Bialystok (2013), bilingualism is not a categorical variable. Some current research avoids this problem of the non-categorical nature of bilingualism by treating bilingualism on a continuum and investigating the impact of the degree of bilingual experience on outcome measures (Gullifer et al., 2018; Pot et al., 2018; DeLuca et al., 2019, 2020; Gullifer and Titone, 2020; Kałamała et al., 2021). In most cases, however, these studies using continuous measures for bilingualism do not include monolinguals and so cannot address the underlying question regarding potential language group differences in performance. Nonetheless, the positive relationship between the degree of bilingual experience and cognitive outcomes in the continuous studies consists of the role of bilingual experience in reshaping cognition.

Despite this new direction, the majority of research on bilingualism compares performance across two binary groups. The categorical approach to defining groups is especially problematic in studies in which the group assignments are made by self-assessment by the participants. How reliable are individuals' self-descriptions of their own bilingualism? There are no consistent or objective standards that determine the point at which someone transitions into a category called "bilingual." More concerning, before one can determine whether their mastery of a language is adequate to be described as "bilingual," there needs to be agreement on what counts as a "language." Again, the criteria are less transparent than one might believe. Although the linguistic distinction between language and dialect is an ongoing topic of inquiry for researchers (Melinger, 2018, 2021), participants in research studies are unlikely to be aware of those discussions.

Anecdotal occurrences in our lab have revealed a substantial number of participants who self-reported to be members of one group but on further inquiry using a detailed questionnaire (Language and Social Background Questionnaire; Anderson et al., 2018) were found to belong to the other group. For example, potential participants who had signed up to participate in a study as "monolingual" reported during the language background interview that they knew a second language, often to a high degree of proficiency. When asked why they considered themselves to be monolingual, the most common responses were, "Well, that language does not really count," or "I only use it at home." Similarly, other participants declared themselves to be "bilingual" but were found to have very less proficiency in the other language or were reporting a language they had briefly studied in school. Relatedly, Kirk et al. (2021) investigated language switching among speakers of Standard Scottish English (SSE) and two regional Scottish dialects of English (Orcadian and Dundonian) and found that most participants would be considered monolingual if language experience was measured using a language use questionnaire. This is because most participants, particularly those who spoke SSE and Orcadian, viewed the regional dialect as a way of speaking, rather than as a language, as it is closely related to English. Therefore, reliable judgments about bilingualism require a clear notion of what counts as a language.

In the absence of a consistent set of criteria for what counts as a language and how much experience is necessary for bilingualism, the group structures in most of this study lack validity, and conclusions that follow from those studies may be incorrect. For example, in a large-scale study by Nichols et al. (2020), the researchers concluded that bilingualism afforded no general cognitive advantage. Participants in that study were classified into two language groups based on their answers to a single question about how many languages they spoke without quantifying or qualifying their ability or use of that language, a procedure that is inadequate for assessing language experience (Luk et al., 2021). Similarly, studies that base group assignment on self-assessment of proficiency (e.g., Paap and Greenberg, 2013; Paap and Sawi, 2014) risk creating groups that fail to reflect relevant differences in bilingual experience. Without clear distinctions about what level of proficiency is needed to be perceived as bilingual and which languages should be considered in the calculation, the criteria for defining the category remain an open question.

Decisions about one's own language proficiency and bilingualism interact with sociolinguistic factors. Tomoschuk et al. (2019) asked Spanish-English and Chinese-English bilingual participants to classify themselves as either balanced bilinguals in that they were equally proficient in both languages or dominant bilinguals in that one language was stronger. Objective tests of proficiency were given to participants in both groups. However, participants whose objective language scores indicated balanced proficiency nonetheless claimed to be dominant in one language. Moreover, the results differed somewhat between the two bilingual groups. Chinese bilinguals used more extreme ratings to describe their own proficiency than the Spanish bilinguals, even when the objective scores were comparable. These results indicate that the bilinguals in the study were either not sufficiently aware of their own proficiency or lacked a definition of the criteria for the balanced vs. dominant categories and that the judgments interacted with the language group, underlining the unreliability of self-assessment. Therefore, addressing the defining conditions for a language and standards for bilingualism precedes resolving the contradictory evidence for the effect of bilingualism on cognitive outcomes. This study investigates the criteria people use when determining what counts as a language or deciding whether an individual is bilingual. Our purpose is not to identify formal linguistic criteria for these concepts, but rather to uncover the assumptions that influence participants when making self-assessments of bilingualism.

Broadly speaking, a language is a structured system of communicating sounds or signs that convey meaning. However, languages differ from each other in important ways, and it is not clear which of these differences are essential to deciding that the system is an independent "language." For example, nearly half of the world's languages have a writing system (Sandler, 2018), but some languages, such as Creole and many Indigenous languages, lack this feature. Is the presence of a writing system necessary for a spoken system to be considered a language?

Linguistic relatedness is also relevant to determining unique language status. For example, the group of Romance languages includes Spanish, French, Italian, Portuguese, and Romanian, all of which are derived from Latin and recognized as distinct but related languages. But what is the limit of similarity for a system to be a distinct language? Many languages include dialectic variations, some of which are spoken only in geographically specific areas. For example, Flemish is a dialect of Dutch spoken only in the Flanders region of Belgium, and Swiss German is a dialect of German spoken only in a region of Switzerland. Are these languages distinct? To what extent do relatedness to another language and geographic specificity determine whether a system is an independent language? Although some researchers have investigated the cognitive effects of bidialectalism (e.g., Lundquist and Vangsnes, 2018; Poarch et al., 2019; Vorwerg et al., 2019; Melinger, 2021), there is no objective standard for determining when a dialect becomes a language.

Similarly, the determination of bilingualism varies across individuals and linguistic contexts (Baum and Titone, 2014; Kroll et al., 2018; Fricke et al., 2019; Kremin and Byers-Heinlein, 2021). These features include proficiency (Rosselli et al., 2016; Tomoschuk et al., 2019), quantity and quality of use (Hofweber et al., 2016; Hartanto and Yang, 2019; Gullifer and Titone, 2020), age of acquisition (Luk et al., 2011; Birdsong, 2018; Gullifer et al., 2018; Hernandez et al., 2018; Bylund et al., 2021), simultaneous (i.e., two languages from birth or at a very young age) or sequential (i.e., learning a second language after significant exposure to a first language) language learning (Brito et al., 2016; Delcenserie and Genesee, 2017; Kousaie et al., 2017), and passive vs. active bilingualism (Hartanto and Yang, 2019). As individual bilinguals have developed different skills to different levels, the boundaries for determining whether an individual is bilingual are unclear.

Surrain and Luk (2019) discussed the lack of a clear definition of bilingualism in a review of the literature on the labels used by researchers to describe bilinguals and monolinguals. They examined 186 studies and reported that 31% of them referred to bilinguals without any qualifiers explaining their linguistic profiles. Although most studies reported language proficiency (77%) or usage (79%), other linguistic experiences, such as the age of language acquisition, language learning status, simultaneous or sequential bilingualism, and sociolinguistic context, were not reported. Surrain and Luk (2019) concluded there is no clear definition of what constitutes bilingual experiences, or which features of those experiences are most important. Therefore, it should not be surprising that participants are potentially less reliable than researchers in making these judgments.

If bilingual experience is considered more broadly, then it extends to individuals who are usually considered to be monolingual (Leivada et al., 2020). Bice and Kroll (2019) reported that passive exposure to a multilingual environment influenced language processing in monolinguals, underlying the importance of group classifications in interpreting results. For example, Prior and MacWhinney (2010) compared monolinguals and bilinguals and found smaller switching costs for bilinguals, but Hernández et al. (2013) replicated the study and found no group difference. However, in the Prior and MacWhinney study, bilinguals had learned both languages before the age of 6 years and used both continuously ever since, but in the Hernandez study, the "monolinguals" self-reported proficiency in a foreign language as 2 on a 4-point scale, in which 2 indicated sufficient proficiency to deal with basic activities. In other words, the studies were not the same.

Standard language ideologies are commonly shared beliefs among individuals who speak a language about how that language "should" be spoken (Forsberg et al., 2020), and these notions can also influence judgments of languages and bilingualism. Forsberg et al. (2020) examined the association between standard language ideologies and self-ratings of language proficiency among bilinguals who spoke Swedish and one other non-dominant or minority language. Participants contextualized their Swedish proficiency within a standard language ideology framework and judged their abilities in terms of their perception of what an outside referee would consider proper speech (Forsberg et al., 2020). Accordingly, participants rated their Swedish proficiency more harshly than their heritage language. Therefore, these beliefs may influence an individual's perception of nonstandard languages and whether speakers of those languages are bilingual (Forsberg et al., 2020).

The contexts in which languages are used may also influence judgments of bilingualism. According to the adaptive control hypothesis model (Green and Abutalebi, 2013), there are three primary interactional contexts, namely, single language, dual language, and dense code-switching. In single language contexts, each language is used in a unique context; in dual language contexts, both languages are used in the same context but with different speakers; and in dense code-switching contexts, the languages are completely intermixed. The perceptions of bilingualism that arise from different home language and social use experiences have not been explored.

Other variations in bilingual experiences that could lead to different perceptions of bilingualism include education level and type, proficiency, and competence with a writing system in one or both languages. Formal second language education is one path to becoming proficient in a second language, but how much education is needed before an individual is perceived as bilingual remains unclear. Moreover, it is unclear if the time since second language education influences perceptions of bilingualism. For example, if someone attended a language immersion program in primary school, are they considered bilingual in adulthood or older age?

Finally, as with determining whether a system counts as a language, it is unclear if a bilingual must be proficient in the writing system of both languages to be considered bilingual. Individuals who speak two languages that have written forms (e.g., English and Spanish) may be perceived as more bilingual than individuals who speak two languages in which only one can be written (e.g., French and Creole). This feature may explain why some participants believe that their language "does not count" in their self-assessment of bilingualism.

This study investigated the criteria by which participants determine whether a system qualifies as a unique language and the standards for deciding whether an individual is bilingual. These questions are implicit in all studies that ask participants to self-determine whether they are monolingual or bilingual. Participants were asked to judge the extent to which a fictional description of a linguistic system constituted a unique language, and the extent to which a fictional description of an individual's linguistic experiences qualified that person as bilingual. Therefore, there were two questions as follows: What is a language? Who is bilingual? For "What is a language," the scenarios manipulated the presence of a writing system, relatedness to another language, and geographic isolation of the spoken language. For "Who is bilingual," the descriptions manipulated patterns of language use, proficiency levels, education in a second language, and the presence of a writing system in both languages. Many studies have examined the effect of these variables on outcomes. For example, studies have compared individuals who speak two standard languages with those who speak a standard language and a dialect (Antoniou et al., 2020), or compared bilinguals who vary in education and age (Bialystok et al., 2005). Our question is not to investigate the impact of these variables on performance but rather to identify the extent to which these variables bias participants' judgments about what counts as a language and who can be considered bilingual. Since so much research relies on those judgments, it is important to understand their basis.

METHODS

Participants were students at York University who completed the study for course credit or community volunteers who were entered into a gift card draw. The study was administered online to 856 participants, but as explained below, the final sample consisted of 528 participants. Participants completed the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018) and responded to 26 fictional scenarios.

The LSBQ is a detailed questionnaire designed to assess bilingualism in diverse populations. It contains three sections of questions that yield participants' demographic information, self-assessments of language proficiency, and self-reported language use patterns. The results are submitted to a calculator to produce three factor scores, namely, non-English home use and proficiency, non-English social use, and English proficiency, which are then weighted to yield a continuous measure of the overall degree of bilingualism. The composite scores were scaled using the *scale* function for R (R Core Team., 2021) to produce a value between 0 and 8, with higher scores indicating more bilingual experience. This score has been shown to relate to the degree of cognitive outcome in both children (Bialystok and Shorbagi, 2021) and adults (DeLuca et al., 2019).

In addition to completing the LSBQ, participants were asked to self-identify as monolingual or bilingual. This classification produced two groups consisting of 157 monolinguals and 371 bilinguals who spoke English plus one of 59 other languages. Considering all participants, 91.5% were residents of Canada, 4% were residents of the United States, and 4.5% were residents of various other countries. Of those Canadian resident participants, most resided in Toronto, a diverse metropolitan city. Of those participants who were not Canadian residents, 82% self-classified as bilingual, most of whom were Spanish-English bilinguals.

The study was conducted online using Qualtrics (2019) (https://www.qualtrics.com). Potential participants gave informed consent before completing the LSBQ and rating the 26 fictional scenarios. All languages were given fictional names, such as "Sloblinch," to remove potential biases against actual languages. To be included in the final analyses, participants had to pass a manipulation check that was presented at a random point in the fixed sequence of scenarios in which they were simply asked to press "2" on this trial. In total, 328 individuals failed the manipulation check and were excluded from further analyses, leaving 528 participants in the final sample (409 females, 103 males, 9 not specified) ranging in age from 18 to 83 years ($M = 24.25$, $SD = 9.99$). All procedures were approved by York University's Office of Research Ethics.

What Is a Language?

To address the question "what is a language," participants were asked to rate 6 fictional language scenarios on a scale from "Not a Language" (0) to "Language" (10). The 6 scenarios reflected the following three binary dimensions of language: presence or absence of a writing system; relatedness to another known language; and geographic specificity, that is, whether the language was confined to a particular region since purely regional languages might be considered dialects.

Each scenario differed from the others on only one dimension but provided information on at least two of the dimensions. For example, a scenario might describe a system that is written and related to another language that could be compared to a language that was not written and related to another language, isolating the impact of written language on judgments. To illustrate, a scenario featuring a "related" fictional language with a writing system says, "You are shopping in the grocery store and hear someone speaking Dostinese. Dostinese is similar to English but is written using a different writing system. Individuals who speak Dostinese can also understand and speak English because of the similarities. Is Dostinese a language?" This scenario could be compared to one that changes the value only for the writing system. Contrasts between scenarios that differed in a single feature allowed for the assessment of the role of that element. To summarize, the factors manipulated in these scenarios are the presence of a writing system, relatedness to another language, and geographic specificity. The scenarios are presented in **Appendix A**.

Who Is Bilingual?

To address the question "who is bilingual," participants rated 20 fictional language use and proficiency scenarios on a scale from "Monolingual" (0) to "Bilingual" (10). Each scenario highlighted a dimension, including level and type of education, time since second language education, continued use of both languages, proficiency in both languages, presence of a writing system in one or both languages, and various social use scenarios.

The role of education and experience in judgments of bilingualism were manipulated by describing young adults or middle-aged adults who had undergone one of the following three language education programs: core-language education, immersion education from elementary through secondary school, or extended immersion education into post-secondary education. Two analyses were conducted, one examining the time since second language education (age) and the second examining the type of education. For the young adult level, the scenario described an individual who was between the ages of 20 and 25 who had recently participated in one of the education programs. For the middle-aged adult, the individual was described as being between the ages of 39 and 45 years and had participated in one of the education programs in the past and had not used those languages in a long time. The name of the individual described in the scenario and the name of the fictional language were counterbalanced across scenarios. For example, the core education young adult scenario states: "Imagine an individual grew up speaking Jantsi in the home and the community but from the ages of 6 to 14 received daily, 1-h lessons in Gronk at school. This individual is now 21 years old. To what extent is that individual bilingual?" The middle-aged adult version of this scenario calls the fictional language that is taught "Brakien," and the fictional individual is 48 years old. These comparisons allowed evaluation of the role of level and type of education and time education on the judgments of bilingualism.

As proficiency is obviously relevant to judgments of bilingualism, three levels of proficiency were compared as follows: low proficiency, in which the individual could only produce a few words in a second language; moderate proficiency, in which a person could speak in a limited capacity such that they defaulted to some words in their native language; and high proficiency, in which a person could speak a second language fluently.

Patterns of usage across various settings have been identified as a significant factor in bilingual experience. Therefore, the scenarios included three levels of community use patterns as follows: less usage in which remnants of a heritage language are spoken in the community; medium usage in which a heritage language is spoken in the community but not at home or school; and high usage that is similar to medium but includes extra-curricular instruction in that language.

Other scenarios manipulated usage patterns in the extended family and with close relatives. The first scenario described an individual who speaks one language at home but once a week the grandmother visits to teach them how to cook, an activity carried out in a second language. In the second scenario, the fictional individual spoke one language at home but spoke to their extended family members once a week on the phone in a second language. Finally, two scenarios described experiences with active or passive receptive language use. In the active scenario, the individual's parents speak to the individual in one language and the individual responds in another. In the passive scenario, the individual's parents speak one language to each other, exposing the individual to the language, but the family speaks a different language.

In another pair of scenarios, the fictional individual either continued to use their heritage language after immigration or not. In both scenarios, the individual immigrated to a new country where a new language was spoken later in life, after about 50 years of age. In the first scenario, the individuals discontinued using their heritage language instead of focusing on using the language of the new country they called home. In the second scenario, the individuals continued to use their heritage language while also learning the language of their new country. These scenarios allowed insight into the role of length of bilingual experience and continuation of bilingual language use in shaping perceptions of bilingualism.

The final factor was the impact of a writing system on judgments of bilingualism. This was examined by comparing two scenarios in which the second language had a written form or not.

To summarize, the factors manipulated in these scenarios were type and level of second-language education, time since second-language education, proficiency, community language use patterns, receptive language exposure, language use with extended family, language use after immigration later in life, and the presence of a writing system in both languages. A complete list of the scenarios is presented in **Appendix B**.

RESULTS

Who Are the Participants?

As there were no language restrictions for participating in the study, the sample included individuals with a range of language experiences. The LSBQ composite scores were used to test the reliability of the self-classification of participants into two groups. The distribution of composite scores is shown in **Figure 1**. Scores ranged from 0 to 8 ($M = 2.3$, $SD = 1.4$), with the mean score for self-classified monolinguals as 1.02 ($SD = 1.2$) and for self-classified bilinguals as 2.8 ($SD = 1.1$). This difference was not statistically significant, $t_{(526)} < 1$, *ns*.

What Is a Language?

Mean scores for each of the features embedded in the language scenarios are presented in **Tables 1A**,**B**. Because not every feature could appear in combination with all other features, standard parametric analyses were not possible, so targeted analyses were needed. Therefore, scores were examined in two 2 × 2 repeated measures ANOVAs. The first analysis evaluated scores for the four scenarios that manipulated the role of writing and relatedness, excluding geographic specificity. The second analysis evaluated scores for the four scenarios that evaluated writing and geographic specificity, excluding relatedness. Since the geographically specific language scenarios were designed to measure the perception of dialects, the languages in these scenarios were necessarily related.

The two-way ANOVA for writing system and relatedness revealed a main effect of a writing system, $F_{(1,527)} = 115.77$, $p < 0.001$, with written languages receiving higher scores than unwritten languages, the main effect of relatedness $F_{(1,527)} = 20.59$, $p < 0.001$, with unrelated languages receiving higher scores than related languages, and an interaction between them, $F_{(1,527)} = 5.3$, $p = 0.02$. Follow-up contrasts showed that for

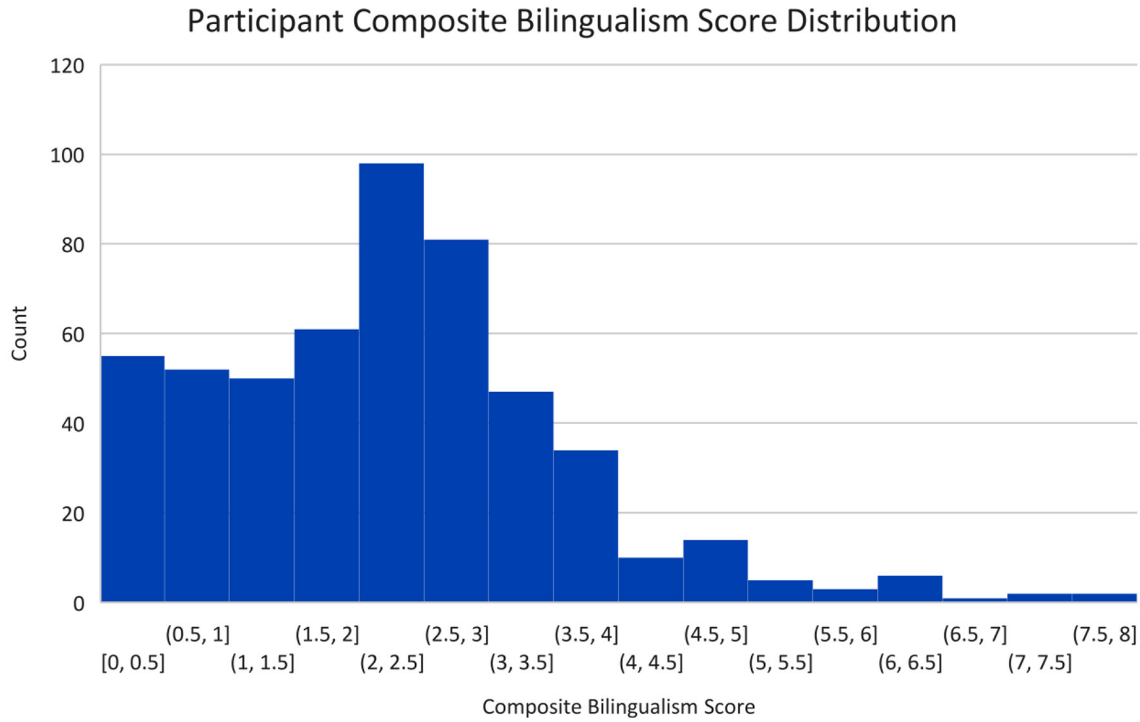

FIGURE 1 | Composite bilingualism scores (ranging from 0 to 8) derived from the LSBQ.

both related, $F_{(1,527)} = 100.2$, $p < 0.001$, and unrelated languages, $F_{(1,527)} = 58.8$, $p < 0.001$, language ratings were higher for written languages than unwritten languages. Similarly, the effect of relatedness was significant for both written, $F_{(1,527)} = 6.15$, $p = 0.01$, and unwritten languages, $F_{(1,527)} = 24.3$, $p < 0.001$. Therefore, the interaction effect is most likely caused by the larger difference between written and unwritten languages in the related scenario (0.59) than in the unrelated scenario (0.34), suggesting that relatedness matters more for unwritten languages than for written ones.

Similarly, a 2-way ANOVA was conducted for geographic specificity and the presence of a writing system. Since all of the languages were related in this case, the values for the geographically broad languages are based on the same scenarios as those reported for related languages in the previous analysis. There was a main effect of writing system, $F_{(1,527)} = 127.68$, $p < 0.001$, an interaction between geographic specificity and writing system, $F_{(1,527)} = 7.04$, $p = 0.008$, but no main effect of geographic specificity, $F < 1$, *ns*. Follow-up analyses revealed a significant difference between written and unwritten language scores for both the geographically broad, $F_{(1,527)} = 100.2$, $p < 0.001$, and geographically specific conditions, $F_{(1,527)} = 71$, $p < 0.001$. However, the contrast for geographic specificity was only significant for the written condition, $F_{(1,527)} = 7.79$, $p = 0.005$, not for the unwritten condition, $F < 1$, *ns*.

Finally, correlations were calculated to determine if overall language scores were related to participants' composite bilingualism score, $r_{(526)} = 0.08$, *ns*, age, $r_{(526)} = -0.02$, *ns*, or education, $r_{(526)} = 0.008$, *ns*. None of the correlations were significant.

TABLE 1A | Mean score out of 10 (standard deviations) for the extent to which the description indicates a unique language, comparing the presence of a writing system and relatedness to another language.

	Written	Unwritten	Mean
Related	8.3 (2.3)	7.1 (2.9)	7.7 (2.6)
Unrelated	8.6 (2.4)	7.7 (2.9)	8.2 (2.7)
Mean	8.5 (2.4)	7.4 (2.9)	

TABLE 1B | Mean score out of 10 (standard deviations) for the extent to which the description indicates a language comparing the presence of a writing system and geographic specificity.

	Written	Unwritten	Mean
Geographically broad	8.3 (2.3)	7.1 (2.9)	7.7 (2.6)
Geographically specific	7.9 (2.7)	7.1 (3.0)	7.5 (2.9)
Mean	8.1 (2.5)	7.1 (2.9)	

Who Is Bilingual?

The mean bilingualism scores for each manipulated variable are presented in **Figure 2**. Again, as it was not possible to conduct multifactor ANOVAs with interaction terms, levels within each category were examined by one-way ANOVAs. First, a one-way

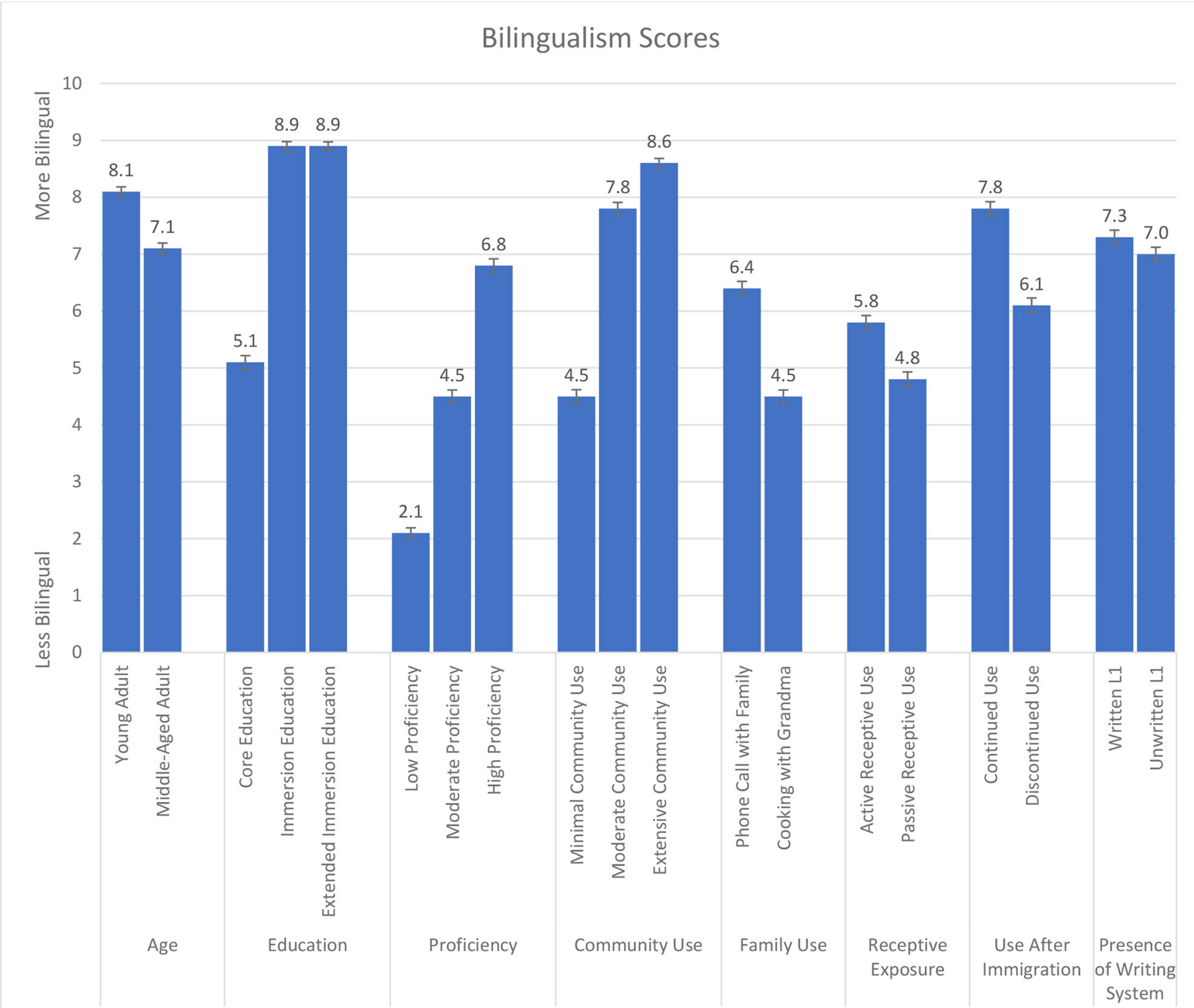

FIGURE 2 | Bilingualism scores (out of 10) illustrating the impact of each manipulated variable on the designation that an individual is bilingual.

ANOVA comparing two age groups (young adult and middle-aged) was conducted to examine the effects of time since second language education. The effect of age was significant, $F_{(1,527)} = 268.81$, $p < 0.001$, with young adults classified as more bilingual than those who are now in middle age.

The three types of education programs (core education, immersion education, and extended immersion education) were significantly different, $F_{(2,1054)} = 919.36$, $p < 0.001$. Fictional individuals who had taken immersion and extended immersion education, $F_{(1,527)} = 351.58$, $p < 0.001$, were perceived as more bilingual than those who learned a second language through core education, $F_{(1,527)} = 273.29$, $p < 0.001$. Not surprisingly, therefore, immersion experiences lead to higher perceived bilingual scores than core language education.

A one-way ANOVA for the three proficiency levels on judgments of bilingualism indicated a significant effect, $F_{(2,1054)} = 703.35$, $p < 0.001$. All contrast intervals were significant: high proficiency was considered more bilingual than moderate proficiency, $F_{(1,527)} = 295.24$, $p < 0.001$, and moderate proficiency was more bilingual than low proficiency, $F_{(1,527)} = 450.35$, $p < 0.001$.

The differences in usage patterns indicated by three levels of community use showed a significant difference between them, $F_{(2,1054)} = 527.49$, $p < 0.001$. Individuals who engaged in extensive community use were considered more bilingual than those who engaged in moderate use, $F_{(1,527)} = 105.45$, $p < 0.001$, and moderate users were perceived to be more bilingual than minimal users in the community context, $F_{(1,527)} = 878.62$, $p < 0.001$.

For usage within the home, there was a significant difference between the two extended family language use scenarios, $F_{(1,527)} = 228.57$, $p < 0.001$, with phone conversations with extended family receiving a higher bilingualism score than cooking with grandma. There was also a significant difference between the two receptive language use scenarios in the home, $F_{(1,527)} = 70.22$, $p < 0.001$, with the active scenario receiving a higher bilingualism score than the passive scenario. Therefore, the productive use of language by responding to the parents confers a higher bilingualism score than simply listening to them.

Continued use of a heritage language after immigrating to a new country produced higher scores for bilingualism than did discontinued use scenarios, $F_{(1,527)} = 168.84$, $p < 0.001$. This difference was significant despite both scenarios featuring a fictitious individual with decades of language experience, suggesting the importance of ongoing usage for perceptions of bilingualism.

Finally, the role of written language on perceptions of bilingualism was evaluated by comparing bilingualism scores for individuals whose two languages were both written or those for whom only one was written. There was a significant difference in which speakers of two written languages were perceived as more bilingual than those for whom only one language had a writing system, $F_{(1,527)} = 7.11$, $p = 0.008$.

Correlations for overall judgements of bilingualism and participants' bilingualism composite score were next examined, $r_{(526)} = -0.07$, *ns,* age, $r_{(526)} = -0.00003$, *ns,* and education, $r_{(526)} = 0.004$, *ns*. Again, none of the correlations were significant.

DISCUSSION

This study explored the influence of several key characteristics on determining how individuals decide whether a system counts as a unique language and the extent to which individuals with different experiences can be considered bilingual. The results revealed that these characteristics have a substantial impact on how individuals arrive at these decisions, making self-classifications relating to languages and bilingualism multidimensional and complex. Judgments were not influenced by participant characteristics including the degree of bilingualism, age, or education. These results have wide implications for research that compares groups of monolinguals and bilinguals across the lifespan and makes conclusions in terms of the group designation. The answers to the questions "What is a language?" and "Who is bilingual?" are summarized below.

What Is a Language?

Participants considered systems that were unrelated to other languages rather than related, written rather than unwritten, and spoken widely rather than geographically specific to be more language-like rather than their counterparts. Consider each of these dimensions in turn. The results for relatedness were in line with expectations that similar systems might be considered dialects of the same language rather than unique languages. However, the distinction between dialects and distinct languages is not clear (Gregory and Carroll, 2018). For example, while Portuguese and Spanish are distinct languages, they have considerable similarity and some mutual intelligibility, whereas Flemish is not considered to be a distinct language from Dutch, despite having several different linguistic properties. Despite being written in different alphabets (Cyrillic vs. Roman), Serbian and Croatian used to be considered a single language, Serbo-Croatian, but after political upheaval in Yugoslavia, they are now simply considered to be different languages. Clearly, the boundaries of similarity that determine whether a system is a unique language are more continuous than categorical.

A few studies have examined the effect of language similarity on cognitive outcomes of bilingualism, but the results are mixed and the conclusions at this point are preliminary (Radman et al., 2021). However, the issue is important as it determines how participants are classified in terms of language status. For example, some individuals in the "monolingual" group may know two dialects that they do not consider to be separate languages, and so falsely consider themselves to be monolingual. However, proficiency in two dialects has been shown to have similar effects on cognitive performance as does proficiency in two languages (Wang et al., 2017; Antoniou and Spanoudis, 2020).

The present findings also showed that respondents considered that it was important for a language to have a written form to be considered a unique language. This factor interacted with relatedness, such that a language that was related to another one and did not have a writing system was considered less language-like than a language that was unrelated to another language. In an informal sense, the factors of being unlike other languages (unrelated) and having a writing system increased judgments that the system was a unique language. Many languages, including Creole and several Indigenous languages, do not have a written component yet are clearly unique languages (Sandler, 2018), a finding that may have led to some of the anecdotal episodes reported earlier.

The geographic specificity of a system reduced its perception as a unique language if it did not also have a written form. At the same time, geographically specific languages with a written form were still considered to be less language-like than were languages with written forms that were spoken broadly. The presence of a writing system always increases the perception of a system as being a language, but the effect is mitigated by the relation to other languages and the breadth or specificity of the region in which the language is spoken.

Who Is Bilingual?

Eight features were evaluated for their role in determining whether an individual should be considered bilingual, and all the features had significant impacts on judgments. Generally, individuals were considered to be more bilingual when they learned a second language more recently than distally, when they took immersion rather than core second-language education, when they were more proficient than less proficient in a second language, when they engaged in extensive rather than minimal usage of the second language, when they were actively receptive rather than passively receptive to a second language, when they continued to use their second language after immigration to a foreign-language country, and when there was a writing system in both languages. None of these results are surprising; they reveal that judgments about whether someone is bilingual are based on multidimensional factors that are all continuous in nature.

Participants classified individuals as more bilingual when both systems had a written component than when only one system had a written component. This finding is in line with the result of the language judgments in which the presence of a writing system increased decisions about the system being a language. Therefore, for both questions, the presence of a writing system and competence with the written forms were important, but research on bilingualism rarely reports this information. Similarly, proficiency was also found to be relevant to judgments of bilingualism. Although many studies report second-language proficiency (e.g., Kaushanskaya and Marian, 2009; Oh et al., 2019), there is rarely any mention of proficiency in reading and writing. These factors likely contribute to whether participants are classified as monolingual or bilingual and in turn to cognitive and brain outcomes.

The type of language education also influenced the judgment of how bilingual an individual was considered to be, with higher judgments of bilingualism for more immersive forms of language instruction. Again, this finding may seem intuitive, yet most studies do not report on the educational background of the participants in the sample. Moreover, by including the current age of the hypothetical individual, the present results demonstrated that longer time intervals since that education took place led to lower judgments of bilingualism. This effect was more pronounced in core education than in immersion education conditions.

The various usage patterns experienced by bilinguals have also been shown to contribute to cognitive and brain outcomes (Green and Abutalebi, 2013; Yang et al., 2018; Struys et al., 2019; Bhandari et al., 2020; Wu et al., 2020), although differences in these patterns are rarely discussed in the research. However, the importance of these differences was confirmed in the present results. For example, an individual who has a weekly phone conversation with extended family in their second language was perceived as more bilingual than an individual who speaks a second language with grandma while cooking dinner. The latter scenario may require less active engagement in the second language because cooking requires both working and speaking/listening, whereas a phone call requires more attention to speaking and listening. A more striking nuance of second-language usage relates to immigration and whether individuals continue to use their first language consistently in the new country. In this study, hypothetical individuals who were now 80 years of age and did not consistently use their first language upon arrival in the new country were rated as less bilingual than individuals who continued to use their first language after arrival, despite both groups having 55 years of consistent use in their first language in their home country and 25 years in the new country. In fact, those who did not consistently use their first language upon arrival to the new country at age 55 were only rated a 6.1/10 for how bilingual they were perceived to be, and ∼38% of individuals classified these scenarios as 5/10 or less. An individual with 55 years of experience in another language should surely not be classified as monolingual, yet these data suggest that many individuals would classify them as such. This finding again adds noise to the signal when comparing groups of "monolinguals" and "bilinguals."

Research on the cognitive and brain consequences of bilingualism remains controversial, with studies showing both positive effects of bilingualism and no difference between groups. There are several reasons for null findings (discussion in Bialystok, 2020), but this study suggests that definitions used to determine group membership are potentially a fundamental source of the controversy. As we have seen, there is little consensus about what constitutes a language or what criteria determine whether an individual is bilingual. Both concepts turn out to be complex and multidimensional. Moreover, the present results demonstrated that participants' self-identification as monolingual or bilingual had questionable reliability when evaluated in terms of more objective indicators of bilingual experience. Since many studies rely exclusively on simple self-classification by participants, it may not be surprising that results differ.

The primary implication of the present findings is that between-groups comparisons require clear and objective definitions for the composition of the groups for any interpretations to be made. Variations on the dimensions investigated here can obfuscate true differences between groups by challenging the validity of the group designations. Calling a system a language does not necessarily make it so, and calling an individual bilingual may or may not reflect relevant linguistic experience. But without attention to these definitions, no conclusions can be made about the role of language experience in producing modifications in cognitive or brain systems. Bilingualism is not a categorical variable, and research investigating its multifaceted and complex role in modifying cognitive systems must be clear about the definition. Finally, a detailed description of the bilingual competence of the participants in the sample is an essential first step.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by York University's Office of Research Ethics. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DW, EB, and JG conceptualized and designed the study. DW performed the statistical analyses. DW and JG wrote the first draft of the manuscript, which was then edited by EB. All authors contributed to the manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.863991/full#supplementary-material

REFERENCES

Adesope, O., Lavin, T., Thompson, T., and Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Rev. Educ. Res.* 80, 207–245. doi: 10.3102/0034654310368803

Anderson, J., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Antoniou, K., and Spanoudis, G. (2020). *An Investigation of the Multilingual and Bi-dialectal Advantage in Executive Control*. Available online at: https://www.google.com/search?q=An+Investigation+of+the+Multilingual+and+Bi-Dialectal+Advantage+in+Executive+Control&oq=An+Investigation+of+the+Multilingual+and+Bi-Dialectal+Advantage+in+Executive+Control&aqs=chrome..69i57.1078j0j7&sourceid=chrome&ie=UTF-8

Antoniou, K., Veenstra, A., Kissine, M., and Katsos, N. (2020). How does childhood bilingualism and bi-dialectalism affect the interpretation and processing of pragmatic meanings? *Bilingualism Lang. Cognit.* 23, 186–203. doi: 10.1017/S1366728918001189

Antoniou, M. (2019). The advantages of bilingualism debate. *Annu. Rev. Linguist.* 5, 395–415. doi: 10.1146/annurev-linguistics-011718-011820

Bak, T. (2016). The impact of bilingualism on cognitive ageing and dementia: Finding a path through a forest of confounding variables. *Linguist. Approach. Bilingualism* 6, 205–226. doi: 10.1075/lab.15002.bak

Baum, S., and Titone, D. (2014). Moving toward a neuroplasticity view of bilingualism, executive control, and aging. *Appl. Psycholinguist.* 35, 857–894. doi: 10.1017/S0142716414000174

Bhandari, P., Prasad, S., and Mishra, R. K. (2020). High proficient bilinguals bring in higher executive control when encountering diverse interlocutors. *J. Cult. Cognit. Sci.* 4, 201–215. doi: 10.1007/s41809-020-00060-7

Bialystok, E. (2016). The signal and the noise: finding the pattern in human behavior. *Linguist. Approach. Bilingualism* 6, 517–534. doi: 10.1075/lab.15040.bia

Bialystok, E. (2020). Null results in bilingualism research: what they tell us and what they don't. *J. Multilingual Theor. Pract.* 1, 8–22. doi: 10.1558/jmtp.17104

Bialystok, E., Martin, M. M., and Viswanathan, M. (2005). Bilingualism across the lifespan: the rise and fall of inhibitory control. *Int. J. Bilingualism* 9, 103–119. doi: 10.1177/13670069050090010701

Bialystok, E., and Shorbagi, S. H. (2021). Subtle increments in socioeconomic status and bilingualism jointly affect children's verbal and nonverbal performance. *J. Cognit. Dev.* 22, 467–490. doi: 10.1080/15248372.2021.1901711

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196, 104644. doi: 10.1016/j.bandl.2019.104644

Birdsong, D. (2018). Plasticity, variability and age in second language acquisition and bilingualism. *Front. Psychol.* 9, 81. doi: 10.3389/fpsyg.2018.00081

Brito, N. H., Murphy, E. R., Vaidya, C., and Barr, R. (2016). Do bilingual advantages in attentional control influence memory encoding during a divided attention task? *Bilingualism Lang. Cogn.* 19, 621–629. doi: 10.1017/S1366728915000851

Bylund, E., Hyltenstam, K., and Abrahamsson, N. (2021). Age of acquisition–not bilingualism–is the primary determinant of less than nativelike L2 ultimate attainment. *Bilingualism Lang. Cogn.* 24, 18–30. doi: 10.1017/S1366728920000188

de Bruin, A., Treccani, B., and Della Sala, S. (2015). Cognitive advantage in bilingualism: an example of publication bias? *Psychol. Sci.* 26, 99–107. doi: 10.1177/0956797614557866

Delcenserie, A., and Genesee, F. (2017). The effects of age of acquisition on verbal memory in bilinguals. *Int. J. Bilingualism* 21, 600–616. doi: 10.1177/1367006916639158

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Nat. Acad. Sci. U. S. A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *Neuroimage* 204, 116222. doi: 10.1016/j.neuroimage.2019.116222

Donnelly, S., Brooks, P. J., and Homer, B. D. (2019). Is there a bilingual advantage on interference-control tasks? A multiverse meta-analysis of global reaction time and interference cost. *Psychon. Bull. Rev.* 26, 1122–1147. doi: 10.3758/s13423-019-01567-z

Forsberg, J., Ribbås, M. T., and Gross, J. (2020). Self-assessment and standard language ideologies: bilingual adolescents in Sweden reflect on their language proficiencies. *J. Multilingual Multicult. Dev.* 42, 137–151. doi: 10.1080/01434632.2020.1715988

Fricke, M., Zirnstein, M., Navarro-Torres, C., and Kroll, J. F. (2019). Bilingualism reveals fundamental variation in language processing. *Bilingualism Lang. Cogn.* 22, 200–207. doi: 10.1017/S1366728918000482

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Gregory, M., and Carroll, S. (2018). *Language and Situation: Language Varieties and their Social Contexts*. London: Routledge. doi: 10.4324/9780429436185

Grundy, J. G. (2020). The effects of bilingualism on executive functions: an updated quantitative analysis. *J. Cult. Cogn. Sci.* 4, 177–199. doi: 10.1007/s41809-020-00062-5

Grundy, J. G., and Timmer, K. (2017). Bilingualism and working memory capacity: a comprehensive meta-analysis. *Second Lang. Res.* 33, 325–340. doi: 10.1177/0267658316678286

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism Lang. Cogn.* 23, 283–294. doi: 10.1017/S1366728919000026

Hartanto, A., and Yang, H. (2019). Does early active bilingualism enhance inhibitory control and monitoring? A propensity-matching analysis.

J. Exp. Psychol. Learn. Mem. Cogn. 45, 360–378. doi: 10.1037/xlm0000581

Hernandez, A. E., Claussenius-Kalman, H. L., Roderos, J., and Vaughn, K. A. (2018). Symbiosis, parasitism and bilingual cognitive control: neuroemergentist perspective. *Front. Psychol.* 9, 2171. doi: 10.3389/fpsyg.2018.02171

Hernández, M., Martin, C. D., Barceló, F., and Costa, A. (2013). Where is the bilingual advantage in task-switching? *J. Mem. Lang.* 69, 257–276. doi: 10.1016/j.jml.2013.06.004

Hofweber, J., Marinis, T., and Treffers-Daller, J. (2016). Effects of dense code-switching on executive control. *Ling. Approach. Bilingualism* 6, 648–668. doi: 10.1075/lab.15052.hof

Kałamała, P., Senderecka, M., and Wodniecka, Z. (2021). On the multidimensionality of bilingualism and the unique role of language use. *Bilingualism Lang. Cognit.* 1–13. doi: 10.1017/S1366728921001073

Kaushanskaya, M., and Marian, V. (2009). The bilingual advantage in novel word learning. *Psychon. Bull. Rev.* 16, 705–710. doi: 10.3758/PBR.16.4.705

Kirk, N. W., Declerck, M., Kemp, R. J., and Kempe, V. (2021). Language control in regional dialect speakers – monolingual by name, bilingual by nature? *Bilingualism Lang. Cogn.* 1–10. doi: 10.1017/S1366728921000973

Kousaie, S., Chai, X. J., Sander, K. M., and Klein, D. (2017). Simultaneous learning of two languages from birth positively impacts intrinsic functional connectivity and cognitive control. *Brain Cogn.* 117, 49–56. doi: 10.1016/j.bandc.2017.06.003

Kremin, L. V., and Byers-Heinlein, K. (2021). Why not both? Rethinking categorical and continuous approaches to bilingualism. *Int. J. Bilingualism* 25, 1560–1575. doi: 10.1177/13670069211031986

Kroll, J. F., Dussias, P. E., and Bajo, M. T. (2018). Language use across international contexts: shaping the minds of L2 speakers. *Annu. Rev. Appl. Linguist.* 38, 60–79. doi: 10.1017/S0267190518000119

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* 144, 394–425. doi: 10.1037/bul0000142

Leivada, E., Westergaard, M., Duñabeitia, J. A., and Rothman, J. (2020). On the phantom-like appearance of bilingualism effects on neurocognition: (how) should we proceed? *Bilingualism Lang. Cogn.* 24, 1–14. doi: 10.1017/S1366728920000358

Lowe, C. J., Cho, I., Goldsmith, S. F., and Morton, J. B. (2021). The bilingual advantage in children's executive functioning is not related to language status: a meta-analytic review. *Psychol. Sci.* 32, 1115–1146. doi: 10.1177/0956797621993108

Luk, G., Anderson, J. A. E., Grundy, J. G., Pliatsikas, C., and Rothman, J. (2021). Letter to the editors of psychological science: what have we learned about bilingualism? *Regarding Nichols et al.* (2020). doi: 10.25384/SAGE.15180460.v1

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: interaction between language proficiency and usage. *J. Cogn. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Luk, G., Sa, E. D., and Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism Lang. Cogn.* 14, 588–595. doi: 10.1017/S1366728911000010

Lundquist, B., and Vangsnes, Ø. A. (2018). Language separation in bidialectal speakers: evidence from eye tracking. *Front. Psychol.* 9, 1394. doi: 10.3389/fpsyg.2018.01394

Melinger, A. (2018). Distinguishing languages from dialects: a litmus test using the picture-word interference task. *Cognition* 172, 73–88. doi: 10.1016/j.cognition.2017.12.006

Melinger, A. (2021). Do elevators compete with lifts? Selecting dialect alternatives. *Cognition* 206, 104471. doi: 10.1016/j.cognition.2020.104471

Monnier, C., Boiché, J., Armandon, P., Baudoin, S., and Bellocchi, S. (2021). Is bilingualism associated with better working memory capacity? A meta-analysis. *Int. J. Biling. Educ. Bilingualism* 1–27. doi: 10.1080/13670050.2021.1908220

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., and Owen, A. M. (2020). Bilingualism affords no general cognitive advantages: a population study of executive function in 11,000 people. *Psychol. Sci.* 31, 548–567. doi: 10.1177/0956797620903113

Oh, T. M., Graham, S., Ng, P., Yeh, I. B., Chan, B. P. L., and Edwards, A. M. (2019). Age and proficiency in the bilingual brain revisited: activation patterns across different L2-learner types. *Front. Commun.* 4, 39. doi: 10.3389/fcomm.2019.00039

Paap, K. R., and Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* 66, 232–258. doi: 10.1016/j.cogpsych.2012.12.002

Paap, K. R., and Sawi, O. (2014). Bilingual advantages in executive functioning: problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Front. Psychol.* 5, 962. doi: 10.3389/fpsyg.2014.00962

Poarch, G. J., Vanhove, J., and Berthele, R. (2019). The effect of bidialectalism on executive function. *Int. J. Bilingualism* 23, 612–628. doi: 10.1177/1367006918763132

Pot, A., Keijzer, M., and De Bot, K. (2018). Intensity of multilingual language use predicts cognitive performance in some multilingual older adults. *Brain Sci.* 8, 1–27. doi: 10.3390/brainsci8050092

Prior, A., and MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism Lang. Cogn.* 13, 253–262. doi: 10.1017/S1366728909990526

Qualtrics, X. M. (2019). *Qualtrics XM-The Leading Experience Management Software.* Provo, UT: Qualtrics XM.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria. Available online at: https://www.R-project.org/.

Radman, N., Jost, L., Dorood, S., Mancini, C., and Annoni, J.-M. (2021). Language distance modulates cognitive control in bilinguals. *Sci. Rep.* 11, 24131. doi: 10.1038/s41598-021-02973-x

Rosselli, M., Ardila, A., Lalwani, L. N., and Vélez-Uribe, I. (2016). The effect of language proficiency on executive functions in balanced and unbalanced Spanish–English bilinguals. *Bilingualism Lang. Cogn.* 19, 489–503. doi: 10.1017/S1366728915000309

Sandler, W. (2018). The body as evidence for the nature of language. *Front. Psychol.* 9, 1782. doi: 10.3389/fpsyg.2018.01782

Struys, E., Woumans, E., Nour, S., Kepinska, O., and Noort, M. V. D. (2019). A domain-general monitoring account of language switching in recognition tasks: evidence for adaptive control. *Bilingualism Lang. Cogn.* 22, 606–623. doi: 10.1017/S1366728918000342

Surrain, S., and Luk, G. (2019). Describing bilinguals: a systematic review of labels and descriptions used in the literature between 2005–2015. *Bilingualism Lang. Cogn.* 22, 401–415. doi: 10.1017/S1366728917000682

Tomoschuk, B., Ferreira, V. S., and Gollan, T. H. (2019). When a seven is not a seven: self-ratings of bilingual language proficiency differ between and within language populations. *Bilingualism Lang. Cogn.* 22, 516–536. doi: 10.1017/S1366728918000421

van den Noort, M., Struys, E., Bosch, P., Jaswetz, L., Perriard, B., Yeo, S., et al. (2019). Does the bilingual advantage in cognitive control exist and if so, what are its modulating factors? A systematic review. *Behav. Sci.* 9, 27. doi: 10.3390/bs9030027

Vorwerg, C. C., Suntharam, S., and Morand, M. A. (2019). Language control and lexical access in diglossic speech production: evidence from variety switching in speakers of Swiss German. *J. Mem. Lang.* 107, 40–53. doi: 10.1016/j.jml.2019.03.007

Wang, T., Wang, D., Zhang, J., and Cui, J. (2017). Effects of "each speaks their own dialect" phenomenon on the executive function of *Jingpo* students. *Acta Psychol. Sin.* 49, 1392. doi: 10.3724/SP.J.1041.2017.01392

Ware, A. T., Kirkovski, M., and Lum, J. A. G. (2020). Meta-analysis reveals a bilingual advantage that is dependent on task and age. *Front. Psychol.* 11, 1458. doi: 10.3389/fpsyg.2020.01458

Wu, J., Zhang, Z., Chen, M., Yuan, Q., Zhang, M., Yang, J., et al. (2020). Language context tunes brain network for language control in bilingual language production. *Neuropsychologia* 147, 107592. doi: 10.1016/j.neuropsychologia.2020.107592

Yang, J., Ye, J., Wang, R., Zhou, K., and Wu, Y. J. (2018). Bilingual contexts modulate the inhibitory control network. *Front. Psychol.* 9, 395. doi: 10.3389/fpsyg.2018.00395

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REVIEW
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The Multifaceted Nature of Bilingualism and Attention

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Attention has recently been proposed as the mechanism underlying the cognitive effects associated with bilingualism. However, similar to bilingualism, the term attention is complex, dynamic, and can vary from one activity to another. Throughout our daily lives, we use different types of attention that differ in complexity: sustained attention, selective attention, alternating attention, divided attention, and disengagement of attention. The present paper is a focused review summarizing the results from studies that explore the link between bilingualism and attention. For each level of attention, a brief overview of relevant theoretical models will be discussed along with a spotlight on paradigms and tasks used to measure these forms of attention. The findings illustrate that different types and levels of attention are modified by the variety of bilingual experiences. Future studies wishing to examine the effects of bilingualism on attention are encouraged to embrace the complexity and diversity of both constructs rather than making global claims about bilingualism and attention.

Keywords: bilingualism, attention, executive control, language experience, cognition

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INTRODUCTION

The question of whether bilingualism leads to performance benefits on various cognitive measures has been the topic of considerable debate in recent years (Antoniou, 2019). While some studies report that speaking two or more languages improves executive functioning on tasks that recruit inhibition, working memory, and cognitive flexibility (see Bialystok, 2017 for a review), others report null results (e.g., Paap and Greenberg, 2013; Gathercole et al., 2014; von Bastian et al., 2016). Several meta-analyses on bilingualism and cognition have added to the debate with contrasting conclusions, again with some meta-analyses in favor of bilinguals (e.g., Adesope et al., 2010; Grundy and Timmer, 2017; Donnelly et al., 2019; Ware et al., 2020), while others conclude equivalent performance after correcting for publication bias (Lehtonen et al., 2018; Lowe et al., 2021). In a large-scale quantitative Bayesian re-analysis of the studies included in the Donnelly et al. (2019) and Lehtonen et al. (2018) meta-analyses, Grundy (2020) found "decisive" evidence that bilinguals outperform monolinguals far more than expected by chance, even after controlling for sample size and publication bias. This re-analysis was not at odds with the previous meta-analyses as they answered different questions. Rather, the study highlighted the need to determine *when* group differences appear rather than *if* they do. The present review highlights the importance of considering the complexity of different forms of attention when examining the effects of bilingualism on cognition. Bilingualism is also extremely complex and consists of a number of unique experiences. However, most of the field treats attention as a unitary construct and bilingualism as a dichotomous variable rather than embracing the complexity of each. This is problematic because it often leads to failed "replications." We highlight the need to determine which specific bilingual experiences affect which attentional processes across the lifespan.

Language group differences have often been attributed to the bilingual's need to direct attention towards the target language, while *ignoring* the non-target language that is co-activated and competing for attention (Marian and Spivey, 2003; review in Kroll et al., 2012). Early proposals included selective attention as the key explanation for how bilingual children excelled in problem-solving tasks compared to monolingual children (Bialystok, 1992, 1999). In the late 1990s and early 2000s, researchers began examining how fluency in a second language influenced one or all three components of executive functioning postulated by Miyake et al. (2000). The components included inhibition (controlled suppression of prepotent responses), working memory (updating and monitoring of mental representations), and shifting (ability to flexibly switch between mental states). Of the three components, inhibition was the most studied based on the assumption that words from the non-target language are suppressed or inhibited (Green, 1998). The inhibitory control model by Green (1998) proposed a supervisory attentional system that tags each lexical representation to a language, such that lexical nodes belonging to the non-target language are then inhibited. However, in a review, Bialystok (2017) noted that an inhibitory account explaining the cognitive outcomes associated with bilingualism is unlikely due to several pieces of evidence.

First, pre-verbal infants raised in bilingual households can correctly anticipate the location of a reward after it has switched locations greater than chance, whereas infants raised in monolingual households perform at chance (Comishen et al., 2019). Pre-verbal infants have yet to produce a language and have only rudimentary representations of either language. The more likely explanation is that the bilingual experience affords bilinguals with a different way to allocate attention to their rich and complex linguistic environment (Bialystok, 2015). Second, in a review of the empirical data across various non-verbal interference tasks, Hilchey and Klein (2011) reported that bilinguals typically outperform monolinguals on *both* congruent and incongruent trials. This is contrary to the inhibitory account which predicts that language group differences would emerge on trials that require conflict and selection (i.e., incongruent trials). Congruent trials do not require inhibition because the distracting or irrelevant information does not produce conflict. In fact, the "distracting" element in congruent trials is often facilitatory, such as in the flanker task (Eriksen and Eriksen, 1974) where the surrounding arrows are pointing in the same direction as the target central arrow. The more likely explanation is that bilinguals are better at adapting to the current task demands regardless of whether the trial is congruent or incongruent by flexibly increasing or decreasing attentional engagement (Hilchey and Klein, 2011; Zhou and Krott, 2018). Third, inhibition is not a unitary construct. On tasks that require withholding a prepotent response (Martin-Rhee and Bialystok, 2008), delaying gratification (Carlson and Meltzoff, 2008; Barac et al., 2016), or controlling impulses (Carlson and Meltzoff, 2008), which are also considered to reflect inhibition, monolinguals and bilinguals perform equivalently. Hence, models based on inhibition alone cannot fully explain the research on bilingualism and cognition. For these reasons, Bialystok (2015, 2017) and more recently Bialystok and Craik (2022) proposed attention as a possible mechanism accounting for the processing differences between monolinguals and bilinguals on non-verbal cognitive tasks.

Similarly, D'Souza et al. (2020, 2021) argued that bilingualism may alter attentional processes because bilinguals are exposed to speech that is varied and less predictable than monolinguals. As bilingually-raised infants divide their time across multiple languages, they receive less input from each of their languages than monolingually-raised infants. In addition, bilingual parents are sometimes themselves in the process of learning the community language and may be providing their infants with less accurate input. As such, bilinguals could potentially be redirecting their attention earlier to less familiar input, leading to longer exploration phases and a preference for novelty. The explanation may shed light on why bilinguals show earlier N2 and P3 components than monolinguals in EEG studies (e.g., Chung-Fat-Yim et al., 2021; Grundy and Chung-Fat-Yim, in press, for a review), take longer to initiate a response but are faster and more efficient at executing a response to the correct location in mouse-tracking studies (Incera and McLennan, 2016, 2018; Damian et al., 2018), and are faster to detect a change than monolinguals on eye-tracking studies (e.g., Kovács and Mehler, 2009).

However, bilingualism is not a monolithic variable and these patterns differ depending on age of acquisition, use, proficiency, context of acquisition, and so on (e.g., DeLuca et al., 2019). Similar to the complexity associated with bilingualism (de Bruin, 2019; Surrain and Luk, 2019), attention also exists along a continuum depending on internal factors (i.e., motivation, prior experience) and external factors (i.e., environmental demands, testing conditions). In fact, the conceptualization of attentional control itself has been debated for decades (Hommel et al., 2019; von Bastian et al., 2020). The definition of attention ranges from "the process of selectively focusing on specific information in the environment" to "directing the mind to an object" or to "the ability to concentrate." Though these descriptions may sound similar, they recruit attentional resources to varying degrees. The present paper provides a review of the literature on attention and bilingualism by covering different types of attention progressing from low levels of attention to high levels of attention, though these levels can change depending on the task demands: Sustained attention, selective attention, alternating attention, and divided attention (**Figure 1**). Also, disengagement of attention which underlies all aforementioned forms of attention will be discussed. These forms of attention were chosen based on the different types of attention that have been examined in the literature concerning the effects of bilingualism on cognition. We predict that the largest difference between language groups will emerge on tasks that require greater attentional

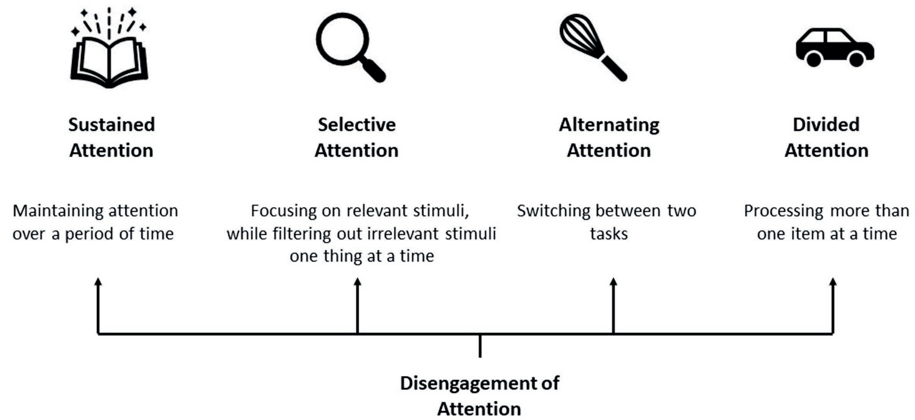

FIGURE 1 | Types of attention and their descriptions.

resources, coinciding with the findings that bilinguals outperform monolinguals when task demands are high (e.g., Qu et al., 2016; Jiao et al., 2019; Comishen and Bialystok, 2021; Kuipers and Westphal, 2021).

Attention is a fluctuating process necessary for concentration when performing a task but also necessary to shift focus, focus on more than one task or avoid distractions (Posner and Boies, 1971; Norman and Shallice, 1986; Hommel et al., 2019; Lindsay, 2020; von Bastian et al., 2020; Wickens, 2021). In general, sustained and selective attention are needed to focus attention on one task at a time, while alternating and divided attention are required for concentration of more than one task. The difference between selective attention and sustained attention is that the former involves focusing on one task while avoiding distractions and the latter refers to a person's ability to focus on an activity continuously. Alternating and divided attention are both cognitively demanding. While alternating attention refers to switching attention back and forth from one task or stimulus to another, divided attention involves processing multiple tasks or stimuli simultaneously. We were unable to find specific studies on focused attention, which is the ability to concentrate on a stimulus for any given period (even a small duration), thus, it will not be covered in the present review.

SUSTAINED ATTENTION

From listening to a lecture, reading a book, writing a paper, or watching a movie, sustained attention is crucial to cognitive function and refers to a person's ability to focus on an activity continuously. Thus, sustained attention is unique in that it involves a duration of a fixed time required to perform an activity (Van Zomeren and Brouwer, 1994; Langner and Eickhoff, 2013). Any momentary lapse in sustained attention due to internal thoughts (e.g., remembering to buy milk while attending a lecture) or external stimuli (e.g., construction noise when trying to read a book) can lead to delays or failure to complete a task. Importantly, these momentary lapses depend on the individual's motivation or the difficulty of the task to perform. In general, an extended network, including the right frontal and parietal cortical areas (Pardo et al., 1991) together with subcortical areas, are recruited for an unchallenging or repetitive task, while the left hemisphere is additionally recruited for challenging or demanding tasks (Langner and Eickhoff, 2013).

Esterman and Rothlein (2019) recognized five different neurocognitive models of sustained attention, which are based on the related physiological and cognitive functions: arousal, attentional allocation, cognitive control, opportunity costs, and information processing. The terms vigilance, sustained attention, and arousal have been used interchangeably. Moreover, different levels of arousal are related to different attentional mechanisms. In general, arousal is relevant to sustained attention because it is the baseline amount of attentional resources available to perform a task. Esterman and Rothlein (2019) stated, "activity in the locus-coeruleus (LC) noradrenergic system would reduce background noise and enhance neural (phasic) response to salient stimuli, thus enhancing task-related information processing capacity and reducing signal-to-noise-ratios" (p. 175). Also important is how attentional resources are allocated, and the cognitive control processes required for allocation. In brief, arousal would allow the necessary degree of attentional resources, and cognitive control would regulate and allocate the available resources devoted to a task. These mechanisms are affected by the intrinsic cost of control and motivation. In a low arousal state, there would be fewer cognitive resources to be allocated and so task performance may not be optimal, while in a high arousal/distracted state, there would be enough resources, but attention will be less sustained because it is directed towards task-unrelated processes as well (Esterman and Rothlein, 2019).

In the case of bilinguals, sustained attention is required to focus on the target language for a fixed period while suppressing interference from the language that is not being used. Thus, sustained attention is a crucial attentional mechanism that bilinguals first use. However, compared to other forms of attention, research on the relationship between bilingualism and sustained attention is scarce. The evidence thus far indicates that differences between bilinguals and monolinguals in sustained attention are affected by methodological issues or limited to specific tasks. Bialystok et al. (2009) were the first to investigate control processes related to sustained attention in bilinguals. Young and old adult monolinguals and bilinguals were assessed in working memory, lexical retrieval, and cognitive control. Crucially, one of the cognitive control tasks, the Sustained Attention to Response Task (SART; Robertson et al., 1997), included a sustained attention manipulation, in which participants were told to press the spacebar for digits 1 through 9, except for number 3. The next trial appeared after approximately 250 ms, whereas for digit 3, the next trial appeared after 2,000 ms. While the SART showed the typical aging effects, no language group differences were found.

Similarly, Kousaie et al. (2014) compared monolingual and bilingual young adults, as well as monolingual and bilingual older adults on a battery of executive functioning tasks, including the Stroop task (Stroop, 1935), Simon task (Simon and Rudell, 1967), Wisconsin Card Sorting Test (Berg, 1948; Grant and Berg, 1948), digit span subtest of the Wechsler Adult Intelligence Scale (Wechsler, 2008), and the SART, together with a set of language tasks. French-English bilinguals performed better than their monolingual counterparts in Stroop interference, but no language group differences emerged in any of the other executive function measures or language tasks. On the SART, bilinguals were faster than monolingual francophones, but performed equivalently to monolingual anglophones. However, the two monolingual groups were tested in different locations using different equipment for the SART. Thus, the authors attributed this pattern to either technical discrepancies or cultural differences.

The null effects for bilinguals in sustained attention seem to extend to adults with varied ages of L2 acquisition. Bak et al. (2014) evaluated different levels of attention through the "Test of Everyday Attention" (Robertson et al., 1994) in monolingual and bilingual young adults who acquired L2 at different ages. Data consisted of behavioral measures in sustained attention, selective attention, and attentional switching. While the bilingual effects were driven by selective attention and attentional switching, no differences were found between monolingual and bilinguals in sustained attention. These results were replicated in a subsequent study by Vega-Mendoza et al. (2015).

Although these studies found null results in sustained attention between language groups, two important methodological caveats should be considered. First, it is important to note that all of these studies have only reported behavioral or neuropsychological data but no brain measures. It is possible that the behavioral measures in accuracy for young adults reported by Bak et al. (2014) and Vega-Mendoza et al. (2015) were not sensitive enough to detect language group differences in sustained attention. Young adults are at the height of cognitive function, so language group differences may be more difficult to detect with behavioral measures in this age group. Previous research often finds no differences between groups in behavior, but demonstrate less neural activity for bilinguals than monolinguals, indicating efficiency for the bilinguals (e.g., Bialystok et al., 2005; Abutalebi et al., 2012; Grundy et al., 2017b).

Moreover, response time distributions are not gaussian distributions, so statistical analyses of restricted means typically introduce a bias (Miller, 1991; Ratcliff, 1993). Outlier removal which is a common practice to solve the distribution problem brings trial responses closer to the mean. This process reduces group differences and has recently been stated as a crucial problem in bilingualism research (Zhou and Krott, 2016; Grundy, 2020). For instance, consider the study by Martin and Altarriba (2016) who evaluated English monolinguals and English-Chinese bilingual young adults on cognitive control and sustained attention tasks using ex-gaussian analysis to measure behavioral responses. Similar effects were observed for stimulus-response congruency on the Gaussian part of response distributions, but groups differed on the distribution tails showing reduced tails for bilinguals in the more demanding condition. The authors reported that these effects were driven by enhanced sustained attention and attention monitoring.

Finally, the SART is based on a specific aspect of control which is response inhibition (Bunge et al., 2002). As discussed in Bialystok et al. (2009), better tasks to assess sustained attention in bilinguals may be those that also involve selection or interference resolution. Indeed, using a sustained selective attention task combined with EEG, Krizman et al. (2012) found more brain plasticity for bilinguals in subcortical auditory processing. The authors examined the auditory brainstem response to complex sounds (cABR), an index of auditory encoding, through the Integrated Visual and Auditory Continuous Performance Test (Richmond, VA).[1] For bilinguals, the authors predicted enhanced cABRs to the speech syllable [da] and activation of the fundamental frequency (F0), a feature that underlies pitch perception and is sensitive to experience and perceptual abilities. Results showed that Spanish-English bilinguals had greater subcortical representation of F0, which means that they encoded the stimulus better than English monolinguals, and showed improved sustained selective attention. The authors concluded that through experience-related tuning of attention, the bilingual auditory system is highly efficient in sound processing. Although bilingualism does not appear to influence sustained attention at the behavioral level, using more time-sensitive measures like EEG can capture the precise timing of when these attentional processes diverge between groups.

In sum, several studies have failed to show that bilingualism enhances performance on sustained attention tasks at the behavioral level, but more sophisticated outcome measures (e.g., ex-Gaussian analysis) and neural evidence from an EEG study (Krizman et al., 2012) points to bilingualism enhancing sustained attention. More research is needed to understand what type of bilingual experiences influence sustained attention.

SELECTIVE ATTENTION

We are constantly bombarded with sensory information from the environment. Yet only a fraction of the information spills into our conscious awareness to guide our behaviors. A classic

[1]www.braintrain.com

example of selective attention is the "Cocktail Party Effect" (Cherry, 1953), in which individuals can focus on a single conversation despite multiple conversations happening in their surrounding environment. To maintain attention to a single conversation, a filter informs the brain which pieces of information require immediate attention and which ones can be tuned out. This process is known as selective attention. The filter is especially important because attention is a limited resource and attending to multiple things at once can overload the system. Similar to a spotlight in a theater production that shines a light on the characters and/or objects that are central to the plot, our brain directs attention to relevant information in the environment.

One of the most prominent theories of selective attention is stage-like filter theory of Broadbent (1958). In this theory, physical attributes (e.g., color, tone, and pitch) of all incoming sensory information are extracted. A filter then selects what gains conscious awareness and what gets blocked out. Inputs that are selected for further processing are extracted for semantic features and stored in short-term memory, whereas unattended inputs are filtered out and not processed beyond the extraction of physical attributes. Treisman (1964) extended stage-like filter theory of Broadbent (1958) by proposing that irrelevant signals still go through all processing stages, but their signals are attenuated, similar to the volume knob on a stereo. Evidence in support of this claim comes from research with English-French bilinguals, who were presented with a message in English in one ear and the same message in French in the other ear (Treisman, 1964). Despite being instructed to shadow only one ear, participants noticed that the message in the unattended ear was identical to the message in the attended ear. The unattended signal gains conscious awareness if it passes a certain threshold, which is determined by contextual and semantic information. For example, important words, such as our name, have low thresholds. The attenuation theory can account for why individuals are still able to process the meaning of both attended and unattended messages, similar to the co-activation of the non-target language when only a single language is required.

The mechanism underlying selective attention emerges around 4–6 months of age (Johnson and Tucker, 1996; Amso and Johnson, 2008). One of the earliest milestones in infancy is the ability to shift attention from preferentially looking at the eyes towards preferentially looking at the mouth of a speaker. This shift occurs as the infant is learning a new language. Selectively attending to the mouth of a speaker has been shown to predict expressive vocabulary in both monolingual and bilingual infants (Tsang et al., 2018). Infants raised in multilingual households are required to continuously monitor the incoming speech stream to discern one language from the other. Thus, infants raised with two languages have complex linguistic environments and must adapt to their environment by deploying attentional resources differently.

Lewkowicz and Hansen-Tift (2012) speculated that as infants learn to speak, audio-visual cues from speech sounds and lip movements are perceptually salient and useful for imitation. As they begin to master language, a second shift in attention emerges, such that infants divide their attention between the eyes and mouths to evaluate various social cues (e.g., desires and beliefs). Studies have shown that bilingual infants have an earlier start in the attentional shift from the eye region to the mouth (e.g., Pons et al., 2015; Ayneto and Sebastian-Galles, 2017; c.f. Morin-Lessard et al., 2019 for null results). Pons et al. (2015) had 4-, 8-, and 12-month-old Catalan or Spanish monolingual infants and Catalan-Spanish bilingual infants watch native speakers of each language recite a passage in Spanish or Catalan (native languages) or in English (non-native language). While monolingual infants shifted their attention from the speaker's eyes (4-months of age) to the mouth (8-months of age) to both the eyes and mouth regions in response to the native language only (12-months of age), bilingual infants showed equivalent preference to both the eyes and mouth regions of a speaker at 4- and 8-months of age regardless of the language. The earlier shift in selective attention to the mouth has been observed more in close-language bilinguals (Spanish-Catalan) than distant-language bilinguals (Spanish-"Other"), suggesting that language proximity influences how audiovisual speech cues are evaluated by bilingual infants (Birulés et al., 2018).

Selective attention has also been investigated in infants using the Visual Expectation Cueing Paradigm (VExCP; Baker et al., 2008). In an eye-tracking study, Comishen et al. (2019) compared selective attention processes between 6-month-old infants raised in monolingual households and infants raised in bilingual households on the VExCP paradigm. In this paradigm, a reward can appear in one of two locations. The location of the reward is determined by the presentation of a cue (bullseye or checkerboard). In the pre-switch condition, a cue (i.e., bullseye) predicted the reward on one side of the screen and a different cue (i.e., checkerboard) predicted the reward on the opposite side of the screen. Both groups of participants correctly anticipated the location of the reward. Without any warning, the cue-reward location was switched in the post-switch condition, such that the cues predicted the reward to be on the opposite side of the screen. After the switch, performance of monolingual infants was reduced to chance, but bilingual infants continued to correctly predict the reward's location. Thus, infants raised in bilingual environments distribute their selective attention more efficiently than monolingual infants and are able to create new associations.

Selective attention differences between monolinguals and bilinguals can also be assessed using the visual search paradigm. The visual search paradigm requires participants to search an array for a particular object (target) amongst multiple objects (distractors). The underlying processes involved when performing a visual search task closely resemble those used to navigate our everyday lives, such as having to find a classmate in a filled lecture hall. Visual search tasks are typically composed of two types of searches: feature and conjunction searches. When the distractors differ from the target by only a single feature, there is a pop-out effect and it is easy to pick out the target from the distractor, this is known as a feature search. In contrast, when the distractors are different from the target by two or more features (e.g., searching for a red triangle among red diamonds and blue triangles), this is known as a conjunction search. For conjunction searches, participants search in a serial manner and use top-down control processes to find the target.

Friesen et al. (2015) compared young adult monolinguals and bilinguals on feature and conjunction searches. For conjunction searches, the authors manipulated discriminability by making the distractors similar in color to the target. Bilinguals outperformed monolinguals only on the most difficult condition (low discriminability, conjunction search; c.f. Paap et al., 2018 for contradictory findings). Similarly, Hernández et al. (2012) compared Catalan-Spanish bilinguals and Spanish monolinguals on three visual search conditions that varied in the recruitment of bottom-up and top-down processes. Bilinguals were faster across all conditions and less impacted by the irrelevant information that was maintained in working memory than monolinguals. Both studies show that bilingualism aids in the development of efficient and effective search strategies, specifically when executing top-down processes.

When searching for a target in a display, top-down processes guide eye-movements through the use of contextual and semantic cues from the environment. In an eye-tracking study, Chabal et al. (2015) had monolingual and bilingual young adults perform a multi-modal visual search task. Participants were first presented auditorily with the name of a target object (e.g., dog). A display of eight objects, including the image of the target object, then appeared along with an auditory sound that could be related (e.g., dog barking) or unrelated (e.g., piano keys) to the target object. A unique feature of the visual search paradigm implemented by Chabal and colleagues is that the objects within the search array were meaningful objects rather than shapes, and were visually different from each other, a scenario that is similar to what is experienced in natural environments. The authors found that bilinguals made more fixations to the target and fewer fixations to the distractor, while monolinguals made the same number of fixations to the target and distractors. Therefore, on visual search tasks, monolinguals and bilinguals employ different search strategies, such that bilinguals are more efficient at locating the target than monolinguals. The combined behavioral and eye-tracking findings provide greater insight into how each language group allocates attentional resources and scans their environment. These findings suggest bilingualism provides a boost on more demanding tasks, such as in conjunction searches, and not on feature searches that involve simple detection.

The ambiguous figures task allows for an examination of selective attention abilities given that the task requires participants to selectively attend to the relevant features of an alternative interpretation in order to see the alternate image during the task. Chung-Fat-Yim et al. (2017) presented young adult monolinguals and bilinguals with an unambiguous image that gradually changed to another unambiguous image. Participants had to name the alternate image using the fewest number of cards. The cards in the middle of the spectrum were ambiguous figures, which are optical illusions that produce different perceptions depending on the perceiver's focal point. Bilingual young adults required fewer cards to see the alternative image than monolingual young adults, suggesting that they were able to come to a single interpretation from a myriad of other potential interpretations and focus on the relevant features of the alternate image.

In sum, several studies across the lifespan using different types of paradigms have shown that bilingualism enhances selective attention. In fact, the effects of bilingualism on selective attention can be detected quite early (as early as 6 months of age), such that infants who are raised in a bilingual household show greater attentional control to stimuli in their surroundings than those raised in a monolingual household. Hence, knowing more than one language can expand the mind to perceive and interpret problems, objects, and concepts in more ways than one. As a consequence of being raised in a more linguistically complex environment, do multilingual speakers shift attention from one stimulus to another more readily than monolingual speakers?

ALTERNATING ATTENTION

Alternating attention refers to the rapid shifting of attentional focus due to the inability to process all available information in parallel (Parasuraman, 2000). This includes activities such as reading a book and stopping to answer a phone call, then returning to read the book. According to the model proposed by Posner and Petersen (1990), alternating attention depends on the "orienting network," which is responsible for directing attention to a target stimulus. Parietal regions and the frontal eye fields have been associated with the orienting network (Fan et al., 2005; Vernet et al., 2014), but the basal ganglia and the cerebellum have also been implicated (Ravizza and Ivry, 2001; Ravizza and Ciranni, 2002).

Alternating attention may be involved in bilingual processing due to the need to shift attention between languages. A common task used to measure alternating attention is the Trail Making Test (TMT). Bialystok (2010) reported evidence showing better performance for bilingual children than monolingual children in the TMT. Crucially, this ability to alternate or shift attention is present from infancy (Posner and Raichle, 1994) and develops with age (Trick and Enns, 1998). However, the evidence for bilingual adults using the TMT is scarce and remains unclear. Goral et al. (2015) assessed alternating attention with the TMT, inhibition with the Simon task, and working memory with the Month Ordering Task. Bilingual older adults, who were either dominant bilinguals or balanced bilinguals, were recruited. The authors found that bilingual type (balanced vs. dominant) predicted performance on the inhibitory control task, but not the working memory task. Later, Estanga et al. (2017) examined cognitive performance on the TMT task while measuring cerebrospinal fluid (CSF) AD-biomarkers amongst monolinguals, early bilinguals, and late bilinguals. Only early bilingualism was associated with lower CSF total-tau. CSF did not interact with the TMT performance, but late bilinguals showed better performance than monolinguals on this task, suggesting enhanced alternating attention for this group.

Similarly, those studies which have assessed task switching in bilinguals generally report different effects in samples containing only young adults. Task switching is relevant to bilingualism because the processes recruited by these tasks are similar to the processes bilinguals engage in code switching and language switching. Using a non-verbal switching paradigm, Wiseheart et al. (2016) compared bilingual and monolingual young adults to investigate the transfer of language switching skills to domain-general task switching. While monolinguals and bilinguals performed similarly when switching between tasks in a mixed block (local switch cost), bilinguals had a reduced mixing cost than monolinguals when comparing performance on the mixed block to the pure block (global switch cost). The authors concluded that using multiple languages leads to more flexibility in task switching due to the attentional mechanisms and cognitive control processes related to this task. Prior and Gollan (2011) used a task switching paradigm that included a non-verbal switching task and a language switching task to evaluate the performance of young adults who were either bilingual or monolingual. Spanish-English bilinguals who reported switching between languages frequently had smaller task switching costs than Mandarin-English bilinguals who reported switching between languages less frequently and monolinguals in both switching paradigms. The bilinguals who switched less frequently performed similarly to monolinguals.

Yim and Bialystok (2012) investigated the relationship between code switching frequency and performance in a verbal and non-verbal task switching paradigm. Cantonese-English bilingual young adults completed a non-verbal code switching paradigm together with a verbal fluency task that required language switching. The authors found that those participants who engaged in more conversational code switching had reduced costs in verbal task switching than those who switched languages less frequently. The non-verbal switching task showed similar results to those reported in previous studies but in this case, performance was not associated with the degree of conversational code-switching. The authors concluded that there might be a dissociation between verbal and non-verbal processes related to cognitive control for the mechanism of task switching. Interestingly, highly proficient bilinguals may have comparable switch costs in both directions when switching languages (L1 and L2), which is known as the "symmetrical cost switch," and this process may also be more sensitive to verbal tasks. Calabria et al. (2012) tested the symmetrical cost switch hypothesis in young adults who were highly proficient in Catalan (L1), Spanish (L2), and had a low proficiency in English (L3). All participants completed both a linguistic switching task and a non-linguistic one. The results revealed in this case that highly proficient bilinguals had symmetrical switch costs in the linguistic task but not in the non-linguistic task. However, it is important to note that these effects may be affected by the properties of the task (e.g., cue size). Stasenko et al. (2017) evaluated Spanish-English bilinguals and English monolinguals using the shape-color switching task and an analogous language switching task with varying cue-target intervals (CTI, long vs. short) in both tasks. Overall, with longer CTI bilinguals revealed significantly reduced task switching costs than monolinguals, but this was only seen in the first half of the trials as practice benefited RTs on short CTI trials.

Task switching may also involve other mechanisms affecting outcomes beyond alternating attention. In an fMRI study, Weissberger et al. (2015) tested Spanish-English bilingual adults on both a non-linguistic and a language switching paradigm. While there were no differences between tasks on single and switch trials, there were task differences in the repeat trials in the mixed block together with more widespread activation for the non-linguistic switching task. Thus, the authors concluded that the cognitive benefits associated with bilingualism may not be related to switching or alternating between tasks but instead to the joint activation of the networks needed to sustain inhibition. Interestingly, recent research with infants has shown that infants exposed to a bilingual environment are better at shifting attention to a novel stimulus and alternate attention more frequently than infants exposed to a monolingual environment (D'Souza et al., 2020). These early adaptations to the attentional system during infancy have been found to persist into adulthood (D'Souza et al., 2021). Hence, bilinguals have an edge in situations requiring flexibly switching attention between tasks to meet the demands of their rapidly changing environment.

In sum, different bilingual experiences, including balance of first and second languages, code switching frequency, proficiency, and age of acquisition, all influence performance on tasks measuring alternating attention, and these experiences interact with task parameters.

DIVIDED ATTENTION

Divided attention is the ability to process two or more pieces of information simultaneously. For example, talking on the phone while driving, or doing data analysis while singing along to your favorite song. Researchers sometimes argue that true divided attention is difficult if not impossible for people to do because of a bottleneck at the response-selection stage, during which a response to the first task must be selected before processing begins at the response-selection stage of the second task (Pashler, 1984, 1994; Pashler and Johnston, 1998). This view continues to influence current research (review in Koch et al., 2018), but others have provided evidence that true divided attention can be achieved when response-selection stages overlap between task 1 and task 2 (Watter and Logan, 2006; Thomson et al., 2010; Koob et al., 2021). For example, using a psychological refractory period paradigm (Telford, 1931), Watter and Logan (2006) showed that task 1 response times were faster when task 2 required the same button press as task 1. This demonstrates that the response selection stage for task 2 must have begun prior to the completion of task 1's response selection stage, otherwise, no priming would occur from task 2 to task 1. It is possible that bilingualism modifies divided attention processes. For instance, unbalanced bilinguals speaking in their second language might simultaneously prime their second language representations (task 1) and their first language representations, which may be automatically primed (task 2).

Very few studies have examined the influence of bilingualism on divided attention. Bialystok et al. (2006) had monolingual and bilingual younger and older adults perform two simultaneous classification tasks. Participants had to determine whether a stimulus, auditorily or visually-presented was: (1) a string of letters or digits and (2) an animal sound or musical instrument. They were also instructed to prioritize the visual modality. Younger and older adult bilinguals were more efficient at categorizing visual stimuli than their monolingual counterparts, suggesting enhanced divided attention. In another study, participants classified objects as either human-made or natural and words as concrete or abstract based on a cue provided to examine non-verbal divided attention. Brito et al. (2016) found that simultaneous bilinguals (i.e., acquired both languages before the age of 5) made fewer errors than monolinguals on switch trials. Sequential bilinguals (i.e., learned a second language after the first language but before the age of 15) did not differ significantly from the other two groups, suggesting that only certain bilingual experiences can lead to enhanced divided attention compared to monolinguals. Fernandes et al. (2007) tested younger and older monolingual and bilingual adults on a verbal divided attention task. The primary task involved memorizing a list of words presented auditorily for a subsequent memory test. In the full attention condition, the lists of words were presented without any distractions. However, in the divided attention condition, a secondary task was administered concurrently with the encoding task, in which participants judged whether visually-presented words were smaller or larger in size than a referent object (e.g., "monitor," "CPU," "mouse," or "keyboard"). In contrast to the authors' predictions, bilinguals recalled fewer words than monolinguals in the full and divided attention conditions. These findings may be due to the type of task used. Because this task involved encoding and retrieving *verbal* information, bilinguals may have been at a disadvantage considering they hold on average a smaller vocabulary (Bialystok et al., in press) and are slower to retrieve words (e.g., Gollan et al., 2005; Ivanova and Costa, 2008) in each of their languages compared to their monolingual counterparts. In other words, the bilinguals' cognitive system may have already been taxed from having to remember the verbal information, and with the additional attentional demands required to perform the task, their cognitive resources may have been depleted much more rapidly. Hence, it is important to consider not only the type of attentional process being measured, but also the domain (verbal or non-verbal) under examination.

In sum, the limited evidence suggests that bilingualism may influence divided attention processes, but that these benefits depend on different bilingual experiences (e.g., only for simultaneous and not sequential bilinguals) and different task parameters (e.g., only non-verbal tasks).

DISENGAGEMENT OF ATTENTION

The ability to engage, disengage, and then re-engage attention on an object of interest is a critical process involved in all of the aforementioned forms of attention. In order to shift attention from one location to another, Posner et al. (1982) argued that attention must first disengage from its current location, move to a new location, and finally fixate on the new location. Critically, disengagement of attention might also be a process enhanced by bilingualism (Mishra et al., 2012; Grundy et al., 2017b). Given that bilinguals must continually focus their attention on multiple aspects of linguistic information over the lifespan, it follows that they may have acquired additional practice and become faster at disengaging attention over time from the information that is no longer relevant in order to focus on current task demands. Rapid disengagement from previously-relevant information would help bilinguals perform better on current task demands when the demands switch, but would hinder performance when demands are repeated (Grundy et al., 2017b). Dense-code switching environments, where bilinguals switch languages between and even within sentences (Green and Abutalebi, 2013), would likely promote rapid disengagement of attention from one language in order to engage in another. Training these domain-general processes helps to explain why bilingualism has been shown to have an influence on task switching performance (Prior and MacWhinney, 2010; Hartanto and Yang, 2016; Wiseheart et al., 2016). Evidence in support of bilingualism leading to more rapid disengagement of attention is supported in several studies across the lifespan.

Grundy et al. (2017b) demonstrated that bilinguals showed smaller sequential congruency effects (SCEs) than monolinguals on a flanker task, consistent with the interpretation of more rapid disengagement of attention for bilinguals. SCEs, also commonly known as Gratton effects or conflict adaptation effects (Gratton et al., 1992), reflect the finding that individuals show smaller congruency effects (difference in RT or accuracy between incongruent and congruent trials) following incongruent than congruent trials (**Figure 2**). In essence, SCEs reflect the influence of previous trials on current trial performance and can index the speed at which disengagement occurs. If individuals are slow to disengage attention, they will show larger SCEs, and if individuals are fast to disengage attention, they will show smaller SCEs.

Previous work that has gone unnoticed bolsters the claims by Grundy et al. (2017b showing that bilinguals are likely faster to disengage attention than monolinguals. Using an Attention Network Task (Fan et al., 2002), Costa et al. (2008)

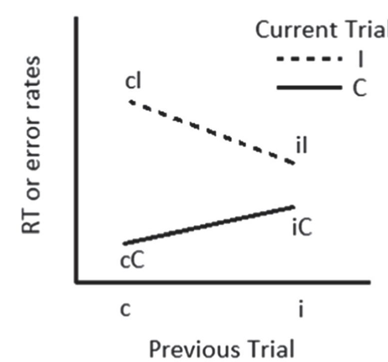

FIGURE 2 | The sequential congruency effect (SCE) is calculated using the following formula: (cI – cC) – (iI – iC). Larger SCEs reflect slower disengagement of attention from previous information on current trial performance. C and c refer to congruent trials. I and i refer to incongruent trials.

examined switch costs between young adult monolinguals and bilinguals. They demonstrated that both groups were slower when responses to congruent trials were preceded by incongruent than congruent trials, but that this "switching cost" was more pronounced for monolinguals than bilinguals. These findings are in line with the SCE findings reported by Grundy et al. (2017b) and consistent with the interpretation that bilinguals disengage attention from previous information more rapidly than monolinguals. More recently, across two experiments, Teubner-Rhodes et al. (2019) showed that trial accuracy decreased for incongruent trials on a Stroop task when preceded by congruent trials (i.e., cI trials) for monolinguals, but not bilinguals. Thus, there is converging evidence that bilinguals show smaller SCEs than monolinguals due to more rapid disengagement of attention.

Some have argued against this position by stating that the group effects for SCEs are not replicable (Goldsmith and Morton, 2018; Paap et al., 2019). Goldsmith and Morton (2018) and Paap et al. (2019) attempted to replicate the patterns observed in the original study by Grundy et al. (2017b) and concluded that the effects were not reliable and that no group differences exist. However, their studies had critical issues with their design features that made the studies non-replications (Grundy and Bialystok, 2019). It is important to note that their studies used long response-to-stimulus intervals (RSI), despite the fact that Grundy and colleagues, in their original 2017 study, clearly argued and demonstrated that group effects were only reliable at shorter (500 ms or less) RSIs. Grundy et al. also showed that when RSIs are long and all individuals have enough time to disengage, the group effects disappear at the behavioral level, but the brain responses show a smaller SCE in the time course for bilinguals than monolinguals. Thus, to date, there is currently only positive evidence for the finding that bilingualism leads to faster disengagement of attention captured by SCEs.

Mishra et al. (2012) provided evidence that within bilinguals, high proficiency bilinguals show a greater inhibition of return effect (IOR) than low proficiency bilinguals and concluded that greater proficiency in a second language leads to more rapid disengagement of attention. The IOR paradigm captures the point at which an irrelevant cue appearing in the target location before presentation of the target becomes inhibitory rather than facilitatory with greater time intervals between cue and target. Earlier and greater IOR effects reflect more rapid disengagement of attention (Posner and Cohen, 1984; Klein, 2000). Saint-Aubin et al. (2018) attempted to replicate the findings by Mishra et al. (2012) study with a different population, but failed to replicate the critical findings. However, without functional brain data, we cannot be certain that the groups were not processing information differently, despite similar behavior. It should also be noted, as previously mentioned, that bilingualism is not a categorical variable (Luk and Bialystok, 2013) and that not all bilingual experiences are the same (de Bruin, 2019); treating them as such risks masking real effects (Grundy, 2020; Leivada et al., 2021). Recent calls in the literature focus on the importance of examining bilingual experiences along a continuum rather than dichotomously.

Grundy et al. (2020) recorded event-related potentials (ERPs) with electroencephalography (EEG) while participants performed the IOR task and showed that there was no difference between low proficiency and high proficiency bilinguals in terms of the IOR effect when examining the groups categorically. Examination of second language proficiency along a continuum revealed a different story—greater second language proficiency reliably predicted greater and earlier IOR effects. Electrophysiological data revealed that disengagement of attention involved multiple cognitive processes across the scalp. Thus, the IOR paradigm provides further evidence that bilingualism leads to more rapid disengagement of attention.

The bivalency effect refers to the slowing that occurs when participants are occasionally presented with a stimulus containing conflicting cues derived from two ongoing tasks. Using a bivalency effect paradigm (e.g., Woodward et al., 2003; Meier et al., 2009; Grundy et al., 2013). Grundy and Keyvani Chahi (2017) showed that bilingual children were less influenced by the appearance of conflicting stimuli while switching between multiple tasks on subsequent non-conflicting stimuli. Grundy and Bialystok (2018) attempted to replicate this pattern in young adults. Considering that young adults are at peak cognitive performance (Hartshorne and Germine, 2015) and behavioral measures often lack the sensitivity to capture subtle differences between groups, the authors tested young adult monolinguals and bilinguals on the bivalency task while EEG was recorded. While bilinguals and monolinguals showed equivalent behavioral performance, event-related potentials demonstrated that monolinguals required greater and longer lasting cognitive processing to handle trials that followed conflict than bilinguals. These findings suggest that younger adult bilinguals are also able to disengage attention more rapidly than monolinguals following conflicting stimuli. Disengagement of attention might contribute to the larger finding that bilinguals are more efficient and faster at processing information on executive function tasks (reviews in Grundy et al., 2017a and Grundy and Chung-Fat-Yim, in press), such that the electrophysiological components associated with attention and conflict monitoring generally appear earlier for bilinguals than monolinguals.

In sum, there is substantial evidence at both the behavioral and neural levels that bilingualism leads to more rapid disengagement of attention from no-longer relevant stimuli. A preliminary experiential contender for more rapid disengagement of attention appears to be greater proficiency in a second language, but other bilingual factors have not yet been explored.

CONCLUSION AND FUTURE DIRECTIONS

The present review provides an overview of the complexity involved in understanding research on bilingualism and attention. Both constructs have often been simplified in the literature, and this runs the risk of masking several ways that different bilingual experiences influence different forms of attention. The evidence outlined in the present review highlights some ways in which bilingualism affects different attentional mechanisms.

Bilinguals appear to develop selective attention abilities earlier than monolinguals possibly as a means of facilitating and promoting language acquisition and discrimination. In other words, attentional resources are recruited in bilinguals to allow them to first recognize which speech sound they heard and from which language. The pattern seems to extend to young adults both at the behavioral (e.g., Chabal et al., 2015; Chung-Fat-Yim et al., 2017) and at the brain (Grundy and Chung-Fat-Yim, in press) level.

Alternating attention is less studied, but the initial findings suggest that whether or not bilingualism enhances alternating attention at the behavioral level depends on whether the switching task includes verbal or non-verbal measures. Neuroimaging studies suggest that EF control mechanisms are crucial when alternating attention between tasks and languages. Most of the evidence comes from young adult populations, but a recent study indicates that the effects may also be present during infancy (D'Souza et al., 2021). Similarly, the literature on divided attention is scarce, making it difficult to determine whether bilingualism influences this type of attention. In this case, the results also vary depending on age of participants, type of task, and the verbal/non-verbal distinction. Importantly, all of these types of attention require participants to engage, disengage, and re-engage attention. The most consistent pattern of findings appears in the literature on attentional disengagement demonstrating that bilinguals are faster and more efficient at disengaging from irrelevant information. Although disengagement of attention is crucial in bilingual processing, more research is needed - especially with regards to which experience-based factors modulate attentional processes.

In order to compare findings across studies, it is important to use tasks that have been well-established in the field. However, the vast majority of the research with young adults has used relatively simple executive function (EF) tasks that often yield fast response times and accuracy rates at ceiling with little variability across participants. In addition, such behavioral measures capture only the endpoint of a dynamic chain of attentional processes. While these simple EF tasks should not be fully abandoned, they do need to be re-evaluated in terms of their purpose in addressing the research questions on bilingualism and cognition. Even in instances where the same task was used across studies, modifications are often implemented to the original designs, such as in the proportion of congruent and incongruent trials, the type of stimulus used (e.g., chevrons versus arrows in the flanker task), the experimental design (i.e., whether a neutral block was included in the paradigm as a control condition), the number of breaks administered to participants, and the visual angle of the stimuli, to name a few, all which likely impact EF performance. As the field continues to embrace the complexity associated with bilingualism by placing individuals along a continuum of language-based factors, the present review sought to highlight the complexity associated with the interaction between attention, task/environmental demands, and bilingualism. Future research should strive to design tasks that account for the types of activities performed on a day-to-day basis in more naturalistic settings. Hence, we echo the recommendations made by Poarch and Krott (2019) for researchers to use more ecologically-valid and age-appropriate tasks.

Furthermore, language-based factors of proficiency and usage are often placed at the forefront, whereas other viable language history measures, although collected, are rarely reported. Few studies, for example, report whether the testing session was conducted in the bilingual's preferred language, despite knowing that this can affect EF outcomes (e.g., Grundy and Timmer, 2017). If the testing session is conducted in the bilingual's non-native language, the results should be interpreted in light of the language of testing and the participants' preferred language. By testing participants in the language they are most comfortable with using, participants may perform at optimal levels, as this would minimize the amount of attentional resources devoted towards language processing.

Bilingualism is not a dichotomous variable (Luk and Bialystok, 2013) and the field is starting to recognize the importance of several bilingual experiences affecting neuroplasticity differently (DeLuca et al., 2019; Pliatsikas et al., 2020; Calabria et al., 2021). This is crucial to consider because failed "replications" using groups of "bilinguals" and "monolinguals" may be examining completely different types of bilinguals that would not be expected to show certain types of neuroplasticity. Thus, one should not expect that all bilinguals will outperform all monolinguals on tasks designed to measure different forms of attention. Even different linguistic contexts influence monolingual EF performance (Bice and Kroll, 2019). Furthermore, a recent large-scale study showed that 80% of their sample ($N = 962$) who self-classified as "monolingual" learned another language at some point (Castro et al., 2022), blurring the line between monolinguals and bilinguals even further. Attentional resources can also affect how people learn a second language, and this has implications for performance. In sum, it is critical that future studies examine the different bilingual experiences and contexts that interact with the various forms of attentional control in order to fully understand how bilingualism affects attention.

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REFERENCES

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., et al. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cereb. Cortex* 22, 2076–2086. doi: 10.1093/cercor/bhr287

Adesope, O. O., Lavin, T., Thompson, T., and Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Rev. Educ. Res.* 80, 207–245. doi: 10.3102/0034654310368803

Amso, D., and Johnson, S. P. (2008). Development of visual selection in 3- to 9-month-olds: evidence from saccades to previously ignored locations. *Infancy* 13, 675–686. doi: 10.1080/15250000802459060

Antoniou, M. (2019). The advantages of bilingualism debate. *Annu. Rev. Linguist.* 5, 395–415. doi: 10.1146/annurev-linguistics-011718-011820

Ayneto, A., and Sebastian-Galles, N. (2017). The influence of bilingualism on the preference for the mouth region of dynamic faces. *Dev. Sci.* 20:e12446. doi: 10.1111/desc.12446

Bak, T. H., Vega-Mendoza, M., and Sorace, A. (2014). Never too late? An advantage on tests of auditory attention extends to late bilinguals. *Front. Psychol.* 5:485. doi: 10.3389/fpsyg.2014.00485

Baker, T. J., Tse, J., Gerhardstein, P., and Adler, S. A. (2008). Contour integration by 6-month-old infants: discrimination of distinct contour shapes. *Vis. Res.* 48, 136–148. doi: 10.1016/j.visres.2007.10.021

Barac, R., Moreno, S., and Bialystok, E. (2016). Behavioral and electrophysiological differences in executive control between monolingual and bilingual children. *Child Dev.* 87, 1277–1290. doi: 10.1111/cdev.12538

Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *J. Gen. Psychol.* 39, 15–22. doi: 10.1080/00221309.1948.9918159

Bialystok, E. (1992). Selective attention in cognitive processing: The bilingual edge. *Adv. Psychol.* 83, 501–513. doi: 10.1016/S0166-4115(08)61513-7

Bialystok, E. (1999). Cognitive complexity and attentional control in the bilingual mind. *Child Dev.* 70, 636–644. doi: 10.1111/1467-8624.00046

Bialystok, E. (2010). Global–local and trail-making tasks by monolingual and bilingual children: Beyond inhibition. *Dev. Psychol.* 46, 93–105. doi: 10.1037/a0015466

Bialystok, E. (2015). Bilingualism and the development of executive function: The role of attention. *Child Dev. Perspect.* 9, 117–121. doi: 10.1111/cdep.12116

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychol. Bull.* 143, 233–262. doi: 10.1037/bul0000099

Bialystok, E., and Craik, F. (2022). How does bilingualism modify cognitive function? Attention to the mechanism. *Psychon. Bull. Rev.* doi: 10.3758/s13423-022-02057-5 [Epub ahead of print].

Bialystok, E., Craik, F. I., Grady, C., Chau, W., Ishii, R., Gunji, A., et al. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *NeuroImage* 24, 40–49. doi: 10.1016/j.neuroimage.2004.09.044

Bialystok, E., Craik, F., and Luk, G. (2009). Cognitive control and lexical access in younger and older bilinguals. *J. Exp. Psychol. Learn. Mem. Cogn.* 35:828. doi: 10.1037/a0015638

Bialystok, E., Craik, F. I., and Ruocco, A. C. (2006). Dual-modality monitoring in a classification task: The effects of bilingualism and ageing. *Q. J. Exp. Psychol.* 59, 1968–1983. doi: 10.1080/17470210500482955

Bialystok, E., Hawrylewicz, K., Grundy, J. G., and Chung-Fat-Yim, A. (in press). The swerve: how childhood bilingualism changed from liability to benefit. *Dev. Psychol.* doi: 10.1037/dev0001376

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196:104644. doi: 10.1016/j.bandl.2019.104644

Birulés, J., Bosch, L., Brieke, R., Pons, F., and Lewkowicz, D. J. (2018). Inside bilingualism: language background modulates selective attention to a talker's mouth. *Dev. Sci.* 22:e12755. doi: 10.1111/desc.12755

Brito, N. H., Murphy, E. R., Vaidya, C., and Barr, R. (2016). Do bilingual advantages in attentional control influence memory encoding during a divided attention task? *Bilingualism* 19, 621–629. doi: 10.1017/S1366728915000851

Broadbent, D. (1958). *Perception and Communication*. London: Pergamon Press.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., and Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron* 33, 301–311. doi: 10.1016/s0896-6273(01)00583-9

Calabria, M., Hernández, M., Branzi, F. M., and Costa, A. (2012). Qualitative differences between bilingual language control and executive control: Evidence from task-switching. *Front. Psychol.* 2:399. doi: 10.3389/fpsyg.2011.00399

Calabria, M., Voits, T., Rothman, J., Robson, H., Marín, L. M., Costumero, V., et al. (2021). The effect of bilingualism on the brain is modulated by language experience. *Alzheimers Dement.* 17:e054437. doi: 10.1002/alz.054437

Carlson, S. M., and Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Dev. Sci.* 11, 282–298. doi: 10.1111/j.1467-7687.2008.00675.x

Castro, S., Wodniecka, Z., and Timmer, K. (2022). Am I truly monolingual? Exploring foreign language experiences in monolinguals. *PLoS One* 17:e0265563. doi: 10.1371/journal.pone.0265563

Chabal, S., Schroeder, S. R., and Marian, V. (2015). Audio-visual object search is changed by bilingual experience. *Atten. Percept. Psychophysiol.* 77, 2684–2693. doi: 10.3758/s13414-015-0973-7

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and two ears. *J. Acoust. Soc. Am.* 25, 975–979. doi: 10.1121/1.1907229

Chung-Fat-Yim, A. (2020). Examining the time course of attention in monolinguals and bilinguals. [dissertation]. Toronto, ON: York University.

Chung-Fat-Yim, A., Poarch, G. J., Comishen, K., and Bialystok, E. (2021). Does language context impact the neural correlates of executive control in monolingual and multilingual young adults? *Brain Lang.* 222:105011. doi: 10.1016/j.bandl.2021.105011

Chung-Fat-Yim, A., Sorge, G. B., and Bialystok, E. (2017). The relationship between bilingualism and selective attention in young adults: Evidence from an ambiguous figures task. *Q. J. Exp. Psychol.* 70, 366–372. doi: 10.1080/17470218.2016.1221435

Comishen, K. J., and Bialystok, E. (2021). Increases in attentional demands are associated with language group differences in working memory performance. *Brain Cogn.* 147:105658. doi: 10.1016/j.bandc.2020.105658

Comishen, K. J., Bialystok, E., and Adler, S. A. (2019). The impact of bilingual environments on selective attention in infancy. *Dev. Sci.* 22:e12797. doi: 10.1111/desc.12797

Costa, A., Hernández, M., and Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: evidence from the ANT task. *Cognition* 106, 59–86. doi: 10.1016/j.cognition.2006.12.013

D'Souza, D., Brady, D., Haensel, J. X., and D'Souza, H. (2020). Is mere exposure enough? The effects of bilingual environments on infant cognitive development. *Royal Soc.* 7:180191. doi: 10.1098/rsos.180191

D'Souza, D., Brady, D., Haensel, J. X., and D'Souza, H. (2021). Early bilingual experience is associated with change detection ability in adults. *Sci. Rep.* 11:2068. doi: 10.1038/s41598-021-81545-5

Damian, M., Ye, W., Oh, M., and Yang, S. (2018). Bilinguals as "experts"? Comparing performance of mono- to bilingual individuals via a mousetracking paradigm. *Biling. Lang. Congn.* 22, 1176–1193. doi: 10.1017/S1366728918000901

de Bruin, A. (2019). Not all bilinguals are the same: a call for more detailed assessments and descriptions of bilingual experiences. *Behav. Sci.* 9:33. doi: 10.3390/bs9030033

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U. S. A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

Donnelly, S., Brooks, P. J., and Homer, B. D. (2019). Is there a bilingual advantage on interference-control tasks? A multiverse meta-analysis of global reaction time and interference cost. *Psychon. Bull. Rev.* 26, 1122–1147. doi: 10.3758/s13423-019-01567-z

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

Estanga, A., Ecay-Torres, M., Ibañez, A., Izagirre, A., Villanua, J., Garcia-Sebastian, M., et al. (2017). Beneficial effect of bilingualism on Alzheimer's disease CSF biomarkers and cognition. *Neurobiol. Aging* 50, 144–151. doi: 10.1016/j.neurobiolaging.2016.10.013

Esterman, M., and Rothlein, D. (2019). Models of sustained attention. *Curr. Opin. Psychol.* 29, 174–180. doi: 10.1016/j.copsyc.2019.03.005

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., and Posner, M. I. (2005). The activation of attentional networks. *NeuroImage* 26, 471–479. doi: 10.1016/j.neuroimage.2005.02.004

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., and Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *J. Cogn. Neurosci.* 14, 340–347. doi: 10.1162/089892902317361886

Fernandes, M. A., Craik, F., Bialystok, E., and Kreuger, S. (2007). Effects of bilingualism, aging, and semantic relatedness on memory under divided attention. *Can. J. Exp. Psychol.* 61, 128–141. doi: 10.1037/cjep2007014

Friesen, D. C., Latman, V., Calvo, A., and Bialystok, E. (2015). Attention during visual search: the benefit of bilingualism. *Int. J. Billing.* 19, 693–702. doi: 10.1177/1367006914534331

Gathercole, V. C., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Viñas Guasch, N., et al. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Front. Psychol.* 5:11. doi: 10.3389/fpsyg.2014.00011

Goldsmith, S. F., and Morton, J. B. (2018). Sequential congruency effects in monolingual and bilingual adults: a failure to replicate Grundy et al. (2017). *Front. Psychol.* 9:2476. doi: 10.3389/fpsyg.2018.02476

Gollan, T. H., Montoya, R. I., Fennema-Notestine, C., and Morris, S. K. (2005). Bilingualism affects picture naming but not picture classification. *Mem. Cogn.* 33, 1220–1234. doi: 10.3758/BF03193224

Goral, M., Campanelli, L., and Spiro, A. III (2015). Language dominance and inhibition abilities in bilingual older adults. *Bilingualism* 18, 79–89. doi: 10.1017/S1366728913000126

Grant, D. A., and Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *J. Exp. Psychol.* 38, 404–411. doi: 10.1037/h0059831

Gratton, G., Coles, M. G. H., and Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *J. Exp. Psychol. Gen.* 121, 480–506. doi: 10.1037/0096-3445.121.4.480

Green, D. (1998). Mental control of the bilingual lexico-semantic system. *Biling. Lang. Congn.* 1, 67–81. doi: 10.1017/S1366728998000133

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Grundy, J. G. (2020). The effects of bilingualism on executive functions: an updated quantitative analysis. *J. Cult. Cogn. Sci.* 4, 177–199. doi: 10.1007/s41809-020-00062-5

Grundy, J. G., Anderson, J., and Bialystok, E. (2017a). Neural correlates of cognitive processing in monolinguals and bilinguals. *Ann. N. Y. Acad. Sci.* 1396, 183–201. doi: 10.1111/nyas.13333

Grundy, J. G., and Bialystok, E. (2018). Monolinguals and bilinguals disengage attention differently following conflict and errors: Evidence from ERPs. *Brain Cogn.* 128, 28–36. doi: 10.1016/j.bandc.2018.11.006

Grundy, J. G., and Bialystok, E. (2019). When a "replication" is not a replication. Commentary: sequential congruency effects in monolingual and bilingual adults. *Front. Psychol.* 10:797. doi: 10.3389/fpsyg.2019.00797

Grundy, J. G., Benarroch, M. F., Woodward, T. S., Metzak, P. D., Whitman, J. C., and Shedden, J. M. (2013). The bivalency effect in task switching: Event-related potentials. *Hum. Brain Mapp.* 34, 999–1012. doi: 10.1002/hbm.21488

Grundy, J. G., and Chung-Fat-Yim, A. (in press). "Domain-general electrophysiological changes associated with bilingualism," in *Understanding Language and Cognition Through Bilingualism*. eds. J. A. E. Anderson, G. Luk and J. G. Grundy (Amsterdam: John Benjamins Publishing Company).

Grundy, J. G., Chung-Fat-Yim, A., Friesen, D. C., Mak, L., and Bialystok, E. (2017b). Sequential congruency effects reveal differences in disengagement of attention for monolingual and bilingual young adults. *Cognition* 163, 42–55. doi: 10.1016/j.cognition.2017.02.010

Grundy, J. G., and Keyvani Chahi, A. (2017). Post-conflict slowing effects in monolingual and bilingual children. *Dev. Sci.* 20:e12488. doi: 10.1111/desc.12488

Grundy, J. G., Pavlenko, E., and Bialystok, E. (2020). Bilingualism modifies disengagement of attention networks across the scalp: A multivariate ERP investigation of the IOR paradigm. *J. Neurolinguistics* 56:100933. doi: 10.1016/j.jneuroling.2020.100933

Grundy, J. G., and Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second. Lang. Res.* 33, 325–340. doi: 10.1177/0267658316678286

Hartanto, A., and Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages: A diffusion-model analysis of the effects of interactional context on switch costs. *Cognition* 150, 10–19. doi: 10.1016/j.cognition.2016.01.016

Hartshorne, J. K., and Germine, L. T. (2015). When does cognitive functioning peak? The asynchronous rise and fall of different cognitive abilities across the life span. *Psychol. Sci.* 26, 433–443. doi: 10.1177/0956797614567339

Hernández, M., Costa, A., and Humphreys, G. W. (2012). Escaping capture: bilingualism modulates distraction from working memory. *Cognition* 122, 37–50. doi: 10.1016/j.cognition.2011.08.002

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

Hommel, B., Chapman, C. S., Cisek, P., Neyedli, H. F., Song, J. H., and Welsh, T. N. (2019). No one knows what attention is. *Atten. Percept. Psychophysiol.* 81, 2288–2303. doi: 10.3758/s13414-019-01846-w

Incera, S., and McLennan, C. T. (2016). Mouse tracking reveals that bilinguals behave like experts. *Biling. Lang. Congn.* 19, 610–620. doi: 10.1017/S1366728915000218

Incera, S., and McLennan, C. T. (2018). Bilingualism and age are continuous variables that influence executive function. *Aging Neuropsychol. Cognit.* 25, 443–463. doi: 10.1080/13825585.2017.1319902

Ivanova, I., and Costa, A. (2008). Does bilingualism hamper lexical access in speech production? *Acta Psychol.* 127, 277–288. doi: 10.1016/j.actpsy.2007.06.003

Jiao, L., Liu, C., Wang, R., and Chen, B. (2019). Working memory demand of a task modulates bilingual advantage in executive functions. *Int. J. Biling.* 23, 102–117. doi: 10.1177/1367006917709097

Johnson, M. H., and Tucker, L. A. (1996). The development and temporal dynamics of spatial orienting in infants. *J. Exp. Child Psychol.* 63, 171–188. doi: 10.1006/jecp.1996.0046

Klein, R. M. (2000). Inhibition of return. *Trends Cogn. Sci.* 4, 138–147. doi: 10.1016/s1364-6613(00)01452-2

Koch, I., Poljac, E., Müller, H., and Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—an integrative review of dual-task and task-switching research. *Psychol. Bull.* 144, 557–583. doi: 10.1037/bul0000144

Koob, V., Ulrich, R., and Janczyk, M. (2021). Response activation and activation–transmission in response-based backward crosstalk: Analyses and simulations with an extended diffusion model. *Psychol. Rev.* doi: 10.1037/rev0000326 [Epub ahead of print].

Kousaie, S., Sheppard, C., Lemieux, M., Monetta, L., and Taler, V. (2014). Executive function and bilingualism in young and older adults. *Front. Behav. Neurosci.* 8:250. doi: 10.3389/fnbeh.2014.00250

Kovács, A. M., and Mehler, J. (2009). Cognitive gains in 7-month-old bilingual infants. *Proc. Natl. Acad. Sci. U. S. A.* 106, 6556–6560. doi: 10.1073/pnas.0811323106

Krizman, J., Marian, V., Shook, A., Skoe, E., and Kraus, N. (2012). Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. *Proc. Natl. Acad. Sci.* 109, 7877–7881. doi: 10.1073/pnas.1201575109

Kroll, J. F., Dussias, P. E., Bogulski, C. A., and Kroff, J. R. V. (2012). "Juggling two languages in one mind: What bilinguals tell us about language processing and its consequences for cognition," in *The Psychology of Learning and Motivation*. ed. B. H. Ross (Cambridge, Massachusetts: Elsevier Academic Press), 229–262.

Kuipers, J. R., and Westphal, K. H. (2021). Auditory processing and high task demands facilitate the bilingual executive control advantage in young adults. *J. Neurolinguistics* 57:100954. doi: 10.1016/j.jneuroling.2020.100954

Langner, R., and Eickhoff, S. B. (2013). Sustaining attention to simple tasks: a meta-analytic review of the neural mechanisms of vigilant attention. *Psychol. Bull.* 139, 870–900. doi: 10.1037/a0030694

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* 144, 394–425. doi: 10.1037/bul0000142

Leivada, E., Westergaard, M., Duñabeitia, J., and Rothman, J. (2021). On the phantom-like appearance of bilingualism effects on neurocognition: (how) should we proceed? *Biling. Lang. Congn.* 24, 197–210. doi: 10.1017/S1366728920000358

Lewkowicz, D. J., and Hansen-Tift, A. M. (2012). Infants deploy selective attention to the mouth of a talking face when learning speech. *Proc. Natl. Acad. Sci. U. S. A.* 109, 1431–1436. doi: 10.1073/pnas.1114783109

Lindsay, G. W. (2020). Attention in psychology, neuroscience, and machine learning. *Front. Comput. Neurosci.* 14:29 doi: 10.3389/fncom.2020.00029

Lowe, C. J., Cho, I., Goldsmith, S. F., and Morton, J. B. (2021). The bilingual advantage in children's executive functioning is not related to language status: A meta-analytic review. *Psychol. Sci.* 32, 1115–1146. doi: 10.1177/0956797621993108

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: interaction between language proficiency and usage. *J. Cogn. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Marian, V., and Spivey, M. (2003). Bilingual and monolingual processing of competing lexical items. *Appl. Psycholinguist.* 24, 173–193. doi: 10.1017/S0142716403000092

Martin, J. M., and Altarriba, J. (2016). "Rapid serial visual presentation: Bilingual lexical and attentional processing," in *Methods in Bilingual reading Comprehension Research*. eds. R. R. Heredia and A. B. Cieślicka. (New York City, New York: Springer), 61–98.

Martin-Rhee, M. M., and Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Biling. Lang. Congn.* 11, 81–93. doi: 10.1017/S1366728907003227

Meier, B., Woodward, T. S., Rey-Mermet, A., and Graf, P. (2009). The bivalency effect in task switching: General and enduring. *Can. J. Exp. Psychol.* 63, 201–210. doi: 10.1037/a0014311

Miller, J. (1991). Reaction time analysis with outlier exclusion: bias varies with sample size. *Q. J. Exp. Psychol.* 43, 907–912. doi: 10.1080/14640749108400962

Mishra, R. K., Hilchey, M. D., Singh, N., and Klein, R. M. (2012). On the time course of exogenous cueing effects in bilinguals: higher proficiency in a second language is associated with more rapid endogenous disengagement. *Q. J. Exp. Psychol.* 65, 1502–1510. doi: 10.1080/17470218.2012.657656

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cogn. Psychol.* 41, 49–100. doi: 10.1006/cogp.1999.0734

Morin-Lessard, E., Poulin-Dubois, D., Segalowitz, N., and Byers-Heinlein, K. (2019). Selective attention to the mouth of talking faces in monolinguals and bilinguals aged 5 months to 5 years. *Dev. Psychol.* 55, 1640–1655. doi: 10.1037/dev0000750

Norman, D. A., and Shallice, T. (1986). "Attention to action," in *Consciousness and Self-Regulation*. eds. R. J. Davidson, G. E. Schwartz and D. Shapiro (Boston, MA: Springer), 1–18.

Paap, K. R., Anders-Jefferson, R., Mason, L., Alvarado, K., and Zimiga, B. (2018). Bilingual advantages in inhibition or selective attention: More challenges. *Front. Psychol.* 9:1409. doi: 10.3389/fpsyg.2018.01409

Paap, K. R., and Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* 66, 232–258. doi: 10.1016/j.cogpsych.2012.12.002

Paap, K. R., Myuz, H., Anders-Jefferson, R., Mason, L., and Zimiga, B. (2019). On the ambiguity regarding the relationship between sequential congruency effects, bilingual advantages in cognitive control, and the disengagement of attention. *AIMS Neurosci.* 6, 282–298. doi: 10.3934/Neuroscience.2019.4.282

Parasuraman, R. (2000). *The Attentive Brain.* Cambridge, Massachusetts: MIT Press.

Pardo, J. V., Fox, P. T., and Raichle, M. E. (1991). Localization of a human system for sustained attention by positron emission tomography. *Nature* 349, 61–64. doi: 10.1038/349061a0

Pashler, H. (1984). Processing stages in overlapping tasks: evidence for a central bottleneck. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 358–377. doi: 10.1037/0096-1523.10.3.358

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. doi: 10.1037/0033-2909.116.2.220

Pashler, H., and Johnston, J. C. (1998). "Attentional limitations in dual task performance," in *Attention*. ed. H. Pashler (Hove, UK: Psychology Press), 155–189.

Pliatsikas, C., DeLuca, V., and Voits, T. (2020). The many shades of bilingualism: language experiences modulate adaptations in brain structure. *Lang. Learn.* 70, 133–149. doi: 10.1111/lang.12386

Poarch, G. J., and Krott, A. (2019). A bilingual advantage? An appeal for a change in perspective and recommendations for future research. *Behav. Sci.* 9:95. doi: 10.3390/bs9090095

Pons, F., Bosch, L., and Lewkowicz, D. J. (2015). Bilingualism modulates infants' selective attention to the mouth of a talking face. *Psychol. Sci.* 26, 490–498. doi: 10.1177/0956797614568320

Posner, M. I., and Boies, S. J. (1971). Components of attention. *Psychol. Rev.* 78, 391–408. doi: 10.1037/h0031333

Posner, M. I., and Cohen, Y. (1984). "Components of visual orienting," in *Attention and Performance X: Control of Language Processes*. eds. H. Bouma and D. G. Bouwhuis (Hillsdale: Erlbaum), 531–556.

Posner, M. I., Cohen, Y., and Rafal, R. D. (1982). Neural systems control of spatial orienting. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 298, 187–198. doi: 10.1098/rstb.1982.0081

Posner, M. I., and Petersen, S. E. (1990). The attention system of the human brain. *Annu. Rev. Neurosci.* 13, 25–42. doi: 10.1146/annurev.ne.13.030190.000325

Posner, M. I., and Raichle, M. E. (1994). *Images of Mind.* New York, USA: W. H. Freeman and Company.

Prior, A., and Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish-English and Mandarin-English bilinguals. *J. Int. Neuropsychol. Soc.* 17, 682–691. doi: 10.1017/S1355617711000580

Prior, A., and MacWhinney, B. (2010). A bilingual advantage in task switching. *Biling. Lang. Congn.* 13, 253–262. doi: 10.1017/S1366728909990526

Qu, L., Low, J., Zhang, T., Li, H., and Zelazo, P. (2016). Bilingual advantage in executive control when task demands are considered. *Biling. Lang. Congn.* 19, 277–293. doi: 10.1017/S1366728914000376

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychol. Bull.* 114, 510–532. doi: 10.1037/0033-2909.114.3.510

Ravizza, S. M., and Ciranni, M. A. (2002). Contributions of the prefrontal cortex and basal ganglia to set shifting. *J. Cogn. Neurosci.* 14, 472–483. doi: 10.1162/089892902317361985

Ravizza, S. M., and Ivry, R. B. (2001). Comparison of the basal ganglia and cerebellum in shifting attention. *J. Cogn. Neurosci.* 13, 285–297. doi: 10.1162/08989290151137340

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., and Yiend, J. (1997). 'Oops!': Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia* 35, 747–758. doi: 10.1016/S0028-3932(97)00015-8

Robertson, I. H., Ward, T., Ridgeway, V., and Nimmo-Smith, I. (1994). *The Test of Everyday Attention (TEA)*. Bury St. Edmunds, UK: Thames Valley Test Company, 197–221.

Saint-Aubin, J., Hilchey, M. D., Mishra, R., Singh, N., Savoie, D., Guitard, D., et al. (2018). Does the relation between the control of attention and second language proficiency generalize from India to Canada? *Can. J. Exp. Psychol.* 72, 208–218. doi: 10.1037/cep0000151

Simon, J. R., and Rudell, A. P. (1967). Auditory S-R compatibility: the effect of an irrelevant cue on information processing. *J. Appl. Psychol.* 51, 300–304. doi: 10.1037/h0020586

Stasenko, A., Matt, G. E., and Gollan, T. H. (2017). A relative bilingual advantage in switching with preparation: Nuanced explorations of the proposed association between bilingualism and task switching. *J. Exp. Psychol. Gen.* 146, 1527–1550. doi: 10.1037/xge0000340

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662. doi: 10.1037/h0054651

Surrain, S., and Luk, G. (2019). Describing bilinguals: a systematic review of labels and descriptions used in the literature between 2005–2015. *Biling. Lang. Congn.* 22, 401–415. doi: 10.1017/S1366728917000682

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *J. Exp. Psychol.* 14, 1–36. doi: 10.1037/h0073262

Teubner-Rhodes, S., Bolger, D. J., and Novick, J. M. (2019). Conflict monitoring and detection in the bilingual brain. *Biling. Lang. Congn.* 22, 228–252. doi: 10.1017/S1366728917000670

Thomson, S. J., Watter, S., and Finkelshtein, A. (2010). Parallel response selection in dual-task situations via automatic category-to-response translation. *Atten. Percept. Psychophysiol.* 72, 1791–1802. doi: 10.3758/APP.72.7.1791

Treisman, A. (1964). Selective attention in man. *Br. Med. Bull.* 20, 12–16. doi: 10.1093/oxfordjournals.bmb.a070274

Trick, L. M., and Enns, J. T. (1998). Lifespan changes in attention: the visual search task. *Cogn. Dev.* 13, 369–386. doi: 10.1016/S0885-2014(98)90016-8

Tsang, T., Atagi, N., and Johnson, S. P. (2018). Selective attention to the mouth is associated with expressive language skills in monolingual and bilingual infants. *J. Exp. Child Psychol.* 169, 93–109. doi: 10.1016/j.jecp.2018.01.002

Van Zomeren, A. H., and Brouwer, W. H. (1994). *Clinical Neuropsychology of Attention.* Oxford, United Kingdom: Oxford University Press.

Vega-Mendoza, M., West, H., Sorace, A., and Bak, T. H. (2015). The impact of late, non-balanced bilingualism on cognitive performance. *Cognition* 137, 40–46. doi: 10.1016/j.cognition.2014.12.008

Vernet, M., Quentin, R., Chanes, L., Mitsumasu, A., and Valero-Cabré, A. (2014). Frontal eye field, where art thou? Anatomy, function, and non-invasive manipulation of frontal regions involved in eye movements and associated cognitive operations. *Front. Integr. Neurosci.* 8:66. doi: 10.3389/fnint.2014.00066

von Bastian, C. C., Blais, C., Brewer, G. A., Gyurkovics, M., Hedge, C., Kałamała, P., et al. (2020). Advancing the understanding of individual differences in attentional control: Theoretical, methodological, and analytical considerations. PsyArXiv [Preprint]. doi: 10.31234/osf.io/x3b9k

von Bastian, C. C., Souza, A. S., and Gade, M. (2016). No evidence for bilingual cognitive advantages: A test of four hypotheses. *J. Exp. Psychol. Gen.* 145, 246–258. doi: 10.1037/xge0000120

Ware, A. T., Kirkovski, M., and Lum, J. (2020). Meta-analysis reveals a bilingual advantage that is dependent on task and age. *Front. Psychol.* 11:1458. doi: 10.3389/fpsyg.2020.01458

Watter, S., and Logan, G. D. (2006). Parallel response selection in dual-task situations. *Percept. Psychophys.* 68, 254–277. doi: 10.3758/BF03193674

Wechsler, D. (2008). Wechsler Adult Intelligence Scale--Fourth Edition (WAIS-IV) [Database record]. APA PsycTests.

Weissberger, G. H., Gollan, T. H., Bondi, M. W., Clark, L. R., and Wierenga, C. E. (2015). Language and task switching in the bilingual brain: Bilinguals are staying, not switching, experts. *Neuropsychologia* 66, 193–203. doi: 10.1016/j.neuropsychologia.2014.10.037

Wickens, C. (2021). Attention: theory, principles, models and applications. *Int. J. Hum. Comput. Interact.* 37, 403–417. doi: 10.1080/10447318.2021.1874741

Wiseheart, M., Viswanathan, M., and Bialystok, E. (2016). Flexibility in task switching by monolinguals and bilinguals. *Biling. Lang. Congn.* 19, 141–146. doi: 10.1017/S1366728914000273

Woodward, T. S., Meier, B., Tipper, C., and Graf, P. (2003). Bivalency is costly: Bivalent stimuli elicit cautious responding. *Exp. Psychol.* 50, 233–238.

Yim, O., and Bialystok, E. (2012). Degree of conversational code-switching enhances verbal task switching in Cantonese-English bilinguals. *Biling. Lang. Congn.* 15, 873–883. doi: 10.1017/S1366728912000478

Zhou, B., and Krott, A. (2016). Data trimming procedure can eliminate bilingual cognitive advantage. *Psychon. Bull. Rev.* 23, 1221–1230. doi: 10.3758/s13423-015-0981-6

Zhou, B., and Krott, A. (2018). Bilingualism enhances attentional control in non-verbal conflict tasks–evidence from ex-Gaussian analyses. *Biling. Lang. Congn.* 21, 162–180. doi: 10.1017/S1366728916000869

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The Nuance of Bilingualism as a Reserve Contributor: Conveying Research to the Broader Neuroscience Community

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The neurological notion of "reserve" arises from an individually observable dissociation between brain health and cognitive status. According to the cognitive reserve hypothesis, high-reserve individuals experience functional compensation for neural atrophy and, thus, are able to maintain relatively stable cognitive functioning with no or smaller-than-expected impairment. Several lifestyle factors such as regular physical exercise, adequate and balanced nutrition, and educational attainment have been widely reported to contribute to reserve and, thus, lead to more successful trajectories of cognitive aging (CA). In recent years, it has become clear that bilingualism is also a potential reserve contributor. Yet, there is little communication between the neuroscience of bilingualism research community and researchers working in the field of CA more generally, despite compelling reasons for it. In fact, bilingualism tends to be overlooked as a contributory factor in the CA literature, or reduced to a dichotomous trait, despite it being a complex experience. Herein, we discuss issues that are preventing recognition of bilingualism as a reserve contributor across all literatures, highlight the benefits of including language experiences as a factor of interest across research disciplines, and suggest a roadmap to better integrate bilingualism and aging moving forward. We close with calls toward a model of aging that examines the contributions across lifestyle factors, including that of bilingual experience.

Keywords: bilingualism, aging, reserve, resilience, dementia

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INTRODUCTION

Dementia is an umbrella term for a set of neurodegenerative diseases [of which Alzheimer's disease (AD) is the most common one] with debilitating symptoms, primarily impairment of memory and other cognitive abilities, eventually leading to loss of autonomy over everyday activities. It is the leading cause of disability for older adults. Increased age is commonly (but not for all types of dementia) a risk factor for development of disease. As the average age of the global population increases, dementia is becoming an increased burden in both societal and financial terms around the world. Dementia was estimated to total to global annual costs of 1.3 trillion USD in 2019, and this figure is projected to reach between 1.7 and 2.8 trillion USD by 2030 (World Health Organization [WHO], 2021). Even in non-clinical aging, numerous cognitive processes and their neural underpinnings are known to naturally degrade (Fletcher et al., 2018; Salthouse, 2019). As there is currently no pharmacological cure of dementia, increasingly more interest has been devoted to understanding the factors that can help delay the onset of cognitive aging (CA) symptoms and promote the longevity of healthy life and cognition. Tackling dementia *via* preventive or treatment measures has thus been defined as a top societal and scientific priority (Winblad et al., 2016).

Given the absence of a cure, it is important to identify and study factors that contribute to cognitive resilience in healthy older individuals and people with dementia (Austad et al., 2019). Indeed, engagement in certain activities and lifestyle choices has been shown to lead to more successful CA outcomes (Harada et al., 2013). Bilingualism is one such component that holds promise as a lifestyle enrichment factor and a non-pharmacological contributor to delayed onset of dementia symptoms leading to preserved quality of life throughout aging. The effects of bilingualism on CA have been relatively widely reported in studies where language experiences themselves are of primary interest. Yet, it is seldom acknowledged in this capacity and often omitted from the relevant parallel literatures examining healthy and pathological aging from a clinical perspective. In other words, unlike other factors that are shown to affect neurocognitive outcomes in the older age, bilingualism is often overlooked. To illustrate this point, at the time of writing, a search for "bilingualism" and "aging" on PubMed returns only 344 results. This is in stark contrast to other lifestyle factors known to affect CA trajectories – for example "exercise" and "aging" yields 28,829 results, while "diet" and "aging" yields 25,480 results. The discrepancy between these figures clearly signals the perception of bilingualism as a factor of lesser interest in the context of understanding CA trajectories and outcomes. But why would that be? We submit that there are good reasons to consider bilingualism as part of a set of lifestyle experiences, known to affect CA and call for researchers across disciplines to consider including bilingualism as a covariate of interest moving forward. Collecting language background data across the wider neuroscientific domain (including clinical research) would help to capture some variance in the data that is currently left unaccounted for, while generating a wealth of language demographics of interest to bilingualism researchers. Herein, we discuss the need to convey bilingualism as a factor of interest to the broader neuroscience community and provide a roadmap for future directions in bilingualism and aging research.

RESERVE AND RESILIENCE

Cognitive aging is characterized by a marked decline across domains of cognition that can be observed starting from early adulthood (Salthouse, 2004). Nonetheless, there is individual variability in CA trajectories that becomes especially pronounced when facing neurodegeneration. As an example, AD pathophysiology is characterized by accumulation of abnormally folded amyloid-β peptide deposits or plaques in the brain, which are causally linked to further neurodegenerative processes (Scheltens et al., 2016). However, the correlation between amyloid burden on the brain and cognitive impairment is weak (Scarmeas and Stern, 2004). In fact, it is not uncommon to find amyloid deposits in the brains of people with no cognitive impairment at all (Aizenstein et al., 2008). This individual variability in cognitive outcomes in face of neural decline has been attributed to the notions of cognitive reserve (CR), brain reserve (BR), and brain maintenance (BM) (Stern, 2002; Stern et al., 2020).

The concepts of CR, BR, and BM have often been used to refer to similar and overlapping, yet diverse phenomena across different studies. To address this heterogeneity of terminology employed in the literature, a recently proposed consensus framework (Collaboratory on Research Definitions for Reserve and Resilience in Cognitive Aging and Dementia, 2022) suggests the following definitions. BR "reflects the neurobiological status of the brain at any point in time." Those individuals who have greater BR from the outset, can tolerate more depletion before onset of any symptoms, i.e., BR translates to greater resilience against age- or disease-related structural atrophy over time. CR, on the other hand, is a theoretical concept that can be defined as a "property of the brain that allows for cognitive performance that is better than expected given the degree of life-course related brain changes and brain injury or disease." As such, individuals who cognitively perform above expected for their levels of neural atrophy (or show no impairment at all, even with marked structural neural decline), are thought to exhibit high levels of CR. The framework also refers to BM, "the relative absence of changes in neural resources or neuropathologic change over time as a determinant of preserved cognition in older age." As bilingualism has been argued to contribute to different types of reserve at different stages of life, and the exact relationship between BR, CR, and BM is unclear, we refer to improved CA outcomes as evidence for increases in *reserve* throughout the manuscript.

Previous research has identified many lifestyle predictors for greater reserve and more successful CA trajectories. These include occupational (Boots et al., 2015) and educational attainment (Mungas et al., 2018; Chan et al., 2021), sustained physical exercise (Sanchez-Lopez et al., 2018), healthy nutrition (Morris, 2012), increased social activity (Wilson et al., 2007), abstinence from smoking (Yaffe et al., 2009), general engagement in demanding cognitive activities (Wilson et al., 2021), and bilingualism (Bialystok et al., 2007; Bialystok, 2021). Reserve is built up over one's lifetime, but continues to develop even in older age, where a combination of life experiences and lifestyle contribute to resilience against declines associated with aging (Burke et al., 2019). It has also been suggested that promoting reserve can be especially effective in populations that are genetically predisposed to dementia (Dekhtyar et al., 2019). Although there is plenty of evidence for reserve from epidemiological data, the neural basis of it is not as well understood (Steffener and Stern, 2012).

BILINGUALISM AS A RESERVE CONTRIBUTOR

Why should bilingualism contribute to reserve? The answer to this question lies in the neurocognitive demands induced by managing two (or more) languages in the mind/brain. All available languages are activated in the bilingual or multilingual individual's mind (Marian and Spivey, 2003). Therefore, bilingual language control requires engagement of cognitive control processes, so that the appropriate language is used in any given communicative context without undue interference of elements from any other languages. Given that all one's languages maintain a level of activation at all times, bilingualism is a type of demanding cognitive activity that puts an extra strain on the brain and requires constant engagement of executive control and attentional resources (Bialystok and Craik, 2022). As the brain is a plastic organ that adapts to varied demands over time, the mental exercise of bilingual language control reinforces the brain structurally and affords stronger functional connectivity across the lifespan (Perani and Abutalebi, 2015). Indeed, there is currently over a decade's worth of literature on neurocognitive adaptations in response to bilingualism, especially in aging populations where effects on CA trajectory and delayed onset of dementia/mild cognitive impairment (MCI) symptoms have been reported (see Gallo et al., 2022, for a recent review).

Literature to date seems to suggest that engagement with bilingual language use leads to a pattern of results corresponding with an interpretation of structural reserve (either BR or BM – in cross-sectional studies it is impossible to tell if structural differences observed are due to a greater initial baseline, a greater resilience to decay over time or, perhaps, a combination of both) in healthy older populations and a compensatory account of reserve (corresponding to the notion CR) in clinical populations, although the relationship is not always clear across different studies. In healthy aging populations bilinguals have been shown to have greater white matter volume (Olsen et al., 2015) and integrity (Luk et al., 2011; Anderson et al., 2018) across a variety of tracts and regions. In terms of gray matter, bilinguals, when compared to monolinguals, exhibit greater gray matter volume across anterior (Abutalebi et al., 2014), parietal (Abutalebi et al., 2015), temporal regions of the brain (Olsen et al., 2015), and the hippocampus (Voits et al., 2022). Evidence of structural reserve has also been found in bimodal bilinguals, showing that effects are not specific to spoken languages (Li et al., 2017). Any structural differences based on language groups seem to be on the account of better maintenance of existing structures over time (as opposed to growth of implicated areas) (Borsa et al., 2018; DeLuca and Voits, 2022), with a tendency for a more rapid decline in more advanced age, as this type of reserve gets exhausted (Heim et al., 2019). Functionally, older bilinguals exhibit greater neural efficiency by recruiting fewer neural resources than their monolingual counterparts to carry out a cognitive task (Gold et al., 2013; Anderson et al., 2021). Furthermore, language status has been shown to be a predictive factor in neural chemistry – bilingualism has been linked to a smaller concentration of AD biomarkers in cerebrospinal fluid, suggesting lower dementia risk in later life (Estanga et al., 2017), and metabolite concentration gradients in structures heavily implicated in cognitive control, which may potentially be a driving force for structural adaptations observed on a macroscopic scale (Pliatsikas et al., 2021).

Evidence for a compensatory account of reserve tends to manifest in studies where clinical aging populations are of interest whose brains have already been subject to structural decay. When matched on cognitive ability, bilingual individuals with AD show greater brain atrophy, suggestive of a compensatory reserve account (Schweizer et al., 2012; Duncan et al., 2018). Bilinguals also exhibit greater cerebral hypometabolism, cognitive performance being equal (Perani et al., 2017; Sala et al., 2022). Incidentally, when matched on brain health in older age where cognitive decline may occur, bilinguals seem to maintain their cognitive status, at a stage where some monolinguals start to exhibit symptoms of decline (Berkes et al., 2021). Taken together, this can be interpreted as bilinguals being able to compensate for neural tissue loss *via* potential formation of alternative neural networks or more efficient use of the resources available. In other words, bilinguals in either very advanced age or atypical aging are able to do more with less. Although the evidence presented so far on bilingualism and aging may seem contradictory at first glance, recent proposals suggest the accounts of bilingualism affecting BR and CR are in fact two different snapshots of the same overarching trajectory. In the first instance, BR manifests as preserved neural structure, whereas CR appears later and manifests as a dissociation between structure and cognition; specifically, preserved cognitive status despite accelerating neural decline (Bialystok, 2021). However, note that the relationship between and the neural basis of BR and CR is still not clear.

The first examination of bilingualism in connection with dementia symptom onset was a study investigating medical case records of monolingual and bilingual memory clinic patients, suggesting a 4-year later onset of dementia symptoms in bilingual individuals (Bialystok et al., 2007). This finding has been subsequently both supported (Craik et al., 2010; Clare et al., 2014; Woumans et al., 2015; Zheng et al., 2018) and contradicted (Yeung et al., 2014; Zahodne et al., 2014; Lawton et al., 2015) across various bilingual populations. Recent meta-analyses, however, have shown convincingly that bilingualism does indeed lead to a later expression of dementia symptoms, although the incidence is not affected by language status (Anderson et al., 2020; Brini et al., 2020; Paulavicius et al., 2020). Bilingualism effects appear independent of other confounders, such as education and migrant status (Alladi et al., 2013). Some studies have linked multilingualism (as opposed to bilingualism) to later symptom onset (Chertkow et al., 2010) and better cognition in healthy aging (Kavé et al., 2008), although bi- vs. multilingual effects remain under-researched.

Similar findings have been reported for MCI – where bilingualism has been found to delay symptom onset by as much as 7.4 years (Ramakrishnan et al., 2017; Calabria et al., 2020). More recently, a later onset of MCI symptoms followed by a more rapid decline and conversion to AD has been reported in bilinguals (Berkes et al., 2020). This finding is in line with the notion of a structural type of reserve, that, as the neural resources become exhausted, tips over to a more compensatory account. Finally, a population-level study revealed that countries where bilingualism was more prevalent reported lower incidence of dementia, lending further support to the notion of the protective nature of bilingualism on a much larger scale (albeit with less nuance) than any individual study can provide (Klein et al., 2016).

In addition to effects of MCI and AD, bilingualism has also been shown to correlate with less severe outcomes in acute neuropathology, such as stroke (Alladi et al., 2016; Paplikar et al., 2018). Moreover, it has been suggested to be a more general protective factor across other types of dementia where increases in reserve (*via* factors other than bilingualism) have been shown to lead to a more successful course of disease (Voits et al., 2020). Due to the mounting literature demonstrating bilingualism as a factor that leads to longer healthy aging and better cognitive outcomes in disease, bilingualism and language learning in the older age have been suggested as a viable public health strategy against CA and dementia (Bubbico et al., 2019), especially in low- and middle-income countries, where promoting reserve *via* other means can be difficult (Mendis et al., 2021).

Despite results showing bilingualism as a factor of interest, studies with otherwise comprehensive designs have omitted any mention of it completely. To provide some examples, Wirth et al. (2014) combined measures of education, cognitive activity, and physical activity with a set of biomarkers and related those to cognitive functioning and brain structure. However, bilingualism was not considered as a variable of interest. In a similar manner, Sowa et al. (2016) studied lifestyle and psychosocial patterns as predictors of healthy CA in Europe (where considerably more than half of the population can communicate in more than one language). While we applaud the consideration of many predictors of interest, the omission of language background and/or experience is a missed opportunity. As a final example, Darwish et al. (2018) examined links between education, occupational attainment, leisure activities and global cognitive functioning in an Arabic-speaking sample. In the demographic information, the authors report that 20.5% of participants spoke another language in addition to Arabic. Yet this factor was not included in statistical models, although, we maintain, it would be useful to see if it captures any of the variance in the data. While all the above are examples of well-conducted research, we aim to draw attention to the fact that they might have benefited from inclusion of a bilingualism measure and that future research should consider doing so, where possible. Bilingualism holds the promise of a significant reserve contributor factor and omitting this information is detrimental to the pursuit of better understanding the aggregate effects of lifestyle choices and experiences on CA outcomes.

Finally, although reserve (specifically CR) is often quantified *via* a proxy measure (years of education is a commonly used one) a set of CR measures have been developed over the years, in the form of self-reported questionnaires (Kartschmit et al., 2019). These tools are relatively quick and easy to administer and attempt to cover the life experiences and factors known to contribute to CR increases. However, in some cases, questions regarding individuals' language background and experience are not included at all (e.g., CRIq; Nucci et al., 2012), or if they do, it is probed with a single question (e.g., CRQ, Rami et al., 2011; CRS, Leoñ et al., 2014). As we discuss below, this cannot provide sufficient richness of data to make any further inferences about the contributions of aspects of bilingualism that can lead to differential neurocognitive and health outcomes.

A COMPLEX LIFETIME OF EXPERIENCES

The picture painted above makes bilingualism appear an attractive lifestyle factor to investigate, not only within the remit of psychological and language sciences but also as a factor of interest in medical research, especially given the ubiquity with which language is used on a daily basis and across nearly every context in life. However, the diverse contexts and requirements for language use also entail a high degree of complexity in bilingual experience (see for Discussion, Titone and Tiv, 2022) and with it a potentially wide range of outcomes in terms of neurocognitive adaptations that would provide the basis for reserve accrual and deployment.

The complexity or degree of engagement in specific lifestyle factors is a widely accepted notion across other areas of aging research. Take, as an example, physical activity and the notion that it delays cognitive decline. It is not simply enough to practice once a week. In a longitudinal study Larson et al. (2006) followed cognitively normal older adults, and reported that those individuals who exercised three or more times per week were more likely to remain dementia-free during the 6-year follow-up period, independent of other risk factors. Likewise, Erickson et al. (2010) show that the amount of walking as a proxy of physical exercise was predictive of higher gray matter volume measured over a 9-year period. Specifically, walking more than 72 blocks/week was the threshold determined for protection against age-related changes in the hippocampus, prefrontal, and temporal brain regions. The amount of physical activity was also associated with a lower risk of developing MCI or dementia during the 9-year follow up. Translated to the bilingualism and neuroprotection field some parallels can be drawn: it should be the degree of second language engagement (usage, exposure, etc.) that provides the turning point. As outlined by Abutalebi et al. (2014) in a study on healthy bilingual seniors from Hong Kong, only those individuals who were still actively using their second language reported greater gray matter volumes in the temporal poles. Equally proficient bilinguals but with less engagement (i.e., usage of the second language) did not exhibit an equivalent level of neuroprotection.

A growing consensus in the field notes that bilingual language experience should not be reduced to a dichotomous distinction of "monolingual vs. bilingual" (just like physical activity should not be dichotomized as only "active vs. sedentary"). Rather it ought to be treated as a spectrum of experiences, where factors within bilingualism (such as age of acquisition, patterns and psychosocial contexts of language use, engagement and disengagement with languages over time) play a role and lead to differential adaptations in the brain (Green and Abutalebi, 2013; DeLuca et al., 2019, 2020; Beatty-Martínez et al., 2020; Pliatsikas, 2020; Gullifer et al., 2021). However, treating bilingualism as a continuous measure in research is relatively new in the field of bilingual neurocognition, and at present has only rarely been applied to aging. Several reasons may determine this. First, capturing and quantifying one's bilingual experience is not a simple undertaking. At present, bilingualism is typically quantified as a composite of factor scores, based on self-reported language background and language use *via* questionnaires. Such questionnaires include the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007), Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018; see also Anderson et al., 2020 for a version applied specifically to aging), and Language History Questionnaire (LHQ3.0; Li et al., 2020). Moreover, recent evidence suggests that social context may both delineate these language experiences and have an impact on bilingualism-related neurocognitive outcomes in their own right (Bice and Kroll, 2019; Gullifer and Titone, 2020; Kałamała et al., 2021; Titone and Tiv, 2022).

It is clear that bilingualism is a complex lifetime of experiences. The bilingualism literature has shifted from a dichotomous, group-level analysis to one investigating individual differences by testing variables that make up one's bilingual experiences and shows a gradient of neurocognitive adaptation commensurate with degree of experience (e.g., Kuhl et al., 2016; Gullifer et al., 2018; Sulpizio et al., 2020; Chung-Fat-Yim et al., 2021). Given the research showing the utility of an individual differences approach in young adults, it is prudent to contend with how these variations in bilingual experience might affect the trajectory of CA, particularly when juxtaposed against the variability within other lifestyle factors.

FUTURE DIRECTIONS IN BILINGUALISM AND AGING RESEARCH

To summarize the above, research to date has shown bilingualism as a reserve contributor, although a truly interdisciplinary recognition of such findings has not come to be. We submit that this presents a limitation – to appreciate the effects of lifestyle choices and life experiences on CA more holistically, language background/experience should be considered alongside other reserve contributor factors and crucially in some nuance. While initial studies in the field bilingualism and neurocognition assessed bilingualism effects in absence of a more complete set of demographic, lifestyle, and background information as a necessary first step in this research program, it is imperative that nuanced information capturing individual variety across multiple domains of life gets collected moving forward. Equally, omitting bilingualism as a factor of interest does disservice to the pursuit of understanding individual variability in trajectories and outcomes of CA. This spans research focusing on both healthy aging and disease.

It can be argued that currently there is little interdisciplinary conversation between the bilingualism and the brain literature and the medical/neuroscientific community commonly concerned with aging research from a clinical perspective. Findings on bilingualism as a factor that has serious implications for CA outcomes primarily come from the former and tend to be published in linguistics, language sciences, and psychology journals that are seldom on the radar of medical professionals. This lack of connection/communication is something we hope will change moving forward.

To bridge this gap and solidify the status of bilingualism as a reserve contributor, research involving bilingualism needs to be conducted more akin to medical research. On the one hand this means starting collaborations with medical/neurological facilities and aging centers where typically studies on cognitive decline and dementia are carried out, and on the other, employing typical medical research protocols such as those that compare between different factors such as pharmacological studies and large-scale longitudinal studies similar to the Betula (Nilsson et al., 1997) or the Lothian Birth Cohort studies (Deary et al., 2007, 2012; see Bak et al., 2014, for a study focusing on bilingualism based on the Lothian Birth Cohort data). Similarly, large-scale population studies are also needed that would consider bilingualism together with other predictive factors and experiences. Studies based on already existing databases of neural and cognitive data can also be helpful [such as the Cambridge Centre for Ageing and Neuroscience (Cam-CAN) repository (Taylor et al., 2017)] provided future datasets like these have information on language experiences and bilingual language use patterns. A wealth of longitudinal data could also be collected with relative ease from patients as they present to memory clinics and even healthy individuals who may be invited to attend regular cognitive check-ups as they age and provide data on their language background and use. However, this is not an easy task for any individual research lab. Coordination and multi-lab collaborations would allow for not only capturing diversity of language contexts but also be helpful in identifying any possible interaction of language use by context on aging (for a roadmap on multi-lab collaborations, see Leivada et al., 2021). Finally, such collaborations would also provide adequate sampling power to more robustly test the effects of multiple complex life experiences on CA trajectories.

A key factor to consider, however, is the operationalization and quantification of bilingual experiences moving forward. One needs to be mindful of the fact that bilingualism is a multifaceted and multidimensional life experience that can be difficult to gauge and quantify, yet future research should embrace this complexity in a responsible manner. We need to move beyond asking simplistic questions that lead to a false dichotomous collapsing across groups and find a way to address the complexity of language experience. Large datasets alone cannot act as a substitute for detailed data that acknowledges the complexity of bilingual experience (see, e.g., Nichols et al., 2020). However, one needs to consider the practicality for including lengthy questionnaires tapping in language experiences in medical practice. By definition, it will need to be a balancing act between attempts to capture as much variance and detail as possible, and the practical feasibility of implementing such tools.

To note, collecting language background information is important not only for those who self-identify as bilinguals, but also those who consider themselves monolingual – as variability in exposure to foreign languages and dialects can be observed even within this group (Castro et al., 2022) and passive language experiences can have observable effects on brain function (Bice and Kroll, 2019; Bice et al., 2020). There is variability even in the monolingual end of the -lingualism spectrum that may be deterministic for CA trajectories.

Finally, the most straight-forward way ahead at present is to conduct comparative studies where bilingual experiences are evaluated in the context of one's wider life experiences and lifestyle choices. And thus, a well-designed study would test one's linguistic background and language use patterns across the lifespan but do so together with information about other factors that are known to contribute to differential outcomes in older age. In essence, future research should try to build complex individual neurocognitive profiles to tease apart individual contributions of reserve contributor factors. Such combined datasets would afford the evaluation of one's cognitive status, structural/functional brain health and also provide insights on the individual and combined effects of bilingualism and other reserve contributor factors.

To conclude, bilingual language experiences have already been shown to affect the mind and brain, across the lifespan and in older populations. It is now essential to work toward solidifying bilingualism (as the multidimensional, rich set of experiences that it is) as a factor of interest in the CA/medical field and clearly communicate findings of bilingualism as a reserve contributor to the medical and clinical aging literatures. Future research needs to measure and quantify individual language experiences and test what language use behaviors and practices contribute most to successful CA outcomes, while also being mindful of the fact that bilingualism is one of several predictive experiences of one's lifetime.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TV, VD, and JA contributed to the conception of the manuscript. TV wrote the first draft of the manuscript. VD and JA wrote sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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REFERENCES

Abutalebi, J., Canini, M., Della Rosa, P. A., Green, D. W., and Weekes, B. S. (2015). The neuroprotective effects of bilingualism upon the inferior parietal lobule: A Structural Neuroimaging Study in Aging Chinese Bilinguals. *J. Neurolinguist.* 33, 3–13. doi: 10.1016/j.jneuroling.2014.09.008

Abutalebi, J., Canini, M., Della Rosa, P. A., Sheung, L. P., Green, D. W., and Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiol. Aging* 35, 2126–2133. doi: 10.1016/j.neurobiolaging.2014.03.010

Aizenstein, H. J., Nebes, R. D., Saxton, J. A., Price, J. C., Mathis, C. A., Tsopelas, N. D., et al. (2008). Frequent amyloid deposition without significant cognitive impairment among the elderly. *Arch. Neurol.* 65, 1509–1517. doi: 10.1001/archneur.65.11.1509

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K., et al. (2013). Bilingualism delays age at onset of dementia, indipendent of education and immigration status. *Neurology* 81, 1938–1944. doi: 10.1212/01.WNL.0000437347.92583.fc

Alladi, S., Bak, T. H., Mekala, S., Rajan, A., Chaudhuri, J. R., Mioshi, E., et al. (2016). Impact of Bilingualism on Cognitive Outcome After Stroke. *Stroke* 47, 258–261. doi: 10.1161/STROKEAHA.115.010418

Anderson, J. A. E., Grundy, J. G., De Frutos, J., Barker, R. M., Grady, C., and Bialystok, E. (2018). Effects of bilingualism on white matter integrity in older adults. *NeuroImage* 167, 143–150. doi: 10.1016/j.neuroimage.2017.11.038

Anderson, J. A. E., Grundy, J. G., Grady, C. L., Craik, F. I. M., and Bialystok, E. (2021). Bilingualism contributes to reserve and working memory efficiency: Evidence from structural and functional neuroimaging. *Neuropsychologia* 163:108071. doi: 10.1016/j.neuropsychologia.2021.108071

Anderson, J. A. E., Hawrylewicz, K., and Bialystok, E. (2020). Who is bilingual? Snapshots across the lifespan. *Bilingualism* 23, 929–937. doi: 10.1017/S1366728918000950

Anderson, J. A. E., Hawrylewicz, K., and Grundy, J. G. (2020). Does bilingualism protect against dementia? A meta-analysis. *Psychonomic Bull. Rev.* 27, 952–965. doi: 10.3758/s13423-020-01736-5

Anderson, J. A. E., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Austad, S. N., Wood, M. A., Villeda, S. A., Voss, J. L., Sahay, A., and Albert, M. (2019). Innovative approaches in cognitive aging. *Neurobiol. Aging* 83, 150–154. doi: 10.1016/j.neurobiolaging.2019.04.013

Bak, T. H., Nissan, J. J., Allerhand, M. M., and Deary, I. J. (2014). Does bilingualism influence cognitive aging? *Ann. Neurol.* 75, 959–963. doi: 10.1002/ana.24158

Beatty-Martínez, A. L., Navarro-Torres, C. A., Dussias, P. E., Bajo, M. T., Guzzardo Tamargo, R. E., and Kroll, J. F. (2020). Interactional context mediates the consequences of bilingualism for language and cognition. *J. Exper. Psychol.* 46, 1022–1047. doi: 10.1037/xlm0000770

Berkes, M., Bialystok, E., Craik, F. I. M., Troyer, A., and Freedman, M. (2020). Conversion of Mild Cognitive Impairment to Alzheimer Disease in Monolingual and Bilingual Patients. *Alzheimer Dis. Associated Disord.* 34, 225-230. doi: 10.1097/WAD.0000000000000373

Berkes, M., Calvo, N., Anderson, J. A. E., and Bialystok, E. (2021). Poorer clinical outcomes for older adult monolinguals when matched to bilinguals on brain health. *Brain Struct. Funct.* 226, 415–424. doi: 10.1007/s00429-020-02185-5

Bialystok, E. (2021). Bilingualism: Pathway to Cognitive Reserve. *Trends Cogn. Sci.* 25, 355-364. doi: 10.1016/j.tics.2021.02.003

Bialystok, E., and Craik, F. I. M. (2022). How does bilingualism modify cognitive function? Attention to the mechanism. *Psychonomic Bull. Rev.* 0123456789. doi: 10.3758/s13423-022-02057-5 [Epub ahead of print].

Bialystok, E., Craik, F. I. M., and Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia* 45, 459–464. doi: 10.1016/j.neuropsychologia.2006.10.009

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196:104644. doi: 10.1016/j.bandl.2019.104644

Bice, K., Yamasaki, B. L., and Prat, C. S. (2020). Bilingual language experience shapes resting-state brain rhythms. *Neurobiol. Lang.* 1, 288–318. doi: 10.1162/nol_a_00014

Boots, E. A., Schultz, S. A., Almeida, R. P., Oh, J. M., Koscik, R. L., Dowling, M. N., et al. (2015). Occupational complexity and cognitive reserve in a middle-Aged cohort at risk for Alzheimer's Disease. *Arch. Clin. Neuropsychol.* 30, 634–642. doi: 10.1093/arclin/acv041

Borsa, V. M., Perani, D., Della Rosa, P. A., Videsott, G., Guidi, L., Weekes, B. S., et al. (2018). Bilingualism and healthy aging: Aging effects and neural maintenance. *Neuropsychol.* 111, 51–61. doi: 10.1016/j.neuropsychologia.2018.01.012

Brini, S., Sohrabi, H. R., Hebert, J. J., Forrest, M. R. L., Laine, M., Hämäläinen, H., et al. (2020). Bilingualism Is Associated with a Delayed Onset of Dementia but Not with a Lower Risk of Developing it: a Systematic Review with Meta-Analyses. *Neuropsychol Rev.* 30, 1–24.

Bubbico, G., Chiacchiaretta, P., Parenti, M., di Marco, M., Panara, V., Sepede, G., et al. (2019). Effects of Second Language Learning on the Plastic Aging Brain: Functional Connectivity, Cognitive Decline, and Reorganization. *Front. Neurosci.* 13:423. doi: 10.3389/fnins.2019.00423

Burke, S. N., Mormino, E. C., Rogalski, E. J., Kawas, C. H., Willis, R. J., and Park, D. C. (2019). What are the later life contributions to reserve, resilience, and compensation? *Neurobiol. Aging* 83, 140–144. doi: 10.1016/j.neurobiolaging.2019.03.023

Calabria, M., Hernández, M., Cattaneo, G., Suades, A., Serra, M., Juncadella, M., et al. (2020). Active bilingualism delays the onset of mild cognitive impairment. *Neuropsychologia* 146:107528. doi: 10.1016/j.neuropsychologia.2020.107528

Castro, S., Wodniecka, Z., and Timmer, K. (2022). Am I truly monolingual? Exploring foreign language experiences in monolinguals. *PLoS One* 17:e0265563. doi: 10.1371/journal.pone.0265563

Chan, M. Y., Han, L., Carreno, C. A., Zhang, Z., Rodriguez, R. M., LaRose, M., et al. (2021). Long-term prognosis and educational determinants of brain network decline in older adult individuals. *Nat. Aging* 1, 1053–1067. doi: 10.1038/s43587-021-00125-4

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., and Bergman, H. (2010). Multilingualism (But Not Always Bilingualism) Delays the Onset of Alzheimer Disease: Evidence From a Bilingual Community. *Alzheimer Dis. Assoc. Dis.* 24, 118–125. doi: 10.1097/WAD.0b013e3181ca1221

Chung-Fat-Yim, A., Poarch, G. J., Comishen, K. J., and Bialystok, E. (2021). Does language context impact the neural correlates of executive control in monolingual and multilingual young adults? *Brain Lang.* 222:105011. doi: 10.1016/j.bandl.2021.105011

Clare, L., Whitaker, C. J., Craik, F. I. M., Bialystok, E., Martyr, A., Martin-Forbes, P. A., et al. (2014). Bilingualism, executive control, and age at diagnosis among people with early-stage Alzheimer's disease in Wales. *J. Neuropsychol.* 10, 163–185. doi: 10.1111/jnp.12061

Collaboratory on Research Definitions for Reserve and Resilience in Cognitive Aging and Dementia (2022). *Framework for Terms Used in the Research of Reserve and Resilience*. https://reserveandresilience.com/framework/ (accessed May 12, 2022).

Craik, F. I. M., Bialystok, E., and Freedman, M. (2010). Delaying the onset of Alzheimer disease. *Neurology* 75, 1726–1729. doi: 10.1212/WNL.0b013e3181fc2a1c

Darwish, H., Farran, N., Assaad, S., and Chaaya, M. (2018). Cognitive reserve factors in a developing country: Education and occupational attainment lower the risk of dementia in a sample of lebanese older adults. *Front. Aging Neurosci.* 10:277. doi: 10.3389/fnagi.2018.00277

Deary, I. J., Gow, A. J., Pattie, A., and Starr, J. M. (2012). Cohort profile: The lothian birth cohorts of 1921 and 1936. *Int. J. Epidemiol.* 41, 1576–1584. doi: 10.1093/ije/dyr197

Deary, I. J., Gow, A. J., Taylor, M. D., Corley, J., Brett, C., Wilson, V., et al. (2007). The Lothian Birth Cohort 1936: A study to examine influences on cognitive ageing from age 11 to age 70 and beyond. *BMC Geriatrics* 7:28. doi: 10.1186/1471-2318-7-28

Dekhtyar, S., Marseglia, A., Xu, W., Darin-Mattsson, A., Wang, H. X., and Fratiglioni, L. (2019). Genetic risk of dementia mitigated by cognitive reserve: A cohort study. *Ann. Neurol.* 86, 68–78. doi: 10.1002/ana.25501

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage* 204:116222. doi: 10.1016/j.neuroimage.2019.116222

DeLuca, V., and Voits, T. (2022). Bilingual experience affects white matter integrity across the lifespan. *Neuropsychologia* 169, 108191. doi: 10.1016/j.neuropsychologia.2022.108191

Duncan, H. D., Nikelski, J., Pilon, R., Steffener, J., Chertkow, H., and Phillips, N. A. (2018). Structural brain differences between monolingual and multilingual patients with mild cognitive impairment and Alzheimer disease: Evidence for cognitive reserve. *Neuropsychologia* 109, 270–282. doi: 10.1016/j.neuropsychologia.2017.12.036

Erickson, K. I., Raji, C. A., Lopez, O. L., Becker, J. T., Rosano, C., Newman, A. B., et al. (2010). Physical activity predicts gray matter volume in late adulthood: The Cardiovascular Health Study. *Neurology* 75, 1415–1422. doi: 10.1212/WNL.0b013e3181f88359

Estanga, A., Ecay-Torres, M., Ibañez, A., Izagirre, A., Villanua, J., Garcia-Sebastian, M., et al. (2017). Beneficial effect of bilingualism on Alzheimer's disease CSF biomarkers and cognition. *Neurobiol. Aging* 50, 144–151. doi: 10.1016/j.neurobiolaging.2016.10.013

Fletcher, E., Gavett, B., Harvey, D., Farias, S. T., Olichney, J., Beckett, L., et al. (2018). Brain volume change and cognitive trajectories in aging. *Neuropsychology* 32, 436–449. doi: 10.1037/neu0000447

Gallo, F., DeLuca, V., Prystauka, Y., Voits, T., Rothman, J., and Abutalebi, J. (2022). Bilingualism and Aging: Implications for (Delaying) Neurocognitive Decline. *Front. Hum. Neurosci.* 16:819105. doi: 10.3389/fnhum.2022.819105

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., and Smith, C. D. (2013). Lifelong Bilingualism Maintains Neural Efficiency for Cognitive Control in Aging. *J. Neurosci.* 33, 387–396. doi: 10.1523/jneurosci.3837-12.2013

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *J. Cogn. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., et al. (2021). Bilingual language experience as a multidimensional spectrum: Associations with objective and subjective language proficiency. *Appl. Psycholinguist.* 42, 245–278. doi: 10.1017/S0142716420000521

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism* 23, 283–294. doi: 10.1017/S1366728919000026

Harada, C. N., Natelson Love, M. C., and Triebel, K. L. (2013). Normal cognitive aging. *Clin. Geriatric Med.* 29, 737–752. doi: 10.1016/j.cger.2013.07.002

Heim, S., Stumme, J., Bittner, N., Jockwitz, C., Amunts, K., and Caspers, S. (2019). Bilingualism and "Brain Reserve": A Matter of Age. *Neurobiol. Aging* 81, 157–165. doi: 10.1016/j.neurobiolaging.2019.05.021

Kałamała, P., Chuderski, A., Szewczyk, J., Senderecka, M., and Wodniecka, Z. (2021). Bilingualism caught in a net. A new approach to understanding the complexity of bilingual experience. *PsyArXiv* [preprint]. doi: 10.31234/osf.io/eba3n

Kartschmit, N., Mikolajczyk, R., Schubert, T., and Lacruz, M. E. (2019). Measuring Cognitive Reserve (CR) – A systematic review of measurement properties of CR questionnaires for the adult population. *PLoS One* 14:1–23. doi: 10.1371/journal.pone.0219851

Kavé, G., Eyal, N., Shorek, A., and Cohen-Mansfield, J. (2008). Multilingualism and cognitive state in the oldest old. *Psychol. Aging* 23, 70–78. doi: 10.1037/0882-7974.23.1.70

Klein, R. M., Christie, J., and Parkvall, M. (2016). Does multilingualism affect the incidence of Alzheimer's disease: A worldwide analysis by country. *SSM Popul. Health* 2, 463–467. doi: 10.1016/j.ssmph.2016.06.002

Kuhl, P. K., Stevenson, J., Corrigan, N. M., van den Bosch, J. J. F., Can, D. D., and Richards, T. (2016). Neuroimaging of the bilingual brain: Structural brain correlates of listening and speaking in a second language. *Brain Lang.* 162, 1–9. doi: 10.1016/j.bandl.2016.07.004

Larson, E. B., Wang, L., Bowen, J. D., McCormick, W. C., Teri, L., Crane, P., et al. (2006). Exercise is associated with reduced risk for incident dementia among persons 65 years of age and older. *Ann. Int. Med.* 144, 73–81. doi: 10.7326/0003-4819-144-2-200601170-00004

Lawton, D. M., Gasquoine, P. G., and Weimer, A. A. (2015). Age of dementia diagnosis in community dwelling bilingual and monolingual Hispanic Americans. *Cortex* 66, 141–145. doi: 10.1016/j.cortex.2014.11.017

Leivada, E., Westergaard, M., Duñabeitia, J. A., and Rothman, J. (2021). On the phantom-like appearance of bilingualism effects on neurocognition: (How) should we proceed? *Bilingualism* 24, 197–210. doi: 10.1017/S1366728920000358

Leoñ, I., Garciá-García, J., and Roldañ-Tapia, L. (2014). Estimating cognitive reserve in healthy adults using the cognitive reserve scale. *PLoS One* 9:39–43. doi: 10.1371/journal.pone.0102632

Li, L., Abutalebi, J., Emmorey, K., Gong, G., Yan, X., Feng, X., et al. (2017). How bilingualism protects the brain from aging: Insights from bimodal bilinguals. *Hum. Brain Mapp.* 38, 4109–4124. doi: 10.1002/hbm.23652

Li, P., Zhang, F., Yu, A., and Zhao, X. (2020). Language History Questionnaire (LHQ3): An enhanced tool for assessing multilingual experience. *Bilingualism* 23, 938–944. doi: 10.1017/S1366728918001153

Luk, G., Bialystok, E., Craik, F. I. M., and Grady, C. L. (2011). Lifelong Bilingualism Maintains White Matter Integrity in Older Adults. *J. Neurosci.* 31, 16808–16813. doi: 10.1523/JNEUROSCI.4563-11.2011

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing Language Profiles in Bilinguals and Multilinguals. *J. Speech Lang.Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Marian, V., and Spivey, M. (2003). Competing activation in bilingual language processing: Within- and between-language competition. *Bilingualism* 6:S1366728903001068. doi: 10.1017/S1366728903001068

Mendis, S. B., Raymont, V., and Tabet, N. (2021). Bilingualism: A Global Public Health Strategy for Healthy Cognitive Aging. *Front. Neurol.* 12:628368. doi: 10.3389/fneur.2021.628368

Morris, M. C. (2012). Nutritional determinants of cognitive aging and dementia. *Proc. Nutr. Soc.* 71, 1–13. doi: 10.1017/S0029665111003296

Mungas, D., Gavett, B., Fletcher, E., Farias, S. T., DeCarli, C., and Reed, B. (2018). Education amplifies brain atrophy effect on cognitive decline: implications for cognitive reserve. *Neurobiol. Aging* 68, 142–150. doi: 10.1016/j.neurobiolaging.2018.04.002

Nichols, E. S., Wild, C. J., Stojanoski, B., Battista, M. E., and Owen, A. M. (2020). Bilingualism affords no general cognitive advantages: a population study of executive function in 11,000 people. *Psychol. Sci.* 31, 548–567. . doi: 10.1177/0956797620903113

Nilsson, L.-G., Bäckman, L., Erngrund, K., Nyberg, L., Adolfsson, R., Bucht, G., et al. (1997). The betula prospective cohort study: Memory, health, and aging. *Aging Neuropsychol.Cogn.* 4, 1–32. doi: 10.1080/13825589708256633

Nucci, M., Mapelli, D., and Mondini, S. (2012). Cognitive Reserve Index questionnaire (CRIq): a new instrument for measuring cognitive reserve. *Aging Clin. Exper. Res. Exp. Res.* 24, 218–226. doi: 10.3275/7800

Olsen, R. K., Pangelinan, M. M., Bogulski, C., Chakravarty, M. M., Luk, G., Grady, C. L., et al. (2015). The effect of lifelong bilingualism on regional grey and white matter volume. *Brain Res.* 1612, 128–139. doi: 10.1016/j.brainres.2015.02.034

Paplikar, A., Mekala, S., Bak, T. H., Dharamkar, S., Alladi, S., and Kaul, S. (2018). Bilingualism and the severity of poststroke aphasia. *Aphasiology* 00, 1–15. doi: 10.1080/02687038.2017.1423272

Paulavicius, A. M., Mizzaci, C. C., Tavares, D. R. B., Rocha, A. P., Civile, V. T., Schultz, R. R., et al. (2020). Bilingualism for delaying the onset of Alzheimer's disease: a systematic review and meta-analysis. *Eur. Geriatric Med.* 11, 651-658. doi: 10.1007/s41999-020-00326-x

Perani, D., and Abutalebi, J. (2015). Bilingualism, dementia, cognitive and neural reserve. *Curr. Opin. Neurol.* 28, 618–625. doi: 10.1097/WCO.0000000000000267

Perani, D., Farsad, M., Ballarini, T., Lubian, F., Malpetti, M., Fracchetti, A., et al. (2017). The impact of bilingualism on brain reserve and metabolic connectivity in Alzheimer's dementia. *Proc. Natl. Acad. Sci.* 114, 1690–1695. doi: 10.1073/pnas.1610909114

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism* 23, 459–471. doi: 10.1017/S1366728919000130

Pliatsikas, C., Pereira Soares, S. M., Voits, T., Deluca, V., and Rothman, J. (2021). Bilingualism is a long-term cognitively challenging experience that modulates metabolite concentrations in the healthy brain. *Sci. Rep.* 11:7090. doi: 10.1038/s41598-021-86443-4

Ramakrishnan, S., Mekala, S., Mamidipudi, A., Yareeda, S., Mridula, R., Bak, T. H., et al. (2017). Comparative Effects of Education and Bilingualism on the Onset of Mild Cognitive Impairment. *Dementia Geriatric Cogn. Dis.* 44, 222–231. doi: 10.1159/000479791

Rami, L., Valls-Pedret, C., Bartrés-Faz, D., Caprile, C., Solé-Padullés, C., Castellví, M., et al. (2011). Cognitive reserve questionnaire. Scores obtained in a healthy elderly population and in one with Alzheimer's disease | Cuestionario de reserva cognitiva. Valores obtenidos en población anciana sana y con enfermedad de Alzheimer. *Revista Neurol.* 52:644003.

Sala, A., Malpetti, M., Farsad, M., Lubian, F., Magnani, G., Frasca Polara, G., et al. (2022). Lifelong bilingualism and mechanisms of neuroprotection in Alzheimer dementia. *Hum. Brain Mapp.* 43, 581–592. doi: 10.1002/hbm.25605

Salthouse, T. A. (2004). What and when of cognitive aging. *Curr. Direct. Psychol. Sci.* 13, 140–144. doi: 10.1111/j.0963-7214.2004.00293.x

Salthouse, T. A. (2019). Trajectories of normal cognitive aging. *Psychol. Aging* 34, 17–24. doi: 10.1037/pag0000288

Sanchez-Lopez, J., Silva-Pereyra, J., Fernández, T., Alatorre-Cruz, G. C., Castro-Chavira, S. A., González-López, M., et al. (2018). High levels of incidental physical activity are positively associated with cognition and EEG activity in aging. *PLoS One* 13:e0191561. doi: 10.1371/journal.pone.0191561

Scarmeas, N., and Stern, Y. (2004). Cognitive reserve: Implications for diagnosis and prevention of Alzheimer's disease. *Curr. Neurol. Neurosci. Rep.* 4, 374–380. doi: 10.1007/s11910-004-0084-7

Scheltens, P., Blennow, K., Breteler, M. M. B., de Strooper, B., Frisoni, G. B., Salloway, S., et al. (2016). Alzheimer's disease. *Lancet* 388, 505–517. doi: 10.1016/j.cub.2018.04.080

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I. M. M., and Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer's disease. *Cortex* 48, 991–996. doi: 10.1016/j.cortex.2011.04.009

Sowa, A., Tobiasz-Adamczyk, B., Topór-Mądry, R., Poscia, A., and La Milia, D. I. (2016). Predictors of healthy ageing: Public health policy targets. *BMC Health Services Res.* 16:289. doi: 10.1186/s12913-016-1520-5

Steffener, J., and Stern, Y. (2012). Exploring the neural basis of cognitive reserve in aging. *Biochim. Biophys. Acta* 1822, 467–473. doi: 10.1016/j.bbadis.2011.09.012

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *J.Int. Neuropsychol. Soc.* 8, 448–460. doi: 10.1017/S1355617702813248

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., and Chetelat, G. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's Dementia* 16, 1305–1311. doi: 10.1016/j.jalz.2018.07.219

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., and Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage* 205:116306. doi: 10.1016/j.neuroimage.2019.116306

Taylor, J. R., Williams, N., Cusack, R., Auer, T., Shafto, M. A., Dixon, M., et al. (2017). The Cambridge Centre for Ageing and Neuroscience (Cam-CAN) data repository: Structural and functional MRI, MEG, and cognitive data from a cross-sectional adult lifespan sample. *NeuroImage* 144, 262–269. doi: 10.1016/j.neuroimage.2015.09.018

Titone, D. A., and Tiv, M. (2022). Rethinking multilingual experience through a Systems Framework of Bilingualism. *Bilingualism* 4, 1–16. doi: 10.1017/S1366728921001127

Voits, T., Pliatsikas, C., Robson, H., and Rothman, J. (2020). Beyond Alzheimer's disease: Can bilingualism be a more generalized protective factor in neurodegeneration? *Neuropsychologia* 147:107593. doi: 10.1016/j.neuropsychologia.2020.107593

Voits, T., Robson, H., Rothman, J., and Pliatsikas, C. (2022). The effects of bilingualism on hippocampal volume in ageing bilinguals. *Brain Struct. Funct.* 227, 979–994. doi: 10.1007/s00429-021-02436-z

Wilson, R. S., Krueger, K. R., Arnold, S. E., Schneider, J. A., Kelly, J. F., Barnes, L. L., et al. (2007). Loneliness and risk of Alzheimer disease. *Arch. Gen. Psychiatry* 64, 234–240. doi: 10.1001/archpsyc.64.2.234

Wilson, R. S., Wang, T., Yu, L., Grodstein, F., Bennett, D. A., and Boyle, P. A. (2021). Cognitive Activity and Onset Age of Incident Alzheimer Disease Dementia. *Neurology* 97, e922–e929. doi: 10.1212/WNL.0000000000012388

Winblad, B., Amouyel, P., Andrieu, S., Ballard, C., Brayne, C., and Brodaty, H. (2016). Defeating Alzheimer's disease and other dementias: A priority for European science and society. *Lancet Neurol.* 15, 455–532. doi: 10.1016/S1474-4422(16)00062-4

Wirth, M., Haase, C. M., Villeneuve, S., Vogel, J., and Jagust, W. J. (2014). Neuroprotective pathways: Lifestyle activity, brain pathology, and cognition in cognitively normal older adults. *Neurobiol. Aging* 35, 1873–1882. doi: 10.1016/j.neurobiolaging.2014.02.015

World Health Organization [WHO] (2021). *Public health response to dementia*. Geneva: World Health Organization.

Woumans, E., Santens, P., Sieben, A., Versijpt, J., Stevens, M., and Duyck, W. (2015). Bilingualism delays clinical manifestation of Alzheimer's disease. *Bilingualism* 18, 568–574. doi: 10.1017/S136672891400087X

Yaffe, K., Fiocco, A. J., Lindquist, K., Vittinghoff, E., Simonsick, E. M., Newman, A. B., et al. (2009). Predictors of maintaining cognitive function in older adults: The Health ABC Study. *Neurology* 72, 2029–2035. doi: 10.1212/WNL.0b013e3181a92c36

Yeung, C. M., St. John, P. D., Menec, V., and Tyas, S. L. (2014). Is Bilingualism Associated With a Lower Risk of Dementia in Community-living Older Adults? Cross-sectional and Prospective Analyses. *Alzheimer Dis. Assoc. Disord.* 28, 326–332. doi: 10.1097/WAD.0000000000000019

Zahodne, L. B., Schofield, P. W., Farrell, M. T., Stern, Y., and Manly, J. J. (2014). Bilingualism does not alter cognitive decline or dementia risk among spanish-speaking immigrants. *Neuropsychology* 28, 238–246. doi: 10.1037/neu0000014

Zheng, Y., Wu, Q., Su, F., Fang, Y., Zeng, J., and Pei, Z. (2018). The Protective Effect of Cantonese/Mandarin Bilingualism on the Onset of Alzheimer Disease. *Dement. Geriatric Cogn. Disord.* 45, 210–219. doi: 10.1159/000488485

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Multifactorial approaches to study bilingualism in the aging population: Past, present, future

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A better understanding and more reliable classification of bilinguals has been progressively achieved through the fine-tuning methodology and simultaneously optimizing the measurement tools. However, the current understanding is far from generalization to a larger population varying in different measures of bilingualism—L2 Age of acquisition (L2 AOA), L2 usage and exposure, and L2 proficiency. More recent studies have highlighted the importance of modeling bilingualism as a continuous variable. An in-depth look at the role of bilingualism, comparing groups, may be considered a reductionist approach, i.e., grouping based on one measure of bilingualism (e.g., L2 AOA) may not account for variability in other measures of bilingualism (L2 exposure, L2 use or L2 proficiency, amongst others) within and between groups. Similarly, a multifactorial dimension is associated with cognitive performance, where not all domains of cognition and subcomponents are equally influenced by bilingualism. In addition, socio-cultural and demographical factors may add another dimension to the impact of bilingualism on cognitive performance, especially in older adults. Nevertheless, not many studies have controlled or used the multiple socio-cultural and demographical factors as a covariate to understand the role of different aspects of bilingualism that may influence cognitive performance differently. Such an approach would fail to generalize the research findings to a larger group of bilinguals. In the present review paper, we illustrate that considering a multifactorial approach to different dimensions of bilingual study may lead to a better understanding of the role of bilingualism on cognitive performance. With the evolution of various fine-tuned methodological approaches, there is a greater need to study variability in bilingual profiles that can help generalize the result universally.

KEYWORDS

multifactorial approach, subjective measures of bilingualism, objective measures of bilingualism, cognitive performance, confounding variables

Introduction

Over the years, studies have demonstrated that bilingualism improves cognitive performance, particularly in older persons (Bialystok, 2021a). However, the role of bilingualism in enhanced cognitive performance has been highly debated. On the one hand, researchers have provided empirical evidence demonstrating faster and more accurate performance in bilingual participants compared to their monolingual peers on a variety of cognitive tasks (Pliatsikas and Luk, 2016; Dash et al., 2019). On the other hand, opponents have failed to replicate the expected group differences (Paap et al., 2018), implying spurious findings. Furthermore, various meta-analyses assessing the link between bilingualism and cognitive performance have supported the accuracy of positive results (Adesope et al., 2010; Baumgart and Billick, 2018; Grundy, 2020) and the null results (Paap and Greenberg, 2013; van den Noort et al., 2019), adding to the unresolved controversy. Most null results come from the behavioral data testing younger bilinguals. However, these research results (both positive and null) need to be interpreted cautiously while acknowledging the individual differences that may exist within and across groups when participants are classified based on a simple binary question. The discrepancies in literature lie in methodological and conceptual understanding, among others, lack of second language competency information and conflicting classification criteria (Grosjean, 1998; Grundy, 2020). In addition, measures of cognitive performance used in bilingual literature vary across studies. These cognitive tasks usually assess different subcomponents of attention, cognitive control, or working memory and are also assessed in verbal or non-verbal modalities adding to the complexity of interaction between language and cognition (Dash et al., 2022). Moreover, there is a lack of standard practices to identify and control confounding socio-cultural and demographic variables in exploring the consequences and antecedents of bilingualism. The present review, thus, sought to assess the evolution of methodological rigor and conceptual understanding of bilingualism and its relation to cognitive performance with a focus on the aging population. Under various subheadings, this review will focus on two main aspects: (1) illustration of different strategies to profile the bilingual population and (2) to demonstrate different indices of the cognitive performance in bilinguals. In doing so, this review highlights the limitation of existing approaches and the use of a multifactorial approach to measuring levels of bilingualism and the related cognitive ability in different domains of cognition. The multifactorial approach to studying bilingualism in the aging population finds support in the concept of *emergentism* described by Hernandez and colleagues in reference to bilingualism (Hernandez et al., 2018, 2019; Claussenius-Kalman et al., 2021). *Emergentism* is a philosophical concept originally described by Mill (1843) in a physical system, where dynamic forces combine to form simple motion. *Emergentism* can also be used to explain the learning of second languages (Gregg, 2004; MacWhinney, 2002). More broadly speaking, *emergentism* in the context of bilingualism can be described as an interaction between the ecosystem and expertise of the learner during second language acquisition. *Emergentism* refers to an interaction between the ecosystem and expertise of the learner during second language acquisition. The term "ecosystem" refers to the characteristics of the second language learning environment, i.e., language usage, frequency, similarities between languages, and mode/environment of learning. On the other hand, "expertise" refers to the learner's aptitude for learning a new language. This includes age and individual differences in cognitive skills like memory, cognitive control, and cognitive flexibility. Emergentism takes a developmental perspective indicating an interaction between *ecosystem* and *expertise* that results in a variable outcome of bilingual language processing. Thus, each second language learner has a different developmental trajectory represented in a unique multidimensional space, depending on the interaction between their ecosystem and ability. Thus, a multifactorial approach allows the researchers to account for the inter-individual variability in the bilingual population by adding an assessment of multiple factors related to bilingual experiences, demographic strata, and cognitive performance simultaneously. Although, we have seen an evolution in the approach to quantifying bilingualism using different tools and methods (Dash et al., 2019, 2022; Gullifer and Titone, 2020; Sulpizio et al., 2020; Macdonald et al., 2022), with restrictions on the use of a single test to assess cognitive performance with only a few studies trying to control for confounding variables.

Toward the understanding of bilingual phenotype

Over the years, evolutionary changes have occurred in the theoretical and methodological ways to characterize bilingualism. Defining bilingualism becomes more complicated when considering what "*knowing a language*" means and how one can define various aspects of bilingualism. When defining bilingualism, researchers often rely on multiple measures of bilingualism, such as the L2 AOA, L2 language usage and exposure, and L2 proficiency (Marian et al., 2007; Li et al., 2014; Anderson et al., 2018; Dash et al., 2019, 2022; Marian and Hayakawa, 2021). Different measures of bilingualism are often interrelated, and given the heterogeneity in the bilingual experience, interrelation may not follow the same trajectory. Therefore, a multidimensional and dynamic phenomenon of bilingualism needs a holistic multifactorial approach to capture the inherent nature of the bilingual experience, more so in the aging population, as the accuracy of reporting bilingual experience may introduce additional variability. In the past several decades, bilingual literature has evolved from a dichotomous to a continuum approach to defining and modeling bilingualism. Researchers have found that the heterogeneity in the traditional approach to categorizing participants in a bilingual and monolingual group may result in inconsistent findings in cognitive performance between the groups (Baum and Titone, 2014; Luk, 2015; de Bruin, 2019; DeLuca et al., 2019). In addition, many studies have failed to find the benefits of bilingualism on cognitive performance in the aging population (Olsen et al., 2015; Keijzer and Schmid, 2016; Papageorgiou et al., 2019; Soltani et al., 2021). The reason for the inconsistency may originate in the way groups are labeled and thus classified. Surrain and Luk (2019) highlights different ways in which researchers have classified their bilingual group; it was evident that 77% of the studies use the label "*bilingual*" or "*specific language pair bilingual,*" and only minimal studies (19%) use combination of factors to label the bilingual group. Another evolutionary transition was understanding variations in cognitive performance within bilingual groups. Various behavioral and neuroimaging studies have compared two extremes of the population within the bilingual category—high vs. low proficiency (Singh and Mishra, 2013), balanced vs. unbalanced (Woumans et al., 2015), early vs. late (Tao et al., 2011). Although such an approach still categorizes the participants into two groups, it has led to much informative literature on bilingualism. The debatable role of bilingualism in cognitive performance also stems from the variability in bilingual experiences; for example, a high proficient bilingual may be an early or late bilingual, or an early bilingual may be an unbalanced bilingual. Therefore, the prediction made using one set of observable variables (for example, proficiency) does not apply to another set of observable variables (for example, language usage), thus limiting reliable and replicable research findings.

Recent studies have used statistical methods to mathematically combine and use continuous variables to predict changes in cognitive performance (Gullifer et al., 2018; Dash et al., 2019, 2022). Moreover, the use of statistical methods to determine outcomes for the measure of bilingualism has found support in a recent study by Macdonald et al. (2022). Authors find convergence between outcomes from various statistical methods (like confirmatory factor analyses and latent profile analyses) and another continuous metric of bilingualism (Vaughn and Hernandez, 2018) and self-reported information (Macdonald et al., 2022). Since bilingualism is a multidimensional construct, there can be an overlapping continuum of different measures of bilingualism. Similarly, a bilingual continuum created using one dimension of bilingual experience (for example, language usage, DeLuca et al., 2019) may have a different trajectory in another dimension. Furthermore, the lack of consensus in bilingual literature also stems from the differences in how different measurement tools are used to study bilingualism. Therefore, it is crucial to determine which task and stimuli are used as measures of bilingualism, and once scholars determine the variables of interest, the next logical step is to figure out how they use them to understand the role of bilingualism in cognitive performance. Depending on the research questions, researchers have often used 1 or 2 measures to categorize participants into different groups; more recent studies use different bilingualism measures on a continuum. Categorizing participants in groups allows for simplification of the analyses, presentation, and interpretation of the results from a study (DeCoster et al., 2011). The data presentation is easier by dichotomizing the variables using a table or graph with the mean scores to demonstrate differences between groups. However, If the predictor variable is continuous, then the slope of the predictor variable with the outcome variable needs to be presented using regression lines. For example, to explore the interaction effect between age and bilingualism on cognitive performance, a researcher may construct distinct regression lines between bilingualism and cognitive performance for different age cohorts (young vs. older adults) and interpret the effect. In addition, when age and bilingualism vary continuously, the statistical approach to presentation needs to be tweaked. Such methods are more complicated than presenting group means. Similarly, categorical analysis is typically more straightforward and traditional than continuous analysis. ANOVA, which requires a categorical predictor variable, is more commonly used by psychologists to test influences on an outcome variable. However, the linear mixed effect model (Gallo et al., 2022) and growth curve analysis (Incera and McLennan, 2017) are gaining popularity in recent times where multiple continuous variables can also be considered to predict the outcome. Some potential arguments in favor of categorization were provided by Farrington and Loeber (2000). They propose that arbitrarily categorizing variables is one method for dealing with variables with highly skewed distributions or when the relationship between predictor and outcome variable is not linear. However, there are more cons than pros in using measures of bilingualism to categorize participants. To begin with, conducting group analyses when the variable of interest may vary on a continuum diminishes statistical power and increases the risk of rejecting the null hypothesis (Cohen, 1983; Altman and Royston, 2006; DeCoster et al., 2011). Secondly, universally accepted grouping criteria are unavailable, limiting the reproducibility of the results in different studies (Altman and Royston, 2006). Especially with the aging population, categorizing participants based on the current language usage and proficiency may ignore the necessary bilingual experience (spanning over decades) crucial for building an accurate bilingual profile. Furthermore, suppose the split is made at an arbitrary cut-off point (say, the median age of acquisition of 10 years). In that case, participants with an age of acquisition of 9 and 11 years are placed in different groups, even though they may be more like each other than other members of their group (i.e., age of acquisition of 9 years is more similar to that of 11 years than that of 1 year; MacCallum et al., 2002; Altman and Royston, 2006).

To summarize, grouping bilinguals when the underlying construct is continuous has statistical implications and may obfuscate our understanding of the measure of bilingualism in the research study. It is comparatively easy to group participants; however, it adds researchers' bias to the study. Finally, when groups are constructed based on the values of a continuous measure, a significant amount of information and variability that may exist within a group are lost (MacCallum et al., 2002). In the following sections, we will elaborate on the most commonly used tools available to measure bilingualism and how these tools are used to classify participants or create a continuum.

Measures of bilingualism: Subjective and objective measures

While highlighting the lack of consensus between the research fraternity on the role of bilingualism in cognition, this section will enumerate different tools used to measure bilingualism. The selection of different measurement variables is based on the way researchers have defined bilingualism and the measures used to ascertain the inclusion of participants. There are currently multiple ways to measure bilingual experience (de Bruin, 2019), broadly classified into subjective and objective measures. Self-report measures of bilingualism are the most widely used tools in various studies across different bilingual populations (Grundy, 2020; Kremin and Byers-Heinlein, 2021). The most used questionnaires for adult bilinguals are Language History Questionnaire (LHQ; Li et al., 2006, 2014, 2020), Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007), and Language and Social Background Questionnaire (Luk and Bialystok, 2013; Anderson et al., 2018). Although not identical, these questionnaires assess fundamental measures of bilingual experience—L2 AOA, language usage and proficiency, and language immersion. Some of the key differences between these questionnaires are how responses are recorded and the range of the rating scale (varies from 5 to 10 Likert scale; use of descriptive terms like "more," strongly agree). LEAP-Q is explicitly designed to measure speech and language skills; hence it also assesses self-perception of accent in participants' speech which is missing in other questionnaires. LEAP-Q provides an extensive set of questions that different research groups can use differently. LHQ, on the other hand, reports language background, proficiency, usage, and dominance; and provides an aggregate score for proficiency, dominance, and immersion. LSBQ is specifically designed for countries with an immigrant population, and the questions focus on the extent of non-English language proficiency and use at home and in other social situations. LSBQ and LHQ have developed a revised version focusing on the interpretation guide and recommended cut-off scores for the continuous outcome variable into categorical groups.

L2 AOA is the commonly used variable to categorize participants into respective groups (bilingual vs. monolingual; early vs. late bilinguals) to compare the executive functioning in the aging population (Luk et al., 2011; Bak et al., 2014; Ansaldo et al., 2015). L2 AOA is a static variable that is comparatively easier to report than L2 proficiency and usage, which may experience dynamic change throughout the language learning experience, especially in the aging population. While reporting L2 AOA, some participants may estimate L2 AoA based on early exposure to the second language (e.g., parents, friends, music, and television); others may indicate the start of formal classroom learning. Furthermore, studies frequently use the age of immigration to a new country (Tao et al., 2011) as an indicator of L2 AOA. Interestingly, previous studies from 2005 to 2015 have more frequently reported L2 proficiency and usage variables (77 and 79%) than L2 AOA (67%; Surrain and Luk, 2019). Most questionnaires measure second language usage or exposure in general and interactional contexts (e.g., language use at home, work, social setting). Researchers have predominantly used raw scores (percentage exposure, rating on the Likert scale) or normalized scores as an indicator of language usage to predict cognitive performance. Estimating the frequency with which each language is used daily is difficult, but it is even more complicated when bilinguals vary the use of a particular language depending on the context of language usage (Grosjean, 1998; Green and Abutalebi, 2013). To obtain a more comprehensive language usage scores, questionnaires often assess exposure and usage in diverse situations, such as with different interlocutors (e.g., family, friends), at different stages of life (e.g., primary school, high school), and topics (e.g., emotions, leisure activities, media). In addition, studies have categorized bilingual participants under three interaction contexts: Single-language contexts, dual-language contexts, and dense code-switching contexts based on the interaction of language usage frequencies in various contexts (Green and Abutalebi, 2013; Lai and O'Brien, 2020). Rodriguez-Fornells et al. (2012) developed the Bilingual Switching Questionnaire (BSWQ) to assess better language context, which examines multiple aspects of code-switching. The BSWQ helps categorize participants into four categories: L1 switcher, L2 switcher, contextual switcher, and accidental switcher. The LSBQ (Anderson et al., 2018) also assesses code-switching and provides composite scores to classify the bilingual population or utilize the measurements on a continuum, along with other measures. Another crucial measure assessed in questionnaires is the L2 language proficiency assessing differences in executive functioning between high and low proficient bilinguals (Singh and Mishra, 2012, 2013). Second language proficiency is usually measured on a Likert scale (for example, 1–7 or 1–10), with an association between self-reported L2 proficiency and standardized language tests is moderate to strong in most questionnaires (Marian et al., 2007; Li et al., 2014, 2020). In comparison, de Bruin et al. (2017) discovered a small to marginally moderate correlation and established objective language assessments (productive vocabulary, receptive vocabulary, and fluency measured in an interview). Given that the participants are estimating their response to the questionnaire after several years, reporting of L2 AoA, usage, and proficiency may encounter over-and under-estimation of self-reported competency, resulting in a lack of association between self-reported measures and conventional language tests (Dash and Kar, 2012; Tomoschuk et al., 2019). Most of these questionnaires do ask specific questions about the language exposure and usage history crucial while understanding bilingual experience in the aging population (i.e., number of years in a second language country, family, school). For example, an elderly, highly proficient bilingual who has gained proficiency over decades of L2 exposure but may not be an active L2 user in the present day and may contribute to a lack of correlation between self-reported information (minimal L2 usage in daily life) and conventional language tests (high scores because of higher language skills). Thus, it is crucial to assess the self-reported variable–L2 usage & proficiency–in greater detail in the aging population. Elderly bilinguals are subjected to intra-individual variability of bilingual experience across different phases of their life that is rarely addressed in research studies.

On the other hand, recent research has recommended using objective measures criteria to assess bilinguals' multifactorial experience (de Bruin, 2019; Tomoschuk et al., 2019; Dash et al., 2022) along with self-reported questionnaires. Picture naming task (Ali et al., 2022), lexical decision time (Pérez et al., 2013), verbal fluency (Suarez et al., 2014), and discourse performances (Dash et al., 2019, 2022) are some of the tasks used to classify participants in different groups or a continuum. MINT (Gollan et al., 2012), the Boston Naming Test (Goodglass et al., 2001), and the Peabody Picture Vocabulary Test (Dunn and Dunn, 1997) are the most common standardized measures of expressive naming ability. These tests are usually available in various languages and have been validated. Another standardized task that is gaining popularity and is available in multiple languages is the LexTALE task (Lemhöfer and Broersma, 2012), which measures receptive vocabulary. It is also vital to recognize that standardized, objective proficiency measurements may limit application in less-studied languages where norms are not easily available. In an attempt to add objectivity to L2 language usage in an interactional context targeting the language switching behavior, researchers have utilized a more ecologically valid technique (EMA, e.g., Shiffman et al., 2008), asking participants to report the frequency of language switching every 2 h for 2 weeks using a smartphone application (Jylkkä et al., 2020). Compared to other questionnaires, assessing switching behavior with an objective tool gives a daily assessment of language switching ability and more accurately captures nuances. Furthermore, numerous objective measures (e.g., production and comprehension, vocabulary, general fluency, etc.) in combination will highlight the multidimensional nature of proficiency. Language proficiency is a multifaceted concept that cannot be reduced to a single metric like naming ability. Multiple objective indices are required to measure language proficiency because a single objective task (usually assessing naming) has a low correlation with the self-reported measure of proficiency (Marian et al., 2007). de Bruin et al. (2017) found that using four objective tasks could better classify bilinguals. Although objective measures of bilingualism are considered important in quantifying bilingual experience, they are rarely reported in bilingual literature. Surrain and Luk (2019) reported that around 38% of the studies assessing language proficiency had provided objective scores. Similarly, Hulstijn (2012) estimated that 45% of studies published in *Bilingualism: Language and Cognition* used objective measures to define language proficiency. However, objective measures of proficiency may benefit from the following recommendations. Firstly, using a single measure of objective language proficiency may not indicate a level of bilingualism. Therefore, it is recommended to use multiple objective measures to create a holistic profile of the bilingual experience (de Bruin, 2019; de Bruin et al., 2021). Secondly, using standardized proficiency measures may not be possible in a different scenario. For example, less popular language combinations may not have standardized tools available in their languages. Also, the use of standardized tools is complicated in studies where multiple language combinations are used. Therefore, we recommend substantiating objective measures with extensive subjective information while assessing bilingual language experience. Simultaneously, there is a greater need to develop tools that apply to different language combinations. For example, the discourse production task as a measure of L2 language proficiency can be considered a holistic measure that can simultaneously provide proficiency scores based on participants' grammatical knowledge, vocabulary skills, organization of content, and fluency. Also, previous studies using L2 discourse proficiency have supported the role of bilingualism in cognitive performances and functional connectivity matrices (Dash et al., 2019, 2022), supporting the use of discourse proficiency as a putative tool. Finally, extensive questionnaires assessing self-reported proficiency information and multiple objective measures tend to increase the number of observable variables in the study. Therefore, it is necessary to substantiate and find appropriate statistical methods to combine the number of observable variables in a meaningful manner. By doing a factorial analysis, these measurements can be merged and utilized to estimate L2 language proficiency levels that can be used as a continuous or categorical measure of bilingualism (Dash et al., 2019, 2022; Calabria et al., 2020). In sum, using a multifactorial approach tapping distinct aspects of bilingualism–L2 AOA, L2 language history, L2 language usage and proficiency, L2 immersion–using multiple self-reported and objective measures may provide a holistic bilingual profile.

Mathematical and statistical ways to combine bilingual variables

It is widely accepted that individual bilinguals' language experiences are diverse, with unique contexts of acquisition, variations in language usage, and proficiency across the lifespan that can impact socio-cultural identity and cognitive and brain function. The diversity in language experience has led to numerous tools to capture the bilingual experience and has similarly led to corresponding mathematical and statistical ways to use the information collected through different questionnaires and proficiency measures to effectively quantify as a single variable or multiple composite variables for further analysis looking at the impact of bilingualism.

As described above, L2 AOA is one of the commonly used measures subjected to cut-off age to create arbitrary categorization. One common approach is assigning a cut-off to the variable of interest and eventually categorizing the participants or using the cut-off for initial screening. However, using an arbitrary cut-off usually led to discrepancies. For example, an early bilingual label is given to participants with L2 age of acquisition below 5 (Champoux-Larsson and Dylman, 2021), 6 years (Tao et al., 2011; Kalia et al., 2018), 7 years (Pelham and Abrams, 2014), 13 years (Baker and Trofimovich, 2005). Some previous studies had defined early bilinguals when their L2 age of acquisition was prior to the fixed cut-off age and late bilinguals when they acquire their L2 after the cut-off age (Kalia et al., 2018; Champoux-Larsson and Dylman, 2021). The use of a cut-off score is often considered to categorize participants into monolingual and bilingual groups. However, when the language experience of the bilingual and monolingual groups is explored further, heterogeneity within each group may emerge. Bilinguals, for example, may have different ages of acquisition and levels of language usage and proficiency, and monolinguals may have some amounts of exposure to a second language (L2), more so in the aging population where there might be foreign language education in school/college. Given the multifactorial nature of bilingual experience and how different bilingualism measures may interact, it is critical to find ways to synthesize an acceptable number of dependent variables while profiling bilinguals. Thus, traditionally defined bilingual and monolingual groups using arbitrary cut-off points may obscure within-group differences in performance (e.g., MacCallum et al., 2002; Abutalebi and Rietbergen, 2014; Baum and Titone, 2014; Luk, 2015; de Bruin, 2019; DeLuca et al., 2019). Studies have mathematically and statistically combined information to find an appropriate bilingual score.

Many researchers have advocated the need for appropriate guidelines to use questionnaire data and create an independent scoring system. Among different questionnaires used in the literature, the latest version of LHQ (LHQ3.0) provides a user-friendly web-based interface. The only tool available that provides a step-by-step guide for the researchers to calculate an aggregate score to represent participants' overall proficiency, dominance, and immersion levels in each language. These aggregate scores are calculated by normalizing the scores using an appropriate scaling factor (for example, cumulative proficiency score is calculated using a 1-7 Likert scale, so a 1/7 scaling factor is used in the equation), current age, age of acquisition of the language and years and hours of usage of the language. LHQ also provides a ratio score for language dominance in reference to other languages known to the participant. LHQ also allows the researchers to manipulate the weightage of certain variables in the equation based on the research question. For example, if the researcher is interested in bilingual reading and writing proficiency, the aggregate proficiency score is calculated by applying equal weight to reading and writing scores without considering self-reported speaking and understanding. LHQ3.0 has evolved as a one-stop holistic tool that can provide researchers with the flexibility to calculate a single bilingual score suitable for further analysis based on their research question. Another method proposed by Gullifer and Titone (2020) suggests using the *Language Entropy* score as a derived measure of bilingualism based on language usage data in an interactional social setting collected in the questionnaire. Language entropy is measured by calculating proportion scores in different language contexts, i.e., by dividing the L2 rating (for example, 5 on a 1-7 Likert scale) by total rating in different languages (i.e., combining self-reported rating in L1 and L2), followed by calculation of Shannon entropy (H) using the proportion score (see details in language Entropy R package; Gullifer and Titone, 2018). Gullifer and Titone (2020) have argued that language entropy is ideal for synthesizing theoretically relevant variables on a continuum while accounting for the social diversity and interactional context of language usage. More recently, studies using language entropy variables have shown the impact of bilingualism on cognitive and neural processes (Gullifer et al., 2018; Sulpizio et al., 2020; Li et al., 2020; Gullifer and Titone, 2021).

We routinely collect language background information about language usage and proficiency in various scenarios, such as overall daily exposure to known languages or the level of language use in communicative situations (e.g., at home, at work, in social settings). Despite their practical and theoretical importance, not many researchers have used them as covariates or predictors of behavior. One reason is that the sheer number of variables associated with bilingual experience collected in different questionnaires is daunting. Another reason for underuse is that the distribution of individual variables acquired *via* discrete replies (using the Likert scale) may not be optimal for analysis. Some of these problems can be solved with statistical manipulation of different variables to obtain an appropriate number of dependent variables. Many studies have efficiently modeled bilingual experience by using a statistical model that relates a set of observable variables to a set of latent variables, allowing to quantify bilingual experience efficiently (Anderson et al., 2018; Dash et al., 2019, 2022; Gullifer et al., 2020; Sulpizio et al., 2020). For example, Anderson et al. (2018) employed an exploratory factor analysis method to identify three variables (non-English home usage and English proficiency, non-English social use, and English use) that can describe different levels of bilingualism when all questionnaire items are included. Dash et al. (2022) used both subjective and objective measures of bilingualism and discovered three-factor structures (L2 Exposure and Proficiency–subjective, L2 Task proficiency–objective, and L2 Age of Acquisition–subjective) that had different effects on resting-state functional connectivity data. This method makes it easier for researchers to access different bilingual profiles and makes it easier to compare data from different cultural and linguistic backgrounds. These findings encourage comprehensive bilingualism tests since different features of bilingualism and the bilingual experience can have varied effects on cognitive performance. Gullifer et al. (2020) found different factor structures for language proficiency (L2 proficiency, L1 subjective proficiency, L1 objective proficiency), language entropy (Internal, external/professional, media), and language exposure (Internal, external/professional). In a recent review paper, Kremin and Byers-Heinlein (2021) proposed two methods to quantify bilingual experience using the factor mixture model and the grade of membership model. These models allow for effective accounts for bilingual language experience within categories and accommodate variations on a continuum. With the broader definition of bilingualism, there is inevitably more variation among people who are now classified as bilingual. Researchers have used factor mixture models to capture heterogeneity within groups (Clark et al., 2013; Sulpizio et al., 2020). Usually, participants are divided into groups based on the patterns of responses to the questionnaire, and each group is assigned a composite score on a continuous scale indicating their position within the group. For example, Sulpizio et al. (2020) used L2 AOA and L2 language entropy as the grouping variable and assessed the resting-state connectivity differences on a continuum of L2 proficiency. Another study by Luk and Bialystok (2013), although not assessing cognitive performance, used confirmatory factor analysis to extract two correlated factors–daily bilingual usage and English proficiency. On the other hand, a grade of membership model allows individuals to have partial membership in either of the groups based on the characteristic of the population. It is a latent structure model in which observable variables are represented as a continuous mixture of fuzzy classes; these classes account for the individual heterogeneity in bilingual groups. However, we are yet to see researchers using a grade of membership approach to the bilingual adult or aging population. Interestingly, a recent study has used a version of the graded membership approach with Spanish-speaking English learners at risk for reading difficulties attending middle school (Macdonald et al., 2022). Authors have used a combination of person-centered (using confirmatory factor analysis) and variable-centered approaches (using latent profile analysis) to characterize language skills and to identify different bilingual profiles within their study sample based on a battery of objective measures of language proficiency. However, the interrelationship of these outcome variables with cognitive performance is not directly assessed. It is crucial to note that the recommended number of participants for using the factor mixture and grade of membership models was 150-200 (Kremin and Byers-Heinlein, 2021), which was not the case in the studies mentioned above. Especially with the aging population, it is hard to reach the prescribed number. While noting the drawbacks of categorization, Grosjean (1998) proposed using one measure of bilingualism (for example, L2 proficiency) to perform regression analysis, with other related observable variables can be used as a covariate variable (i.e., L2 AOA), that may allow participants to be their controls. Given that different measures of bilingualism are interrelated to each other, one may also opt for partial correlation analysis. We expect that these scores will assist the researcher in quickly determining a proper estimation/classification of measures of bilingualism.

Performance-based cognitive measures and their neural correlates as an index of benefits related to bilingualism

Just like "bilingualism," "cognitive performance" also is a multifactorial reality. Beyond the intricacies of second language experience, Grosjean (1998) has stressed the necessity of taking multiple cognitive tasks into account when studying the impact of bilingualism on cognitive performance. The present debate on the role of bilingualism on cognition is suffering from oversimplified definitions for bilingualism and cognitive processes under study (Bialystok, 2021a). Usually, the impact of bilingualism is studied separately in different cognitive processes, like attention (Costa et al., 2008; Marzecová et al., 2013; Dash et al., 2019), cognitive control (Bialystok et al., 2005), working memory (Grundy and Timmer, 2017). However, cognitive processes are a multidimensional construct with interrelated thus, a single factor description of bilingualism and cognition is a reductionist approach to understanding the relationship between bilingualism and cognition (Bialystok, 2021a,b). Most of the studies discuss bilingual performance on executive function abilities using a wide variety of tasks (anti-saccade task, Stroop task, stop-signal task, letter memory task, letter-shape task, Simon task, flanker task, ANT, Wisconsin Card Sorting task, AX-CPT among others). However, performance on different cognitive tasks cannot be equated to the executive function ability and may have been influenced by other cognitive processes. In addition, other variables are known to influence executive function abilities (like education, leisure activities, socio-economic status), more so in the aging population (see Valian, 2014 for details). According to Valian (2014), lack of clarity on the definition and assessment of executive function and a lack of control over the confounding variables are the primary reasons for the discrepancies that are evident in the bilingual literature. Another example of discrepancy in the literature on the role of bilingualism in cognitive performance arises from the modality of testing the cognitive performance, i.e., by using verbal and non-verbal tasks. It is well-established that bilinguals perform poorer on verbal tasks across the lifespan (Bialystok, 2009), specifically in tasks requiring language production (Gollan et al., 2005; Sullivan et al., 2018), receptive vocabulary (Bialystok and Luk, 2012), lexical access in sentence comprehension (Shook et al., 2015) and verbal fluency (Rosselli et al., 2000). As a result, bilinguals perform worse on cognitive tasks involving verbal processing. These tasks do not correctly reflect the domain-general cognitive performance because of bilingual experiences, resulting in more evidence of sizeable cognitive advantage in non-verbal tasks. Usually, verbal fluency tasks that place more demand on the cognitive mechanism (i.e., letter fluency, Patra et al., 2020) have shown better performance in bilinguals than monolinguals, whereas, in the category fluency task, the gap between bilingual and monolingual performance is narrowed (Kormi-Nouri et al., 2012).

Another variability in bilingual literature is the multifactorial nature of demographic and life experiences, such as age, education, gender, social-economic status, and leisure. Some of these variables directly influence cognitive performance, whereas others relate to the bilingual experience. On average age-related cognitive decline begins in the Middle Ages (50–60 years old) and accelerate with increasing age (Ghisletta et al., 2019). Age-related changes are evident in many cognitive domains, such as memory, attention, executive function, visual perception, and linguistic abilities (Salthouse, 2004; Dash and Joanette, 2017). Furthermore, environmental influences and lifestyle choices can compensate for the magnitude of age-related changes in cognitive and structural brain alterations. Individuals with a higher premorbid IQ (Deary et al., 2004), educational (Franzmeier et al., 2017) or occupational attainment (Scarmeas and Stern, 2003), and engagement in leisure activities (Stern, 2021) may maintain cognitive ability despite age-related neural changes or neuropathology (Zahodne et al., 2015). Another demographic variable that may contribute to cognitive difference is gender. Women score higher on cognitive tasks that require verbal processing, whereas males score better on tasks that require visuospatial processing in adulthood (Hyde, 2016). A systematic study concluded that gender differences in cognitive decline are similar between 60 and 80 years. However, gender differences in cognitive decline may exist after the age of 80, albeit the directions of the relationships discovered were occasionally conflicting (Ferreira et al., 2014). Not many studies in the bilingual literature account for gender differences; studies in Figure 1 show that only 5 out 35 studies have used gender as a confounding variable. In a series of studies, Hilchey and Klein (2011) noted the significant variations in socio-cultural backgrounds of bilinguals vs. monolinguals and caution that there may be many other "hidden factors" that lead to performance discrepancies while comparing monolingual and bilingual participants.

To assess the relationship between bilingualism and cognition in older adults, we reviewed studies conducted in the past decade focusing on the methodological approaches discussed above. Figure 1 illustrates different studies that have highlighted (1) the multifactorial nature of bilingualism, (2) the multifactorial nature of cognitive performance, and (3) the multifactorial nature of confounding variables. Only a few studies have tried to assess all three aspects of multifactoriality (Keijzer and Schmid, 2016; Incera and McLennan, 2017; Dash et al., 2019, 2022). The multifactorial nature of bilingualism is established by using the measure of bilingualism on a continuum (Incera and McLennan, 2017; Dash et al., 2019, 2022) or by including subjective and multiple objective measures of bilingualism (Abutalebi et al., 2015; Keijzer and Schmid, 2016; Anderson et al., 2018) or my correlation L2 proficiency differences within the bilingual group with cognitive performance (Abutalebi et al., 2015; Antón et al., 2016; Clare et al., 2016). Dash et al. (2019, 2022) created the continuum of bilingualism by using four objective measures of language proficiency and self-reported information using LEAP-Q; and assessed the impact of bilingualism using factor scores on cognitive and neural processes. Incera and McLennan (2017) assessed participants varying in their level of L2 language usage and exposure (i.e., from completely monolingual to balanced bilinguals). It is worth acknowledging that the continuum approach is also used to study bilingualism in the younger population (DeLuca et al., 2019; Sulpizio et al., 2020). Studies using objective measures of bilingualism and self-reported information are another way to give weightage to the multifactorial nature of bilingualism (Abutalebi et al., 2015; Keijzer and Schmid, 2016; Anderson et al., 2018). Abutalebi et al. (2015) and Keijzer and Schmid (2016) used multiple measures of bilingualism to evaluate the impact of language competence on the cognitive performance of their bilingual groups (Abutalebi et al., 2015; Keijzer and Schmid, 2016). Also, Bak et al. (2014) reported differences in cognitive performance between the groups categorized based on AOA (Early vs. Late), language usage (active vs. passive) & the number of languages (2 vs. multi). However, there is a possibility of overlapping participants in different groups, and there can be substantial interaction between these categorizations.

The multifactorial nature of cognitive performance is assessed using multiple cognitive tasks to understand the impact of bilingualism. It was interesting that not all cognitive processes are impacted by bilingualism. Moreover, different aspects of bilingualism may impact different subcomponents of cognition. For example., Dash et al. (2022) reported that the objective measures of L2 proficiency, in contrast to self-reported information, as a measure of bilingualism, have a more significant potential to tap into the role of bilingualism in attentional processes. Similarly, Kousaie and Phillips (2017) reported an advantage in cognitive performance only in the Stroop task and not in the flanker and Simon task. Although Kousaie and Phillips (2017) found electrophysiological differences in task performance between groups, there was a lack of convergent validity in electrophysiological markers between tasks, suggesting that

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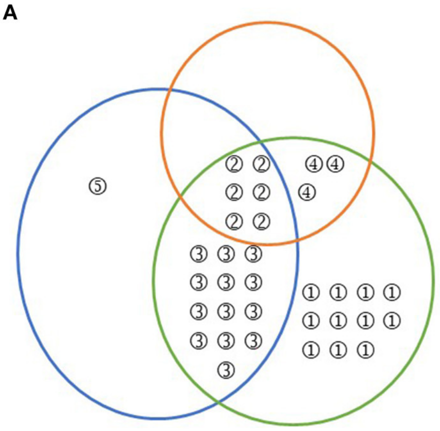
A



B

① Ansaldo et al., 2015
① Friesen et al., 2015
① Gold et al., 2013
① Grady et al., 2015
① Luk et al., 2011
① Olsen et al., 2015
① Rieker et al., 2020
① Soltani et al., 2019
① Berkes et al., 2021
① Del Maschio et al., 2018
① Luo et al., 2013
② Dash et al., 2019
② Dash et al., 2022
② Incera & McLennan 2017
② Bak et al., 2014
② Clare et al., 2016
② Keijzer & Schmid 2016
③ Bialystok et al., 2014
③ Blumenfeld et al., 2016
③ Anderson et al., 2017
③ Borsa et al., 2018
③ Cox et al., 2016
③ Ihle et al., 2016
③ Kousaie et al., 2014
③ Kousaie & Phillips 2017
③ Massa et al., 2020
③ Nielsen et al., 2019
③ Padilla et al., 2016
③ Papageorgious et al., 2019
③ Zirnstein et al., 2019
④ Abutalebi et al., 2014
④ Abutalebi et al., 2015
④ Anton et al., 2016
⑤ Gathercole et al., 2014

FIGURE 1
(A) Venn diagram to visually group bilingual research conducted with the aging population within three categories (1) the multifactorial nature of bilingualism (in Orange), (2) the multifactorial nature of cognitive performance (in Blue), and (3) the multifactorial nature of confounding variables (in Green). **(B)** Numbers refer to the references shown in the corresponding panel.

these tasks might assess different underlying mechanisms. The multifactorial nature of confounding variables is often assessed by accounting for the common demographic variables like age, education, and performance on the neuropsychological test, where groups are matched on these variables. More recently, studies are controlling for cognitive reserve variables and looking at the impact of age and bilingualism on cognitive performance (Incera and McLennan, 2017; Dash et al., 2022). Nevertheless, there is a lack of studies that account for all three aspects of multifactoriality within a single study. Figure 1 provides an exciting point of view on how researchers have used the different aspects of multifactoriality in combination. Bilingual research in the aging population will benefit from the inclusion of the three aspects of multifactoriality in forming a theoretical framework that can account for the role of bilingualism in different cognitive processes while including cognitive reserve framework (age, education, leisure, occupation) to further look at the three-way interaction.

Conclusion: Multifactorial approach to study bilingualism: A way forward

We agree with previous authors (Bialystok, 2021a; Marian and Hayakawa, 2021) to have a transparent definition of bilingualism and use multiple tools (de Bruin, 2019) to understand the bilingual population under study. After understanding the bilingual phenotype in a particular study, the next logical step is to see if researchers want to categorize or use the measures of bilingualism on a continuum depending on the research questions. This review enumerates multiple approaches that can effectively allow the researchers to use different measures of bilingualism. However, using a larger diverse dataset and advanced statistical methods to select bilingualism-related predictor variables is recommended. Methodological rigor is needed to define and assess bilingualism and to study the impact of bilingualism on different cognitive processes and their subprocesses. The inclusion of complementary performance-based cognitive measures contributes to understanding the role of bilingualism on individual cognitive processes, ultimately translating into identifying different markers of bilingualism that may influence cognition. In addition, measures of bilingualism (age of acquisition, language usage, and proficiency) may influence language representation in the brain differently and may thus influence different aspects of cognition. Different measures of bilingualism allow for a refined perspective on the impact of bilingualism on cognition, contrarily to the conflicting results obtained with past approaches. The multifactorial continuum approach to studying bilingualism allows an in-depth look at how bilingualism may contribute to cognitive and neural advantages. Finally, growing interest in the idea of bilingualism as a proxy of cognitive reserve (Bialystok, 2021b) needs to be carefully assessed by acknowledging the interaction of bilingual experience with other life experiences like education, occupation, leisure, and socio-economic status. Future researchers should assess the interaction between bilingualism and other cognitive reserve variables on cognitive performances rather than merely controlling them in studies.

Although the current paper aims to encourage researchers to consider the multifactorial approach in studying bilingualism, we have focused predominantly on the external factors (i.e., environmental factors) related to the bilingual experience. However, previous studies have effectively addressed the impact of organism internal factors like genetics on the level of bilingualism (Vaughn and Hernandez, 2018). Similarly, studies have shown that inter-individual differences in cognitive performance (Friedman et al., 2008; Kanai and Rees, 2011; Parasuraman and Jiang, 2012) and cognitive/neural reserve (Stern, 2017; Pettigrew and Soldan, 2019; Stern et al., 2020) are influenced by biological/genetic factors. The genetic factors may interact with environmental factors (L2 usage and exposure, SES, occupation, education) to produce variations in cognitive functions like memory, attention, and language. It is beyond the scope of the current review to discuss the multifactorial nature of organism internal factors and the current review has focused on the multifactorial nature of external/environmental factors. We hope that the multifactorial nature of bilingualism, cognition, and confounding variables delineated in this review will provide a framework for researchers to create a working model of the impact of bilingualism on cognition.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

TD drafted the initial article. TD, AA, and YJ participated in the manuscript preparation. All authors read the final manuscript and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abutalebi, J., Canini, M., Della Rosa, P. A., Sheung, L. P., Green, D. W., and Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiol. Aging* 35, 2126–2133. doi: 10.1016/j.neurobiolaging.2014.03.010

Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P. A., Parris, B. A., et al. (2015). Bilingualism provides a neural reserve for aging populations. *Neuropsychologia* 69, 201–210. doi: 10.1016/j.neuropsychologia.2015.01.040

Abutalebi, J., and Rietbergen, M. J. (2014). Neuroplasticity of the bilingual brain: Cognitive control and reserve. *Appl. Psycholinguist.* 35, 895–931. doi: 10.1017/S0142716414000186

Adesope, O. O., Lavin, T., Thompson, T., and Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Rev. Educ. Res.* 80, 207–245. doi: 10.3102/0034654310368803

Ali, S., Elliott, L., Biss, R. K., Abumeeiz, M., Brantuo, M., Kuzmenka, P., et al. (2022). The BNT-15 provides an accurate measure of English proficiency in cognitively intact bilinguals—a study in cross-cultural assessment. *Appl. Neuropsychol. Adult* 29, 351–363. doi: 10.1080/23279095.2020.1760277

Altman, D. G., and Royston, P. (2006). The cost of dichotomising continuous variables. *BMJ* 332, 1080. doi: 10.1136/bmj.332.7549.1080

Anderson, J., Mak, L., Keyvani Chahi, A., and Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behav. Res. Methods* 50, 250–263. doi: 10.3758/s13428-017-0867-9

Anderson, J. A., Saleemi, S., and Bialystok, E. (2017). Neuropsychological assessments of cognitive aging in monolingual and bilingual older adults. *J. Neurolinguistics* 43, 17–27. doi: 10.1016/j.jneuroling.2016.08.001

Ansaldo, A. I., Ghazi-Saidi, L., and Adrover-Roig, D. (2015). Interference control in elderly bilinguals: appearances can be misleading. *J. Clin. Exp. Neuropsychol.* 37, 455–470. doi: 10.1080/13803395.2014.990359

Antón, E., García, Y. F., Carreiras, M., and Duñabeitia, J. A. (2016). Does bilingualism shape inhibitory control in the elderly? *J. Mem. Lang.* 90, 147–160. doi: 10.1016/j.jml.2016.04.007

Bak, T. H., Nissan, J. J., Allerhand, M. M., and Deary, I. J. (2014). Does bilingualism influence cognitive aging?. *Ann. Neurol.* 75, 959–963. doi: 10.1002/ana.24158

Baker, W., and Trofimovich, P. (2005). Interaction of native- and second-language vowel system(s) in early and late bilinguals. *Lang. Speech* 48, 1–27. doi: 10.1177/00238309050480010101

Baum, S., and Titone, D. (2014). Moving toward a neuroplasticity view of bilingualism, executive control, and aging. *Appl. Psycholinguist.* 35, 857–894. doi: 10.1017/S0142716414000174

Baumgart, C. Q., and Billick, S. B. (2018). Positive cognitive effects of bilingualism and multilingualism on cerebral function: a review. *Psychiatr. Q.* 89, 273–283. doi: 10.1007/s11126-017-9532-9

Berkes, M., Calvo, N., Anderson, J., and Bialystok, E. (2021). Poorer clinical outcomes for older adult monolinguals when matched to bilinguals on brain health. *Brain Struct. Funct.* 226, 415–424. doi: 10.1007/s00429-020-02185-5

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Biling. Lang. Cogn.* 12, 3–11. doi: 10.1017/S1366728908003477

Bialystok, E. (2021a). Bilingualism as a slice of swiss cheese. *Front. Psychol.* 12, 769323. doi: 10.3389/fpsyg.2021.769323

Bialystok, E. (2021b). Bilingualism: Pathway to cognitive reserve. *Trends Cogn. Sci.* 25, 355–364. doi: 10.1016/j.tics.2021.02.003

Bialystok, E., Craik, F. I. M., Grady, C., Chau, W., Ishii, R., Gunji, A., et al. (2005). Effect of bilingualism on cognitive control in the Simon task: Evidence from MEG. *Neuroimage* 24, 40–49. doi: 10.1016/j.neuroimage.2004.09.044

Bialystok, E., and Luk, G. (2012). Receptive vocabulary differences in monolingual and bilingual adults. *Biling. Lang. Cogn.* 15, 397–401. doi: 10.1017/S136672891100040X

Bialystok, E., Poarch, G., Luo, L., and Craik, F. (2014). Effects of bilingualism and aging on executive function and working memory. *Psychol. Aging* 29, 696–705. doi: 10.1037/a0037254

Blumenfeld, H. K., Schroeder, S. R., Bobb, S. C., Freeman, M. R., and Marian, V. (2016). Auditory word recognition across the lifespan: Links between linguistic and nonlinguistic inhibitory control in bilinguals and monolinguals. *Linguistic Approach. Biling.* 6, 119–146. doi: 10.1075/lab.14030.blu

Borsa, V. M., Perani, D., Della Rosa, P. A., Videsott, G., Guidi, L., Weekes, B. S., et al. (2018). Bilingualism and healthy aging: Aging effects and neural maintenance. *Neuropsychologia* 111, 51–61. doi: 10.1016/j.neuropsychologia.2018.01.012

Calabria, M., Hernández, M., Cattaneo, G., Suades, A., Serra, M., Juncadella, M., et al. (2020). Active bilingualism delays the onset of mild cognitive impairment. *Neuropsychologia* 146, 107528. doi: 10.1016/j.neuropsychologia.2020.107528

Champoux-Larsson, M.-F., and Dylman, A. S. (2021). Bilinguals' inference of emotions in ambiguous speech. *Int. J. Biling.* 25, 1297–1310. doi: 10.1177/13670069211018847

Clare, L., Whitaker, C. J., Craik, F. I., Bialystok, E., Martyr, A., Martin-Forbes, P. A., et al. (2016). Bilingualism, executive control, and age at diagnosis among people with early-stage Alzheimer's disease in Wales. *J. Neuropsychol.* 10, 163–185. doi: 10.1111/jnp.12061

Clark, S. L., Muthen, B., Kaprio, J., D'Onofrio, B. M., Viken, R., and Rose, R. J. (2013). Models and strategies for factor mixture analysis: An example concerning the structure underlying psychological disorders. *Struct. Eqn. Model.* 20, 681–703. doi: 10.1080/10705511.2013.824786

Claussenius-Kalman, H., Hernandez, A. E., and Li, P. (2021). Expertise, ecosystem, and emergentism: Dynamic developmental bilingualism. *Brain Lang.* 222, 105013. doi: 10.1016/j.bandl.2021.105013

Cohen, J. (1983). The cost of dichotomization. *Appl. Psychol. Meas.* 7, 249–253. doi: 10.1177/014662168300700301

Costa, A., Hernández, M., and Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: evidence from the ANT task. *Cognition* 106, 59–86. doi: 10.1016/j.cognition.2006.12.013

Cox, S. R., Bak, T. H., Allerhand, M., Redmond, P., Starr, J. M., Deary, I. J., et al. (2016). Bilingualism, social cognition and executive functions: A tale of chickens and eggs. *Neuropsychologia* 91, 299–306. doi: 10.1016/j.neuropsychologia.2016.08.029

Dash, T., Berroir, P., Joanette, Y., and Ansaldo, A. I. (2019). Alerting, orienting, and executive control: The effect of bilingualism and age on the subcomponents of attention. *Front. Neurol.* 10, 1122. doi: 10.3389/fneur.2019.01122

Dash, T., and Joanette, Y. (2017). "Neurocognitive markers of aging," In *Encyclopedia of Geropsychology*, ed N. A. Pachana (Singapore: Springer). doi: 10.1007/978-981-287-082-7_302

Dash, T., Joanette, Y., and Ansaldo, A. I. (2022). Exploring attention in the bilingualism continuum: A resting-state functional connectivity study. *Brain Lang.* 224, 105048. doi: 10.1016/j.bandl.2021.105048

Dash, T., and Kar, B. R. (2012). Characterizing language proficiency in Hindi and English language: Implications for bilingual research. *Int. J. Mind Brain Cognit.* 3, 73–105.

de Bruin, A. (2019). Not all bilinguals are the same: A call for more detailed assessments and descriptions of bilingual experiences. *Behav. Sci.* 9, 33. doi: 10.3390/bs9030033

de Bruin, A., Carreiras, M., and Duñabeitia, J. A. (2017). The BEST dataset of language proficiency. *Front. Psychol.* 8, 522. doi: 10.3389/fpsyg.2017.00522

de Bruin, A., Dick, A. S., and Carreiras, M. (2021). Clear theories are needed to interpret differences: Perspectives on the bilingual advantage debate. *Neurobiol. Lang.* 2, 433–451. doi: 10.1162/nol_a_00038

Deary, I. J., Whiteman, M. C., Pattie, A., Starr, J. M., Hayward, C., Wright, A. F., et al. (2004). Apolipoprotein E gene variability and cognitive functions at age 79: A follow-up of the scottish mental survey of 1932. *Psychol. Aging* 19, 367–371. doi: 10.1037/0882-7974.19.2.367

DeCoster, J., Gallucci, M., and Iselin, A.-M. R. (2011). Best practices for using median splits, artificial categorization, and their continuous alternatives. *J. Experi. Psychopathol.* 2, jep.008310. doi: 10.5127/jep.008310

Del Maschio, N., Sulpizio, S., Gallo, F., Fedeli, D., Weekes, B. S., and Abutalebi, J. (2018). Neuroplasticity across the lifespan and aging effects in bilinguals and monolinguals. *Brain Cogn.* 125, 118–126. doi: 10.1016/j.bandc.2018.06.007

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U.S.A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

Dunn, L. M., and Dunn, L. M. (1997). *Peabody Picture Vocabulary Test-III*. Circle Pines, MN: American Guidance Service. doi: 10.1037/t15145-000

Farrington, D. P., and Loeber, R. (2000). Some benefits of dichotomization in psychiatric and criminological research. *Crim. Behav. Mental Health* 10, 100–122. doi: 10.1002/cbm.349

Ferreira, L., Ferreira Santos-Galduróz, R., Ferri, C. P., and Fernandes Galduróz, J. C. (2014). Rate of cognitive decline in relation to sex after 60 years-of-age: a systematic review. *Geriatr. Gerontol. Int.* 14, 23–31. doi: 10.1111/ggi.12093

Franzmeier, N., Duering, M., Weiner, M., Dichgans, M., and Ewers, M. (2017). Left frontal cortex connectivity underlies cognitive reserve in prodromal Alzheimer disease. *Neurology* 88, 1054–1061. doi: 10.1212/WNL.0000000000003711

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., and Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *J. Exp. Psychol. Gen.* 137, 201–225. doi: 10.1037/0096-3445.137.2.201

Friesen, D. C., Luo, L., Luk, G., and Bialystok, E. (2015). Proficiency and control in verbal fluency performance across the lifespan for monolinguals and bilinguals. *Lang. Cognit. Neurosci.* 30, 238–250. doi: 10.1080/23273798.2014.918630

Gallo, F., Kubiak, J., and Myachykov, A. (2022). Add bilingualism to the Mix: L2 proficiency modulates the effect of cognitive reserve proxies on executive performance in healthy aging. *Front. Psychol.* 13, 780261. doi: 10.3389/fpsyg.2022.780261

Gathercole, V. C., Thomas, E. M., Kennedy, I., Prys, C., Young, N., Viñas Guasch, N., et al. (2014). Does language dominance affect cognitive performance in bilinguals? Lifespan evidence from preschoolers through older adults on card sorting, Simon, and metalinguistic tasks. *Front. Psychol.* 5, 11. doi: 10.3389/fpsyg.2014.00011

Ghisletta, P., Mason, F., von Oertzen, T., Hertzog, C., Nilsson, L.-G., and Lindenberger, U. (2019). On the use of growth models to study normal cognitive aging. *Int. J. Behav. Dev.* 44, 88–96. doi: 10.1177/0165025419851576

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., and Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *J. Neurosci.* 33, 387–396. doi: 10.1523/JNEUROSCI.3837-12.2013

Gollan, T. H., Montoya, R. I., Fennema-Notestine, C., and Morris, S. K. (2005). Bilingualism affects picture naming but not picture classification. *Mem. Cognit.* 33, 1220–1234. doi: 10.3758/BF03193224

Gollan, T. H., Weissberger, G. H., Runnqvist, E., Montoya, R. I., and Cera, C. M. (2012). Selfratings of spoken language dominance: A Multilingual Naming Test (MINT) and preliminary norms for young and aging Spanish-English bilinguals. *Biling. Lang. Cogn.* 15, 594–615. doi: 10.1017/S1366728911000332

Goodglass, H., Kaplan, E., and Weintraub, S. (2001). *BDAE: The Boston Diagnostic Aphasia Examination*. Philadelphia, PA: Lippincott Williams & Wilkins.

Grady, C. L., Luk, G., Craik, F. I., and Bialystok, E. (2015). Brain network activity in monolingual and bilingual older adults. *Neuropsychologia* 66, 170–181. doi: 10.1016/j.neuropsychologia.2014.10.042

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *J. Cognit. Psychol.* 25, 515–530. doi: 10.1080/20445911.2013.796377

Gregg, K. (2004). The state of emergentism in second language language acquisition. *Second Lang. Res.* 19, 95–128. doi: 10.1191/0267658303sr213oa

Grosjean, F. (1998). Studying bilinguals: Methodological and conceptual issues. *Biling. Lang. Cogn.* 1, 131–149. doi: 10.1017/S136672899800025X

Grundy, J. G. (2020). The effects of bilingualism on executive functions: an updated quantitative analysis. *J. Cult. Cognit. Sci.* 4, 177–199. doi: 10.1007/s41809-020-00062-5

Grundy, J. G., and Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. Second *Lang. Res.* 33, 325–340. doi: 10.1177/0267658316678286

Gullifer, J., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Biling. Lang. Cogn.* 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., et al. (2020). Bilingual language experience as a multidimensional spectrum: Associations with objective and subjective language proficiency. *Appl. Psycholinguist.* 42, 245–278. doi: 10.1017/S0142716420000521

Gullifer, J. W., and Titone, D. (2018). *Compute Language Entropy With {languageEntropy}*. Available online at: https://github.com/jasongullifer/languageEntropy (accessed July 27, 2020).

Gullifer, J. W., and Titone, D. (2021). Bilingualism: A neurocognitive exercise in managing uncertainty. *Neurobiol. Lang.* 2, 464–486. doi: 10.1162/nol_a_00044

Hernandez, A. E., Claussenius-Kalman, H. L., Ronderos, J., Castilla-Earls, A. P., Sun, L., Weiss, S. D., et al. (2019). Neuroemergentism: A framework for studying cognition and the brain. *J. Neurolinguistics* 49, 214–223. doi: 10.1016/j.jneuroling.2017.12.010

Hernandez, A. E., Claussenius-Kalman, H. L., Ronderos, J., and Vaughn, K. A. (2018). Symbiosis, parasitism and bilingual cognitive control: a neuroemergentist perspective. *Front. Psychol.* 9, 2171. doi: 10.3389/fpsyg.2018.02171

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

Hulstijn, J. (2012). The construct of language proficiency in the study of bilingualism from a cognitive perspective. *Biling. Lang. Cogn.* 15, 422–433. doi: 10.1017/S1366728911000678

Hyde, J. S. (2016). Sex and cognition: gender and cognitive functions. *Curr. Opin. Neurobiol.* 38, 53–56. doi: 10.1016/j.conb.2016.02.007

Ihle, A., Oris, M., Fagot, D., Maggiori, C., and Kliegel, M. (2016). The association of educational attainment, cognitive level of job, and leisure activities during the course of adulthood with cognitive performance in old age: the role of openness to experience. *Int. Psychogeriatr.* 28, 733–740. doi: 10.1017/S1041610215001933

Incera, S., and McLennan, C. T. (2017). Bilingualism and age are continuous variables that influence executive function. *Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn.* 25, 443–463. doi: 10.1080/13825585.2017.1319902

Jylkkä, J., Soveri, A., Laine, M., and Lehtonen, M. (2020). Assessing bilingual language switching behavior with ecological momentary assessment. *Biling. Lang. Cogn.* 23, 309–322. doi: 10.1017/S1366728918001190

Kalia, V., Lane, P. D., and Wilbourn, M. P. (2018). Cognitive control and phonological awareness in the acquisition of second language vocabulary within the Spanish-English dual immersion context. *Cogn. Dev.* 48, 176–189. doi: 10.1016/j.cogdev.2018.08.010

Kanai, R., and Rees, G. (2011). The structural basis of inter-individual differences in human behaviour and cognition. *Nat. Rev. Neurosci.* 12, 231–242. doi: 10.1038/nrn3000

Keijzer, M. C., and Schmid, M. S. (2016). Individual differences in cognitive control advantages of elderly late Dutch-English bilinguals. *Linguistic Approach. Biling.* 6, 64–85. doi: 10.1075/lab.14032.kei

Kormi-Nouri, R., Moradi, A., Moradi, S., Akbari-Zardkhaneh, S., and Zahedian, H. (2012). The effect of bilingualism on letter and category fluency tasks in primary school children: Advantage or disadvantage? *Biling. Lang. Cogn.* 15, 351–364. doi: 10.1017/S1366728910000192

Kousaie, S., and Phillips, N. A. (2017). A behavioural and electrophysiological investigation of the effect of bilingualism on aging and cognitive control. *Neuropsychologia* 94, 23–35. doi: 10.1016/j.neuropsychologia.2016.11.013

Kousaie, S., Sheppard, C., Lemieux, M., Monetta, L., and Taler, V. (2014). Executive function and bilingualism in young and older adults. *Front. Behav. Neurosci.* 8, 250. doi: 10.3389/fnbeh.2014.00250

Kremin, L. V., and Byers-Heinlein, K. (2021). Why not both? Rethinking categorical and continuous approaches to bilingualism. *Int. J. Biling.* 25, 1560–1575. doi: 10.1177/13670069211031986

Lai, G., and O'Brien, B. A. (2020). Examining language switching and cognitive control through the adaptive control hypothesis. *Front. Psychol.* 11, 1171. doi: 10.3389/fpsyg.2020.01171

Lemhöfer, K., and Broersma, M. (2012). Introducing LexTALE: a quick and valid Lexical Test for Advanced Learners of English. *Behav. Res. Methods* 44, 325–343. doi: 10.3758/s13428-011-0146-0

Li, P., Sepanski, S., and Zhao, X. (2006). Language history questionnaire: A Web-based interface for bilingual research. *Behav. Res. Methods* 38, 202–210. doi: 10.3758/BF03192770

Li, P., Zhang, F., Tsai, E., and Puls, B. (2014). Language history questionnaire (LHQ 2.0): A new dynamic web-based research tool. *Biling. Lang. Cogn.* 17, 673–680. doi: 10.1017/S1366728913000606

Li, P., Zhang, F., Yu, A., and Zhao, X. (2020). Language History Questionnaire (LHQ3): An enhanced tool for assessing multilingual experience. *Biling. Lang. Cogn.* 23, 938–944. doi: 10.1017/S1366728918001153

Luk, G. (2015). Who are the bilinguals (and monolinguals)? *Biling. Lang. Cogn.* 18, 35–36. doi: 10.1017/S1366728914000625

Luk, G., and Bialystok, E. (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *J. Cognit. Psychol.* 25, 605–621. doi: 10.1080/20445911.2013.795574

Luk, G., Bialystok, E., Craik, F. I., and Grady, C. L. (2011). Lifelong bilingualism maintains white matter integrity in older adults. *J. Neurosci.* 31, 16808–16813. doi: 10.1523/JNEUROSCI.4563-11.2011

Luo, L., Craik, F. I., Moreno, S., and Bialystok, E. (2013). Bilingualism interacts with domain in a working memory task: evidence from aging. *Psychol. Aging* 28, 28–34. doi: 10.1037/a0030875

MacCallum, R. C., Zhang, S., Preacher, K. J., and Rucker, D. D. (2002). On the practice of dichotomization of quantitative variables. *Psychol. Methods* 7, 19–40. doi: 10.1037/1082-989X.7.1.19

Macdonald, K. T., Francis, D. J., Hernandez, A. E., Castilla-Earls, A. P., and Cirino, P. T. (2022). Characterization of English and Spanish language proficiency among middle school English learners with reading difficulties. *Biling. Lang. Cognit.* 2022, 1–14. doi: 10.1017/S1366728922000104

MacWhinney, B. (2002). "Language emergence: Five timeframes and three illustrations," in *An Integrated View of Language Development*, eds P. Burmeister, T. Piske, and A. Rohde (Trier: Wissenschaftlicher Verlag), 17–42.

Marian, V., Blumenfeld, H. K., and Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. *J. Speech Lang. Hear. Res.* 50, 940–967. doi: 10.1044/1092-4388(2007/067)

Marian, V., and Hayakawa, S. (2021). Measuring bilingualism: The quest for a "bilingualism quotient". *Appl. Psycholinguist.* 42, 527–548. doi: 10.1017/S0142716420000533

Marzecová, A., Asanowicz, D., Krivá, L., and Wodniecka, Z. (2013). The effects of bilingualism on efficiency and lateralization of attentional networks. *Bilingualism* 16, 608–623. doi: 10.1017/S1366728912000569

Massa, E., Köpke, B., and El Yagoubi, R. (2020). Age-related effect on language control and executive control in bilingual and monolingual speakers: Behavioral and electrophysiological evidence. *Neuropsychologia* 138, 107336. doi: 10.1016/j.neuropsychologia.2020.107336

Mill, J. S. (1843). *A System of Logic, Ratiocinative and Inductive: Being a Connected View of the Principles of Evidence, and the Methods of Scientific Investigation (Cambridge Library Collection - Philosophy)*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9781139149846

Nielsen, T. R., Antelius, E., and Waldemar, G. (2019). Cognitive Advantages in Adult Turkish Bilingual Immigrants - a Question of the Chicken or the Egg. *J. Cross Cult. Gerontol.* 34, 115–129. doi: 10.1007/s10823-019-09375-7

Olsen, R. K., Pangelinan, M. M., Bogulski, C., Chakravarty, M. M., Luk, G., Grady, C. L., et al. (2015). The effect of lifelong bilingualism on regional grey and white matter volume. *Brain Res.* 1612, 128–139. doi: 10.1016/j.brainres.2015.02.034

Paap, K. R., Anders-Jefferson, R., Mason, L., Alvarado, K., and Zimiga, B. (2018). Bilingual advantages in inhibition or selective attention: More challenges. *Front. Psychol.* 9, 1409. doi: 10.3389/fpsyg.2018.01409

Paap, K. R., and Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* 66, 232–258. doi: 10.1016/j.cogpsych.2012.12.002

Padilla, C., Mendez, M. F., Jimenez, E. E., and Teng, E. (2016). Bilingualism in older Mexican-American immigrants is associated with higher scores on cognitive screening. *BMC Geriatr.* 16, 1–9. doi: 10.1186/s12877-016-0368-1

Papageorgiou, A., Bright, P., Periche Tomas, E., and Filippi, R. (2019). Evidence against a cognitive advantage in the older bilingual population. *Q. J. Experi. Psychol.* 72, 1354–1363. doi: 10.1177/1747021818796475

Parasuraman, R., and Jiang, Y. (2012). Individual differences in cognition, affect, and performance: behavioral, neuroimaging, and molecular genetic approaches. *Neuroimage* 59, 70–82. doi: 10.1016/j.neuroimage.2011.04.040

Patra, A., Bose, A., and Marinis, T. (2020). Performance difference in verbal fluency in bilingual and monolingual speakers. *Biling. Lang. Cogn.* 23, 204–218. doi: 10.1017/S1366728918001098

Pelham, S. D., and Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *J. Experi. Psychol.* 40, 313–325. doi: 10.1037/a0035224

Pérez, M., Izura, C., Stadthagen-González, H., and Marín, J. (2013). "Assessment of bilinguals' performance in lexical tasks using reaction times," In *Issues in the Assessment of Bilinguals*, ed V. Gathercole (Bristol: Multilingual Matters). doi: 10.21832/9781783090105-008

Pettigrew, C., and Soldan, A. (2019). Defining cognitive reserve and implications for cognitive aging. *Curr. Neurol. Neurosci. Rep.* 19, 1. doi: 10.1007/s11910-019-0917-z

Pliatsikas, C., and Luk, G. (2016). Executive control in bilinguals: A concise review on fMRI studies. *Biling. Lang. Cognit.* 19, 699–705. doi: 10.1017/S1366728916000249

Rieker, J. A., Reales, J. M., and Ballesteros, S. (2020). The effect of bilingualism on cue-based vs. memory-based task switching in older adults. *Front. Hum. Neurosci.* 14, 610548. doi: 10.3389/fnhum.2020.610548

Rodriguez-Fornells, A., Krämer, U. M., Lorenzo-Seva, U., Festman, J., and Münte, T. F. (2012). Self-assessment of individual differences in language switching. *Front. Psychol.* 2, 388. doi: 10.3389/fpsyg.2011.00388

Rosselli, M., Ardila, A., Araujo, K., Weekes, V. A., Caracciolo, V., Padilla, M., et al. (2000). Verbal fluency and repetition skills in healthy older Spanish-English bilinguals. *Appl. Neuropsychol.* 7, 17–24. doi: 10.1207/S15324826AN0701_3

Salthouse, T. A. (2004). What and when of cognitive aging. *Curr. Dir. Psychol. Sci.* 13, 140–144. doi: 10.1111/j.0963-7214.2004.00293.x

Scarmeas, N., and Stern, Y. (2003). Cognitive reserve and lifestyle. *J. Clin. Exp. Neuropsychol.* 25, 625–633. doi: 10.1076/jcen.25.5.625.14576

Shiffman, S., Stone, A. A., and Hufford, M. R. (2008). Ecological momentary assessment. *Annu. Rev. Clin. Psychol.* 4, 1–32. doi: 10.1146/annurev.clinpsy.3.022806.091415

Shook, A., Goldrick, M., Engstler, C., and Marian, V. (2015). Bilinguals show weaker lexical access during spoken sentence comprehension. *J. Psycholinguist. Res.* 44, 789–802. doi: 10.1007/s10936-014-9322-6

Singh, N., and Mishra, R. (2012). Does language proficiency modulate oculomotor control? Evidence from Hindi–English bilinguals. *Biling. Lang. Cognit.* 15, 771–781. doi: 10.1017/S1366728912000065

Singh, N., and Mishra, R. K. (2013). Second language proficiency modulates conflict-monitoring in an oculomotor Stroop task: evidence from Hindi-English bilinguals. *Front. Psychol.* 4, 322. doi: 10.3389/fpsyg.2013.00322

Soltani, M., Moradi, N., Rezaei, H., Hosseini, M., and Jasemi, E. (2021). Comparison of verbal fluency in monolingual and bilingual elderly in Iran. *Appl. Neuropsychol. Adult* 28, 80–87. doi: 10.1080/23279095.2019.1594234

Stern, Y. (2017). An approach to studying the neural correlates of reserve. *Brain Imag Behav.* 11, 410–416. doi: 10.1007/s11682-016-9566-x

Stern, Y. (2021). How can cognitive reserve promote cognitive and neurobehavioral health? *Arch. Clin. Neuropsychol.* 36, 1291–1295. doi: 10.1093/arclin/acab049

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., et al. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer Dementia* 16, 1305–1311. doi: 10.1016/j.jalz.2018.07.219

Suarez, P., Gollan, T., Heaton, R., Grant, I., and Cherner, M. (2014). Second-language fluency predicts native language stroop effects: Evidence from Spanish–English Bilinguals. *J. Int. Neuropsychol. Soc.* 20, 342–348. doi: 10.1017/S1355617714000058

Sullivan, M., Poarch, G., and Bialystok, E. (2018). Why is lexical retrieval slower for bilinguals? Evidence from picture naming. *Biling. Lang. Cognit.* 21, 479–488. doi: 10.1017/S1366728917000694

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., and Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *Neuroimage* 205, 116306. doi: 10.1016/j.neuroimage.2019.116306

Surrain, S., and Luk, G. (2019). Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005–2015. *Biling. Lang. Cogn.* 22, 401–415. doi: 10.1017/S1366728917000682

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., and Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Front. Psychol.* 2, 123. doi: 10.3389/fpsyg.2011.00123

Tomoschuk, B., Ferreira, V., and Gollan, T. (2019). When a seven is not a seven: Self-ratings of bilingual language proficiency differ between and within language populations. *Biling. Lang. Cogn.* 22, 516–536. doi: 10.1017/S1366728918000421

Valian, V. (2014). Bilingualism and cognition. *Biling. Lang. Cogn.* 18, 3–24. doi: 10.1017/S1366728914000522

van den Noort, M., Struys, E., Bosch, P., Jaswetz, L., Perriard, B., Yeo, S., et al. (2019). Does the bilingual advantage in cognitive control exist and if so, what are its modulating factors? A Systematic Review. *Behav. Sci.* 9, 27. doi: 10.3390/bs9030027

Vaughn, K. A., and Hernandez, A. E. (2018). Becoming a balanced, proficient bilingual: Predictions from age of acquisition & genetic background. *J. Neurolinguistics* 46, 69–77. doi: 10.1016/j.jneuroling.2017.12.012

Woumans, E., Ceuleers, E., Van der Linden, L., Szmalec, A., and Duyck, W. (2015). Verbal and nonverbal cognitive control in bilinguals and interpreters. *J. Experi. Psychol.* 41, 1579–1586. doi: 10.1037/xlm0000107

Zahodne, L. B., Stern, Y., and Manly, J. J. (2015). Differing effects of education on cognitive decline in diverse elders with low versus high educational attainment. *Neuropsychology* 29, 649–657. doi: 10.1037/neu0000141

Zirnstein, M., van Hell, J. G., and Kroll, J. F. (2019). Cognitive control and language ability contribute to online reading comprehension: Implications for older adult bilinguals. *Int. J. Biling.* 23, 971–985. doi: 10.1177/1367006918763143

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Bilingualism is always cognitively advantageous, but this doesn't mean what you think it means

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For decades now a research question has firmly established itself as a staple of psychological and neuroscientific investigations on language, namely the question of whether and how bilingualism is cognitively beneficial, detrimental or neutral. As more and more studies appear every year, it seems as though the research question itself is firmly grounded and can be answered if only we use the right experimental manipulations and subject the data to the right analysis methods and interpretive lens. In this paper we propose that, rather than merely improving prior methods in the pursuit of evidence in one direction or another, we would do well to carefully consider whether the research question itself is as firmly grounded as it might appear to be. We identify two bodies of research that suggest the research question to be highly problematic. In particular, drawing from work in sociolinguistics and in embodied cognitive science, we argue that the research question of whether bilingualism is cognitively advantageous or not is based on problematic assumptions about language and cognition. Once these assumptions are addressed head on, a straightforward answer to the question arises, but the question itself comes to seem to be a poor starting point for research. After examining why this is so, we conclude by exploring some implications for future research.

KEYWORDS

bilingualism, multilingualism, language ideologies, sociolinguistics, communities of practice, information processing, embodied cognition, ecological psychology

Introduction

Is the ability to speak more than one language cognitively beneficial, cognitively detrimental, or cognitively neutral? In the past couple of decades the literature seems to have converged on a mixed conclusion: bilingualism confers to the speaker some cognitive advantages while also bringing with it some cognitive disadvantages.

On the one hand, for instance, there is a wealth of evidence suggesting that bilinguals exhibit increased executive function and executive control, including better performance than monolinguals in some problem-solving tasks, especially those requiring self-monitoring and the inhibition of irrelevant information (Bialystok et al., 2008; Festman et al., 2010; Pelham and Abrams, 2014). This positive relation between bilingualism and greater executive function has been found to apply throughout the lifespan, from childhood to old age (Bialystok, 2007). Yet it's especially later in life that the advantage appears to be greater, as bilingualism is associated with increased cognitive flexibility and mental health benefits for the elderly, including delayed dementia onset (Fox et al., 2019).

On the other hand, however, many studies (including some of the same ones already cited) also report clearly negative cognitive effects of bilingualism. Most prominent among these cognitive disadvantages are a deficit in lexical access and retrieval (Bialystok et al., 2008; Pelham and Abrams, 2014) and worse performance in speech production tasks (Sadat et al., 2012), as well as diminished metacognitive efficiency (Folke et al., 2016). Not only that, but even some of the cognitive advantages cited above have come to be questioned in the recent literature. For instance, in a meta-analysis Lehtonen and colleagues propose that the findings showing an advantage of bilingualism with regard to executive function suffer from publication bias, and they conclude that, correcting for this bias, the cognitive advantage is minimal if at all existent: "If some enhancement of cognitive control functions exists attributable to bilingualism, it is restricted to very specific circumstances, and its magnitude and extent are modest" (Lehtonen et al., 2018, p. 416). Negative results like these are made even more impactful in light of research that more generally challenges psychometric constructs such as "inhibition" (Rey-Mermet et al., 2018).

Despite this recent flood of work arguing in favor of these diverse answers, the debate is far from new. Writing in 1966, Diebold (1968) notes that, among educators in the United States, the dominant view at that time was that bilingualism is "a damaging experience for the child, one which poses hurdles to the child's intellectual development and later emotional adjustment" (pp. 1–2). And even while he had reservations about extreme versions of this view, Diebold also cites prior research, from the 1950s and 60s, to suggest that at that point the idea that bilingualism is cognitively deleterious was scientifically well founded: "Let this be clear from the start: competent recent surveys of the literature (…) do reveal that there is an association between bilingualism and lower intelligence ratings" (p. 2). In reality, however, then as now, evidence could be found supporting different conclusions about the cognitive advantages or disadvantages of bilingualism. Doctoral dissertations from that period make this point very clear.

Consider, for instance, Potts's (1965) doctoral work on the effect that one year of instruction in a foreign language (French) played in the reading proficiency and overall school achievements of monolingual American first grade students. The usual recommendation then was that second-language instruction should be provided only later, after students had developed strong reading and writing skills in English, to avoid interference from the foreign language. But having found no cognitive effect, whether positive or negative, Potts (1965) proposed that first grade was a perfectly fine time to include second-language instruction in the curriculum. For another example, in contrast with Potts's focus on monolingual American first-graders who were starting to learn a foreign language at school, Anisfeld's (1964) doctoral research studied teenagers and adults with life-long experiences with two languages. Anisfeld defined cognitive functioning in terms of performance in intelligence tests and related tasks, and found that, controlling for IQ scores, subjects who were proficient in more than one language had a clear cognitive advantage: "bilinguals are superior to monolinguals on intellectual tasks requiring abilities to abstract rules and manipulate symbols and to maintain a flexible approach or a flexibility set to problem solving" (1964, p. 87).

On the surface level, early studies like these show that the co-existence of evidence both in support of and against claims of cognitive advantages to bilingualism is not a new phenomenon. More fundamentally, however, these studies show that the research question itself has a relatively long history (i.e., long for psychology, neuroscience, and allied fields), and that more than sixty years ago it was already seen as an important frontier in research. This long history gives the research question an aura of credibility, which motivates new work to focus on how to improve prior methods so as to more conclusively answer the question and determine whether bilingualism is cognitively advantageous or cognitively disadvantageous in certain respects or others. But having a long history does not mean that the research question is in fact a good one.

In contrast with contributions trying to answer the research question in one direction or another, our goal in this paper is to examine the research question itself. We think that the research question is problematic for a number of different reasons. Here we focus on just two types of reasons stemming from work in sociolinguistics and in embodied cognitive science. As we propose, the question of whether bilingualism is cognitively advantageous or cognitively disadvantageous, as currently framed, is built upon inadequate essentialist and internalist assumptions about the nature of language(s) and about the nature of cognition. We examine these assumptions in two separate sections, one titled "What is 'bilingualism' such that it may be cognitively advantageous or disadvantageous?" and the other titled "What is 'cognition' such that something may be cognitively advantageous or disadvantageous?" We conclude in the final section by articulating how these different perspectives on language and on cognition motivate skepticism about *any* of the usual answers to the research question. Ultimately, we conclude that linguistic knowledge is always cognitively beneficial—but this does not mean what most people would think it means: rather than answering the research question, these ideas from sociolinguistics and embodied cognitive science suggest that the research question is misguided and not as solid a starting point for research as it might have seemed.

What is "bilingualism" such that it may be cognitively advantageous or disadvantageous?

In this section we will present a number of different but related reasons for seeing "bilingualism" as a problematic category. Each point will build upon the previous one, but as we continue moving through them, we come to a more nuanced appreciation of the inadequacy of the conceptual framework that grounds the research question of bilingualism's cognitive advantage or disadvantage. As will become clear, the research question is not a good starting point for research because the concepts "bilingual" and "bilingualism" are not clear enough to make it possible to answer the question.

"Bilingualism" is problematic because it's in continuity with "monolingualism"

It might seem intuitive to think that monolingualism and bilingualism are discrete, mutually exclusive categories: either you know only one language and are therefore monolingual, or you know more than one language and are therefore bilingual. But this assumption is clearly inadequate, and this is not news (see Surrain and Luk, 2019 for a review of inconsistent definitions used by researchers to distinguish between bilinguals and monolinguals). Even the earliest scientific research on bilinguals recognized the need for a more nuanced conceptualization of people's language knowledge. Instead of seeing monolingualism and bilingualism as distinct "boxes" with no overlap, it makes more sense, as Anisfeld (1964) proposed, to understand them as a continuum. In this view, although there are people at both extremes—i.e., people who are unquestionably monolingual and others who are unquestionably bilingual—there are many others who fall somewhere in between and who have partial knowledge of additional languages. This gradation of linguistic knowledge makes the label "bilingual" not very informative if defined in complete opposition to "monolingual": how much of another language do you need to know in order to be promoted from one box ("monolingual") to the other ("bilingual")? Is a little bit of knowledge sufficient, and you are bilingual even if not fully proficient? Or is full proficiency a prerequisite for you to count as bilingual? Understanding the categories as in continuity with one another makes it possible to recognize that people's varying levels of knowledge count in favor of seeing them as falling somewhere along the bilingualism spectrum (see Figure 1). A first reason why "bilingualism" is a problematic concept, then, is that it's not a discrete category completely distinct from monolingualism: although it might seem intuitive, the assumption of a dichotomy oversimplifies the realities of language knowledge and learning, which is a pitfall that recent research has been careful to avoid (see, e.g., Gullifer and Titone, 2020, 2021a; Bialystok, 2021; Kremin and Byers-Heinlein, 2021; Tiv et al., 2021).

"Bilingualism" is problematic because of inter- and intra-individual variation in language skills

Moving to a conception of monolingualism and bilingualism as a continuum is an improvement from the dichotomous conception, but it is still inadequate. Just because someone can speak well in two or more languages, it does not follow that they can write well in all of those languages, and vice versa. Thinking in terms of a single, absolute continuum that applies to everyone (i.e., a continuum in which different individuals can be placed and compared to each other) fails to account for this variation *between* individuals, as well as *within* a single individual, across different *skills* (see, e.g., Wagner et al., 2022). In the recent literature, there have been proposals to combine different continua for separate variables (e.g., Kremin and Byers-Heinlein, 2021): while efforts like these improve our ability to identify complex *inter*-individual differences, they still fall short from fully capturing the multifaceted nature of bilingualism as exhibited in *intra*-individual variation in skills.

To refer once again to Figure 1, consider how the idea of an absolute, objective continuum makes it impossible to acknowledge the complexity of person B's knowledge. Person B can be distinguished from person D in having only partial overall knowledge of more than one language, but the absolute impersonal continuum does not tell us anything beyond that. It could be that some of B's skills (e.g., reading) are nearly equivalent to those of a fully proficient bilingual such as person D, even if other skills fall short. *There's no "language ability in general"* but only ability in different language skills, and these skills do not all develop together and at the same pace.

In contrast with a continuum between monolingualism and bilingualism that is absolute and impersonal, one that applies to everyone at once, it seems better to think in terms of individuals having their own continuum in which their monolingual and bilingual skills stand (see Figure 2). This idea is present at the foundations of virtually all formal language instruction and it's also something that standardized tests capture well. The language abilities of individuals aren't monolithic blocks of homogeneous linguistic knowledge, but instead vary across different receptive skills (listening and reading) and productive skills (speaking and writing). This has long been understood in second language acquisition and teaching (see, e.g., Davies, 1976), and the same insight continues to guide sociolinguistic research, where continua are used to illustrate an individual's abilities across different languages and skills (see, e.g., Blommaert and Backus, 2013). Conceptualizing the monolingualism-bilingualism continuum in terms of the particular skills of individuals makes it possible to qualify the comparison between persons B and D in a way that the models shown in Figure 1 did not allow. Moreover, it makes it possible to acknowledge that different people who are not fully proficient bilinguals can have different bilingual language abilities, as Figure 2 illustrates with the similarities and differences between persons B and C.

This well-known way of thinking about language ability reveals a second reason why we think "bilingualism" is a problematic concept. Acknowledging that monolingualism and bilingualism are in continuity with each other is a step in the right direction, but it's not enough because it neglects the ways in which bilinguals can differ from one another in their skills. On its own

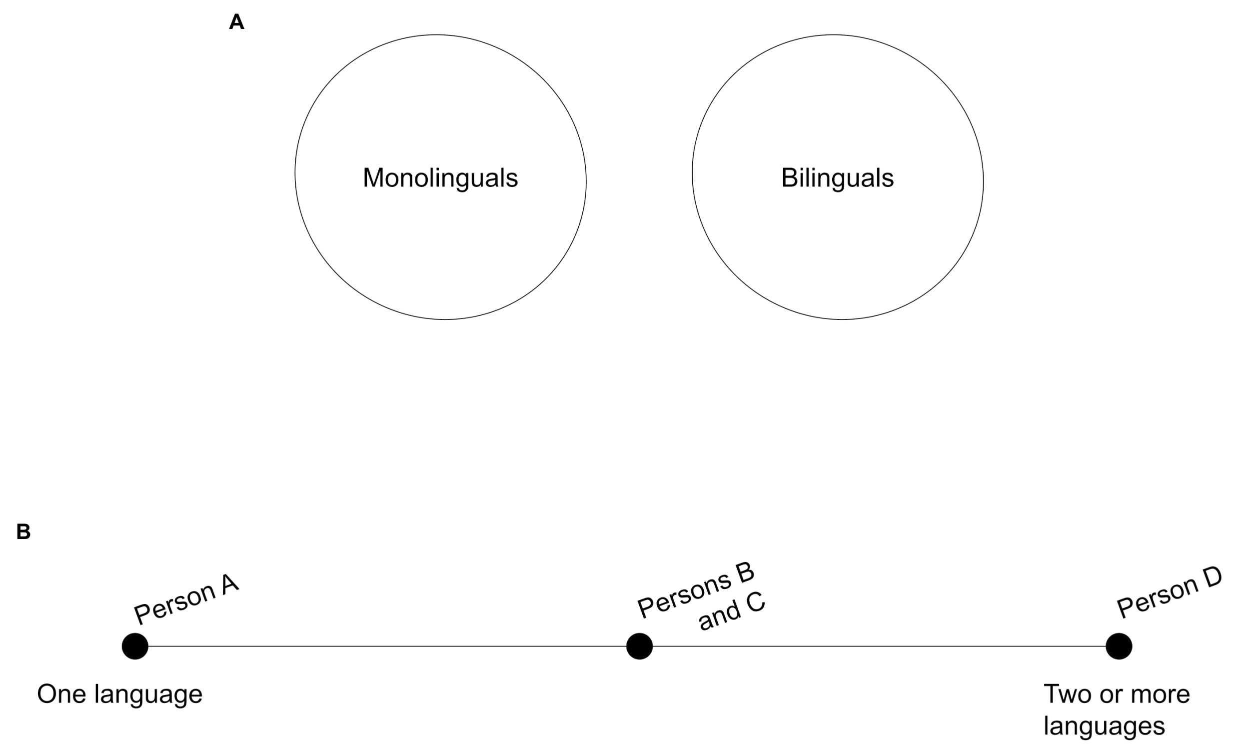

FIGURE 1
Conceived of as mutually exclusive categories, monolingualism and bilingualism divide all people into two groups based on whether they can speak one language or more than one (top, **A**). But there are many people who seem to fall somewhere in the middle, suggesting that it is better to understand bilingualism and monolingualism as in continuity with each other rather than as discrete categories (bottom, **B**): here, person A is monolingual, and person D is bilingual, but persons B and C have partial knowledge of more than one language and cannot be properly categorized at either extreme of the continuum.

the label "bilingual" is just not very informative (Surrain and Luk, 2019), which is why researchers increasingly find it necessary to take into account the dynamic nature of language ability and the diversity, across a wide range of variables, between individuals who might otherwise have appeared to be comparable as "bilinguals" (see, e.g., Hartanto and Yang, 2016, 2020; Gullifer et al., 2018; Gullifer and Titone, 2020; Sulpizio et al., 2020; Kremin and Byers-Heinlein, 2021). Given the complex differences in skill that people can have, it's not clear what the category "bilingual" should include and what it should leave out. Are B and C bilingual? Compared to A, the answer seems to be obviously affirmative. But what about compared to person D?

"Bilingualism" is problematic because language and language skills are context specific

In order to more accurately describe people's linguistic abilities, the move from an objective, absolute continuum that applies to all individuals toward individualized distributions of productive and receptive skills is an improvement. But it's still not quite so good because, even if well intended, it can lead to thinking of language ability as a set of decontextualized skills.

Recent work in sociolinguistics provides reasons to see talk of skills as too simplistic. Blommaert and Backus (2013) criticize the way standardized proficiency tests focus on skills. In their example, they consider how one bilingual person's abilities would be assessed by the widely used testing scale of the Common European Framework of Reference for Languages. They explain:

> If we apply the Common European Framework levels for language proficiency, our subject would undoubtedly score a C2—the most advanced level of proficiency—for English, when the language test concentrates on academic genres of text and talk. The same subject, however, would score A2—the most elementary level of proficiency—if the test were based on how he would interact with a medical doctor, a plumber, an IT helpdesk operative, an insurance broker, and so on. So, 'how good is his English' then? Let it be clear that this question can only be appropriately answered with another one: 'which English?' (Blommaert and Backus, 2013, p. 30).

In the previous sub-section we suggested that it's not appropriate to think of "language ability in general" but rather in terms of ability levels in specific skills. However, these authors show that even this is not good enough because even skills are

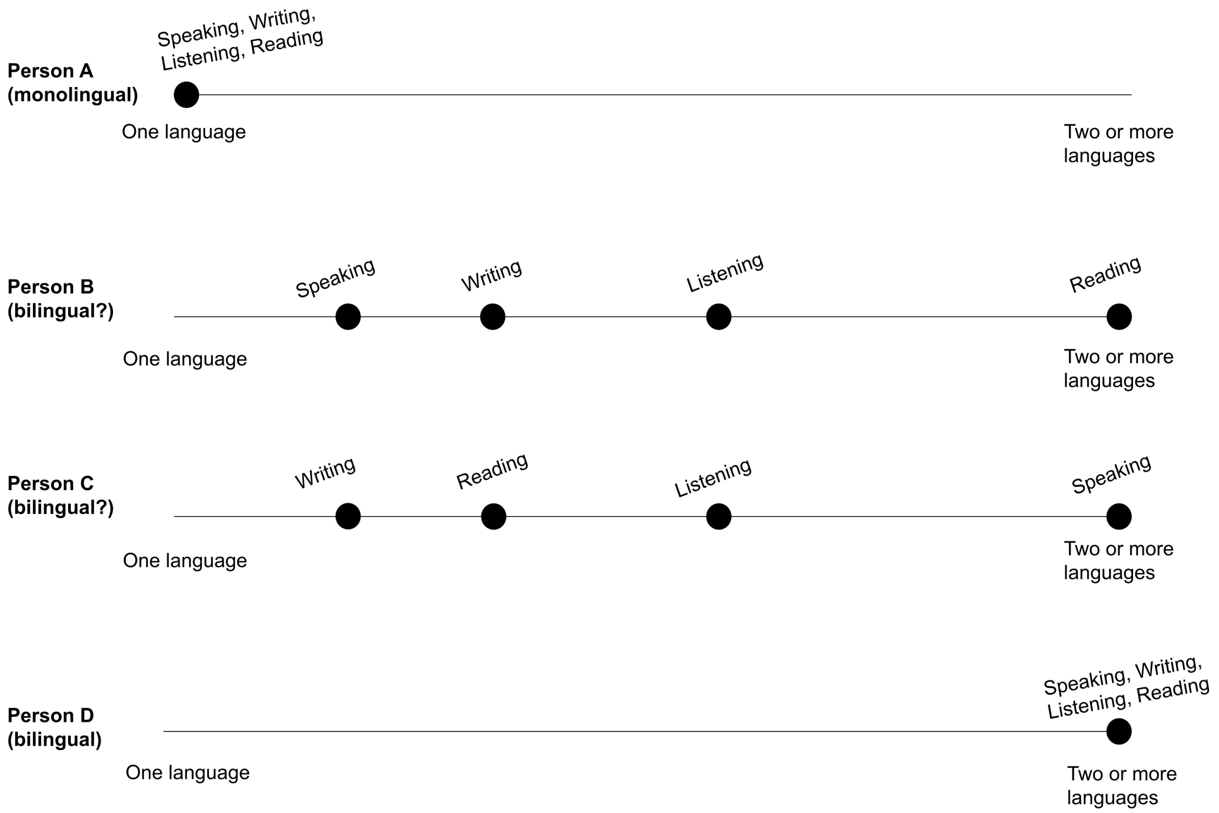

FIGURE 2
An improvement on Figure 1B is to think not of a single absolute continuum that applies to all people, but to acknowledge that each individual will have a continuum of skills they can employ in one language (left side) or in multiple languages (right side), or somewhere in the middle. As a monolingual, person A's skills are all on the extreme left side of the continuum. Similarly, as a fully proficient bilingual, person D's skills are all on the extreme right side of the continuum. Persons B and C have partial proficiency in more than one language but they differ from one another with respect to how advanced each of their skills is in more than one language. For instance, person B is fully proficient in speaking in one language but is very limited in other languages, while being able to read highly proficiently in more than one language; contrast this distribution with person C's.

context dependent: there's no "speaking in general" but speaking in this kind of context, that other kind of context, and so on. From this it follows that proficiency tests are necessarily limited: skills are grounded in particular activities, and any given test can only simulate a limited range of activities (Shardakova, 2022).

This criticism of general language skills echoes broader interest in language instruction for specific purposes. The assumption behind programs offering "language for specific purposes" is that students are best served when the language they learn is tailored to the particular activities and contexts they wish to engage in. In English for Specific Purposes, for example, specific types of English contexts include academic English, business English, and even more specifically, civil engineering English (Otto, 2021), brewing English (Orsi and Orsi, 2002), hospitality and tourism English (Hsu, 2014), for just a few examples. The purpose-specificity of linguistic skill has important implications not only for instruction, but also for proficiency testing (see Grapin, 2017 for a helpful historical overview).

Similar to the critiques of generic language skills from sociolinguistics and language teaching is the related emphasis other literatures have placed on recognizing that language is made up of particular ways of speaking and writing according to context. Illustrating this concern, some researchers have turned to investigating "registers," which they describe as "any language variety defined by its situational characteristics, including the speaker's purpose, the relationship between speaker and hearer, and the production circumstances" (Biber, 2009, p. 823; see also Biber and Conrad, 2019, Bowcher, 2019, Szmrecsanyi, 2019). This body of research highlights the fact that language ability cannot be properly understood other than in relation to specific situations of use. And along similar lines, researchers in psycholinguistics have pushed for taking into account multiple linguistic variables to paint a richer picture of "bilinguals" in terms of their potentially very diverse experiences and exposure to languages (see, e.g., Hartanto and Yang, 2016; Gullifer et al., 2018; DeLuca et al., 2019, 2020; Gullifer and Titone, 2020, 2021a).

In light of these considerations, it becomes clear that language skills such as writing and speaking cannot be properly accounted for in a vacuum, apart from the many different

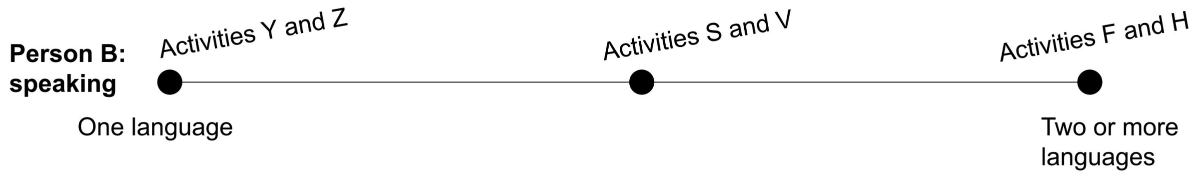

FIGURE 3
An illustration of how a person's speaking proficiency is differently distributed across all of the activities this person engages in in life (e.g., communicating with coworkers, bargaining at a flea market, participating in a religious ceremony). Some or all of the different canonical language skills may be at play in each of these activities. The continuum displayed in this figure represents how proficiency in a single skill (here, speaking) can be distributed across different activities for the same person. Person B's speaking abilities in activities Y and Z might be limited to one language (e.g., they can do Y only in English, and Z only in French), whereas in activities F and H they can speak fluently in two or more languages. It could be that, for this specific person, if they could engage in activity Y (say, contacting their landlord) in writing rather than orally, their ability to succeed in that situation would be greatly improved.

situations, contexts, and activities in which individuals write and speak, for example. Recognizing that an individual's language knowledge is distributed along a continuum of skills (as shown previously in Figure 2) is good, but does not go far enough. Language skills are not context independent: there is no "writing in general" or "speaking in general," but each of these competencies are inextricable from some context-specific, real-life activity or other in which the person is more or less well equipped to succeed. To better capture the complex reality of language knowledge, it's more appropriate to characterize individuals not in terms of a continuum of proficiency in general skills but a continuum *within* specific skills (e.g., speaking) distributed along specific activities in which the person is capable of successful engagement in one or more languages (see Figure 3). Instead of thinking of someone's "speaking in general" as being more or less advanced, different lines of research like the ones mentioned above increasingly recognize that a person's speaking may be at an advanced level for some types of activities but at a lower level for other types of activities, and that the same applies to other canonical skills.

This being the case, the category "bilingual" is problematic because, on its own, it fails to acknowledge (i) the many ways in which language itself varies in different contexts and types of activities, and accordingly, (ii) the many ways in which individual language ability is always specific to some contexts and types of activities and not others, varying even within a single skill (e.g., speaking). Not only do bilinguals differ from one another in how their skills are distributed across levels of proficiency, but their level of proficiency even in a single skill will vary according to specific contexts and types of activities (Blommaert and Backus, 2013). In light of this, many psycholinguistic researchers increasingly consider how individual differences in language abilities arise from distinct situational contexts of language use as well as different, changing life experiences (see, e.g., Gullifer et al., 2018; Gullifer and Titone, 2020; Tiv et al., 2021). Acknowledging this complexity of variation adds greater granularity to the question "What counts as being bilingual?," and we cannot answer the research question about bilingualism's cognitive advantages and disadvantages without first answering this one.

"Bilingualism" is problematic because "full proficiency" is problematic

So far we have considered different and increasingly nuanced reasons why "bilingual" and "bilingualism" are seen as problematic categories. Figures 2 and 3 improved upon the view of an absolute, objective continuum that applies to everyone (Figure 1B) by recognizing the intra-individual variability of linguistic skills (Figure 2), and even better, the diversity of activities in which the individual skills of individual people are grounded (Figure 3). As shown in Figure 3, context-specific abilities range from fully proficient in one language to fully proficient in more than one language. However, if language ability is more adequately understood in terms of the proficiency an individual has developed *for engaging in specific activities*, it becomes crucial to think more carefully about what we mean by "proficiency" and, in particular, about *which activities* matter and which do not for considering an individual as a fully proficient bilingual.

It can be tempting to think that having full bilingual proficiency means to be like a monolingual in each of the languages you speak. Pennycook and Makoni (2020) give this view of bilingualism the name "plural monolingualisms" because it assumes that a plurality of monolingualisms can coexist inside a single person. Their critique resonates with Grosjean (1985), who problematized the idea that bilinguals need to have the sum of two complete monolingual repertoires and instead emphasized that each bilingual person has a unique linguistic profile. But we think it's important to extend this critique to monolinguals as well. In the progression from Figure 2 to Figure 3 we highlighted that each bilingual person's language skills are context specific. The same point applies to so-called monolinguals: the skills of each "monolingual" individual are context dependent, and no monolingual develops the ability to engage equally successfully in all of the contexts that are possible in their society. As Blommaert (2010) puts it, "No one knows all of a language. That counts for our so-called mother tongues and, of course, also for the other 'languages' we acquire in our life time. Native speakers are not perfect speakers" (p. 103).

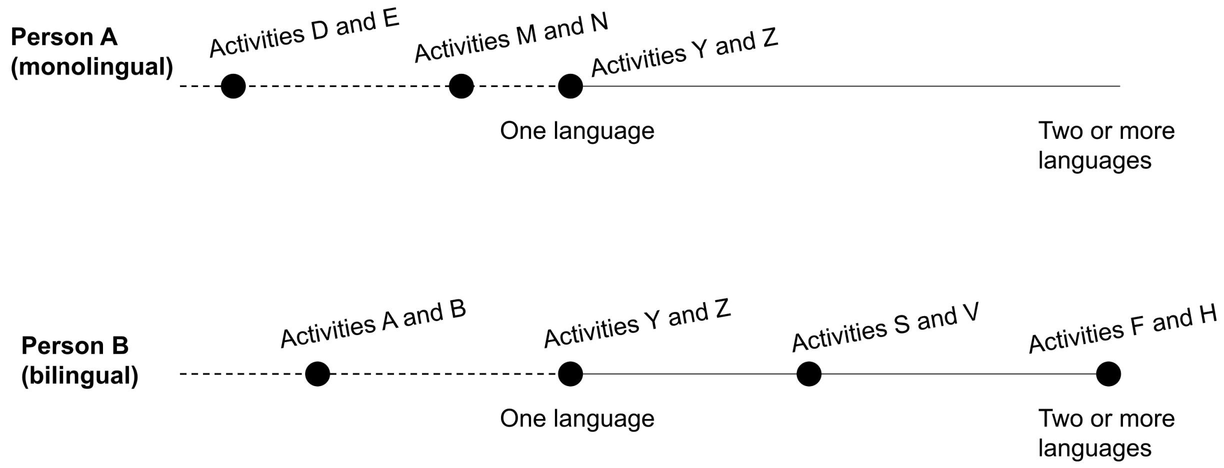

FIGURE 4
There's no such thing as literal "full proficiency": as language skills are grounded in activities, there are always going to be activities for which anyone (whether monolingual or bilingual to some degree) lacks proficiency. To illustrate this, in contrast to the previous figures, here we add space to the left of "One Language" to capture how some activities fall outside the range of an individual's linguistic repertoire (dotted line).

What Figure 3 still does not capture is the fact that there are activities that an individual is *not* capable of engaging fully successfully in, no matter who the individual is (whether monolingual or bilingual). Consider for instance a single, middle-aged, white monolingual woman who works as the manager of a grocery store in suburban Australia. She will be able to engage in activities such as meeting with supervisors, making schedules, organizing sales events, going bowling with friends, texting with family, reading the local newspaper, booking a flight online, speaking at an Alcoholics Anonymous meeting, and volunteering at a homeless shelter. However, even as a "native" English speaker, this monolingual person may not be able to tactfully fire a difficult employee, negotiate a better salary, read and interpret a complicated medical diagnosis, calm a fearful child, discuss video games with teenagers, interrogate a suspected criminal, deliver a speech at a campaign rally, host a seance, write a legal brief, tell enthralling stories at a fancy dinner party, and so on. Given the uniqueness and unavoidable limitations of each person's linguistic profile, there are always going to be situations they could not be randomly inserted into and still have sufficient linguistic knowledge to thrive—even in their "native" language. A monolingual person's particular life experiences allow them to develop language abilities for a wide range of regular activities but still myriad activities will remain outside that person's scope of ability (see Figure 4).

Once we start thinking of proficiency in terms of activity-grounded skills, it follows that no one is equally proficient as anyone else because no one participates in exactly all and only the same activities as others. In debates surrounding language instruction and testing research, as Shardakova (2022) explains, the view of "proficiency as a single trait (…) was rejected on the grounds of its methodological flaws in the use of statistical analyses and empirical evidence in favor of a complex multifaceted nature of communicative proficiency" (p. 86). Full proficiency is not a single thing, and even so-called "monolinguals" do not possess the linguistic abilities needed to engage equally successfully in *all* of the activities that exist in the society that they live in. Monolinguals vary considerably in language abilities because of the specific contexts in which they develop language skills and are exposed to the languaging practices of others (Dąbrowska, 2012, 2018, 2019; Bice and Kroll, 2019; Gullifer and Titone, 2020; Castro et al., 2022). Describing someone as a "fully proficient bilingual" raises the question: *proficient to succeed in what activities?* And understanding "bilingualism" as monolingual-like proficiency in more than one language does not help, because the question then becomes: *fully proficient like which monolingual?* From these difficulties it follows that "bilingualism" as a category is problematic because it is not *one* thing, just as monolingualism itself is not a single thing: there are as many bilingualisms as there are bilinguals, and there are as many monolingualisms as there are monolinguals—and, as we have been emphasizing from the start, in the real world there are always going to be people in the gray areas where the usual distinctions do not straightforwardly apply.

"Bilingualism" is problematic because it relies on a problematic distinction between languages

Bilingualism is a problematic category because, in relying on a questionable and unrealistic idea of full proficiency, it also takes for granted a potentially problematic conception of what people are proficient *in*: that is, it presupposes that languages are countable bounded entities. But named languages aren't objects that exist independently of human activities. As Heller (2007) argues, we need to move away from "a 'common-sense', but in fact highly ideologized, view of bilingualism as the coexistence of two linguistic systems" and instead adopt a view of "language as social practice, speakers as social actors and boundaries as products of social action" (p. 1). Recent work coming from many directions motivates rejecting an essentialist view of language by considering the social, historical, and political embeddedness of language practices (see, e.g., Brunstad, 2003; Makoni and Pennycook, 2007; Blommaert, 2010; Lähteenmäki, 2010; Pennycook, 2010; Pennycook and Makoni, 2020; Gullifer and Titone, 2021b; Tiv et al., 2022).

Languages, and particularly standard varieties of languages, are best understood as political instruments (Bourdieu, 1991; Silverstein, 1998/2018). They are powerful markers of group identity, and are used as part of projects to broaden and constrain who is included (Gal and Irvine, 1995). A modern example of a language acting as an umbrella to encompass many different language practices is "Arabic." For native Arabic speakers, their local vernacular Arabic language is contrasted with "Classical Arabic," which includes both the historical religious language of the Quran and the Modern Standard Arabic used in formal institutional settings (Haeri, 2003). However, despite Arabic speakers using the same labels to refer to their language practices, it is well documented that the local vernacular varieties of Arabic can vary considerably, posing a challenge to mutual intelligibility (Trentman and Shiri, 2020). The case could be made that in order to speak Arabic to people both in Morocco and in Syria, one has to be bilingual; and yet, a Moroccan and a Syrian would both likely claim that their vernacular is a *variety* of Arabic, rather than a distinct language.[1] Another example of a standard language which consolidates people across vast territories and spoken varieties is "Mandarin." In contrast with Modern Standard Arabic, Modern Standard Mandarin was strategically created as part of a larger project of societal reform "in which all the nation's people would have access to the new official language, and thus increased opportunities for advancement" (Weng, 2018, p. 611). In the cases of both Arabic and Mandarin, there is a powerful single language that groups together what then come to be understood as local variations.

These examples show how named languages can be forces of unification. But they can also act to create divisions, as is the case in Europe for Romance languages (Varvaro, 2013) or Scandinavian languages (Faarlund and Haugen, 2007). Here, languages with significant similarities—e.g., Portuguese and Spanish, or Swedish and Danish—are considered separate languages because of political projects to maintain sovereignty through the promotion of a distinct national identity (Auer, 2005a). Consider the fact that "[s]peakers of Danish, Norwegian, and Swedish normally use their own languages in communicating with one another" (Faarlund and Haugen, 2007). In light of this, can a Swede be considered bilingual if she can use Swedish to communicate effectively with a Dane who is speaking Danish? Or are Swedish and Danish so similar that communication across languages is possible while the speakers remain classified as monolingual? There are also forces within Romance language countries in Europe to create further linguistic distinctions by giving political recognition to languages such as Galician, Catalan, Sardinian, etc. Degrees of differences that in some contexts are seen as merely a distinction between varieties or dialects, in other contexts suffice to distinguish between languages. According to Schneider, "[t]he development of *languages* (and of *dialects*, for that matter) is no socially neutral development but related to political structures and administrative institutions of states, which are co-responsible for the hierarchisation of some varieties into 'sub'-languages or dialects of others" (Schneider, 2019, p. 4). The dominant variety may be portrayed as objectively superior in terms of grammar, style, etc. when in reality, it is only deemed to be superior because it is the variety of social elites; there is nothing inherently better in the arbitrary variables that distinguish it from "sub-languages." And by extension, for empirical research, "there is no objective standard for determining when a dialect becomes a language" (Wagner et al., 2022, p. 3).

Although psycholinguistics researchers often acknowledge the complexity of labeling and distinguishing between languages and dialects, the distinctions between and within linguistic varieties are not properly understood unless seen as part of projects that are political in a broad sense, projects of affirming group identity and of differentiation from others (Gal, 2016). While in each context these projects differ in the scope of who's in and who's out, they are always about policing some boundary or other. And this poses a fundamental problem for research on "bilingualism." By definition a person is bilingual because she speaks two (or more) languages. But what counts as a distinct language or merely as a variety of the same language varies widely, and *does not straightforwardly correspond to the amount of linguistic difference people have to be able to navigate*. Some researchers investigate second dialect acquisition as a phenomenon distinct from second language acquisition (e.g., Hazen, 2001; Mordaunt, 2011; Kirk et al., 2014; Wu et al., 2016; Ross and Melinger, 2017; Oschwald et al., 2018), which in turn requires an imperfect decision about how to define dialects as opposed to languages. This decision might be made on the basis of the percentage of lexical similarity (Antoniou et al., 2016) or in the case of Siegel (2010), based not only on several aspects of linguistic similarity and shared history, but also on "the common perception of the speakers of these varieties and not on a technical decision made by linguists" (p. 2). Siegel and others who use this line of reasoning (e.g., Rowe and Grohmann, 2013) do consider the sociolinguistic complexities of the relations between the varieties they study, but the fundamental problem remains that their decision to call some varieties "dialects" is not, and cannot be, established empirically. The

1 Anecdotally, a Franco-Syrian colleague fluent in both French and Arabic told us that it took her a month of immersion to understand Arabic spoken in Morocco, the same amount of immersion time she needed to be able to understand Italian based on her knowledge of French. From this experience, the description of one contrast as holding between dialects and the other as between separate languages would appear to be artificial.

trouble remains that what counts as "bilingual" in some contexts requires navigating minimal differences, while in other contexts the obstacles may be more significant and yet not be seen as amounting to a difference between distinct languages, such that the people navigating those obstacles would not technically count as bilingual. Ultimately, there may not be good answers to the question whether bilingualism is cognitively advantageous or disadvantageous because bilingualism is not a single thing.

What is "cognition" such that something may be cognitively advantageous or disadvantageous?

Is bilingualism cognitively advantageous or disadvantageous? In the previous section we drew from work in sociolinguistics and related fields to identify one type of reason why this research question is problematic: namely, because it is built upon a problematic way of thinking about language(s) and linguistic skills as aspects of human activity in particular contexts. The present section will shift gears to explore a related but different type of reason for seeing the research question as problematic: it relies on an understanding of mind and cognition that's increasingly disputed by a growing body of research in the sciences of the mind. Before we can try to find out whether bilingualism is cognitively advantageous or not, it's crucial to examine the assumptions we might be taking for granted concerning the nature of "cognition," because these assumptions inform how we define "cognitive" advantages and disadvantages in the first place.

Since the "Cognitive Revolution" of the 1950s and 60s, the dominant way of thinking in the sciences of the mind has been to conceptualize "mind" in analogy to computers. In particular, the distinction between software and hardware is often taken to correspond to the distinction between research at two distinct levels of description: these are, on the one hand, research on cognition at the abstract level of the "programs" or "algorithms" underlying mental function and behavior, and on the other hand, research at the level of how our mental software is actually implemented in the brain. The goal of a science of cognition was explicitly articulated along these lines already in its early days (see Neisser, 1967/2014). According to classical cognitivism, then, psychological or mental phenomena are properly explained in terms of two things: *internal knowledge structures* (i.e., symbolic structures that internally represent information about the external world) and *internal mechanisms* for manipulating those knowledge structures (i.e., rules or algorithms for storing the incoming sensory input and processing it, transforming it into some behavioral output).

In this paradigm, the adjective "cognitive" has come to be predominantly used as synonymous with *information processing*. Neisser, one of the pioneers of the computational perspective, articulates quite clearly the intended terminology: "As used here, the term "cognition" refers to all the processes by which the sensory input is transformed, reduced, elaborated, stored, recovered, and used" (Neisser, 1967/2014, p. 4). Understood in this way, cognitive processes are processes of *processing* information. That is, cognition is a process (broadly speaking, a chain of events) in which bits of information are internalized (e.g., some specific type of input derived from sensory stimulation) and then get manipulated (processed, computed) in certain ways that are (hypothesized to be) necessary for supporting the agent's behavior now or later. Many details in computational approaches to mind have changed over the years, especially following important theoretical and technological advances since the 1970s and 80s (see, e.g., Dreyfus, 1972, 1992; Dennett, 1984; Rumelhart et al., 1986; Fodor and Pylyshyn, 1988); and still, the idea that cognition amounts to information processing remains the "central hypothesis of cognitive science" (Thagard, 2005; see also Pinker, 2005; Gentner, 2019; Thagard, 2019). Accordingly, it's safe to see this computationalist conception of "cognition" (or something in its vicinity) as the assumption guiding contemporary research on the "cognitive" advantages or disadvantages that bilingualism might have (see, e.g., Grosjean and Li, 2013); in contrast, rejecting the traditional internalist view of cognition and language that focuses on "assessments of individual-level attributes," and instead acknowledging the inherently social nature of "neurocognitive processes, like language" motivates a "reorienting toward external constraints" (Tiv et al., 2022, p. 13). We will have more to say about this in the last section. For now, in the remainder of this section we consider how work in embodied cognitive science offers a radically different way to understand mind and cognition and, consequently, to approach language and the bilingualism research question.

Reframing the "cognitive": Not computational states and procedures, but epistemic relations

A major criticism of classical cognitivism is that, insofar as it equates "cognition" to abstract processes of "information processing," it thereby also sees cognition as being only marginally related to the body. In this classical view, cognition is informed by the body (i.e., through incoming sensory inputs from the eyes, ears, skin, etc.) and the outcome of cognition is implemented by the body (e.g., through the execution of motor commands in locomotion), but cognition itself is separate and distinct from bodily activity. This construes the body as playing a peripheral role, even in a literal sense, much like the peripherals of computers: these are responsible for the input of information (e.g., mouse, keyboard) and the output of information (e.g., screen, printer), but they are distinct from, and not directly involved in, the computational processing that goes on in between. Hurley (2001) describes this as the "sandwich model" of mind, where cognition is the filling, distinct from the (separate) bread slices of perception and of action: that is, thus understood, "cognition" comprises disembodied, abstract states and processes (the internal mental "cogs") that are "sandwiched" in between bodily processes of perceptual input and of behavioral output.

All work on "embodied cognition" can be seen as rejecting classical computationalism, but there's variation between different embodied views when it comes to what exactly is rejected and why. Some work rejects this way of thinking by challenging the *abstractness* inherent to classical computational conceptualizations of cognition. For instance, some researchers propose that the *contents* of cognition are modality-specific because they are grounded in specific bodily experiences, whether sensory (e.g., visual) or motor, or both (Barsalou, 1999; Barsalou et al., 2003). Other researchers have also proposed that the *mechanisms* underlying cognitive function are themselves "embodied" in that neural resources associated with bodily activity also contribute to thought—for instance, when the neural underpinnings of action execution also support imagining that same action (Lakoff and Johnson, 1980a, 1980b; Gallese et al., 1996; Gallese, 1999; Gallese and Lakoff, 2005). These examples illustrate the idea that, rather than cognition being the disembodied processing of disembodied symbolic knowledge structures, the body plays a constitutive role in cognition itself, shaping it both in terms of the representational content (i.e., *what* type of information gets processed) and of the computational procedures (i.e., *how* that information gets processed).

Even while challenging certain aspects of classical computationalism, the versions just mentioned of work on "embodied cognition" clearly leave other aspects unquestioned. On the one hand, they challenge classical views about the nature of the computational states and procedures at play in cognition, namely, questioning their supposed abstractness or disembodied nature, and promoting instead concepts such as "bodily-formatted representation"; but in so doing, on the other hand, they take for granted the computationalist paradigm and, with it, they accept the more fundamental assumption that cognition is properly understood in terms of the storage and processing of bits of information.

Our focus here is on a different perspective and line of research in embodied cognitive science, one that rejects these computationalist foundations and that offers an alternative conception of cognition. This radical embodied view is rooted in the functionalist psychology of the end of the 19th century, as developed by the likes of William James and John Dewey, but in some respects it dates even further back (see Green, 1996; Heft, 2001; Crippen and Schulkin, 2020).[2] In this view, "cognitive" is understood as synonymous not with "computational" (or *that which concerns information processing*) but rather with "epistemic" (or *that which concerns knowledge*). Understood in this way, cognition is still a process, but it's not a process of *processing* something: it is, rather, a process of *coming to know* something, of becoming familiar with it. Put differently: the computational conception equates cognition to computational states (i.e., bits of information) and procedures (i.e., algorithms for handling those bits of information), which are typically taken to happen inside the organism; in contrast, in the embodied, epistemic conception we see cognition as a *relation* that holds between organism and environment and that, although dependent on organismic processes (e.g., perception-action cycles), is not reducible to what happens inside the organism—cognition is not "in the head," as Noë (2009) puts it; rather cognition is a feature of the organism-environment system as a whole (see Figure 5).

Let us consider more carefully how exactly the two conceptions differ. Saying that the radical embodied view treats "cognitive" as "having to do with knowledge" might sound like practically the same thing as the computationalist view: after all, the core of the computationalist perspective is the idea that cognition is precisely about what we know and how we store and use that knowledge. So what's the difference? The key lies in the novelty that the pioneers of cognitive science (in the 1950s/60s onward) introduced for modeling mind and behavior using computing technology and computer-related concepts. This was the idea of operationalizing what someone knows, logically speaking, as statements you could make to express that knowledge, or more technically, as bits of data that encode that information. So, for instance, the fact of your knowing a person (e.g., a friend) or a building (e.g., your friend's house) came to be operationalized, in light of then emerging computer technology, as internal knowledge structures that represent features of the person or building, from simple facts (e.g., your friend's hair color, or the number of rooms in the house, which can be assigned a discrete value) all the way up to more complex models (e.g., of what the person looks and sounds like, or the layout of the building). These operationalizations immediately proved that computers could be useful for modeling psychological phenomena, but they quickly came to be interpreted as a theory of what the mind literally is and does.

The computationalist picture is thus built upon the attempt to explain knowledge in terms of what happens inside the organism that knows: this is a view that James criticized, more than a century ago, for holding that "knowledge is explained as the *passage* of something from without into the mind" (James, 1890/1983, p. 215), and in particular that "the mind must in some fashion *contain* what it knows" (p. 472; emphasis added)—or as more recent critics have put it, this is the idea that "one cannot have knowledge of what is *outside* oneself except through the ideas one has *inside* oneself" (Di Paolo et al., 2017, p. 23). The problem is that, as Costall (2007) makes clear, the computationalist picture cannot explain how we gain knowledge through perception because, in that account, "knowledge is invoked to explain perceiving" (p. 22): consider how computational accounts often describe our perception of something as the process of comparing incoming visual inputs to some stored, internal model, based on which we come to categorize the thing now perceived as being X or Y; this description does not explain

2 Awareness of this history should inform how we see the "burden of proof" in contemporary research. That is, some see the radical embodied conception as a recent invention that needs to be justified and shown to be superior to the computationalist conception it's trying to replace. But it's historically more accurate to see it as an older idea potentially worth rescuing, and in particular one that the computationalist conception itself can be evaluated as a new competitor to.

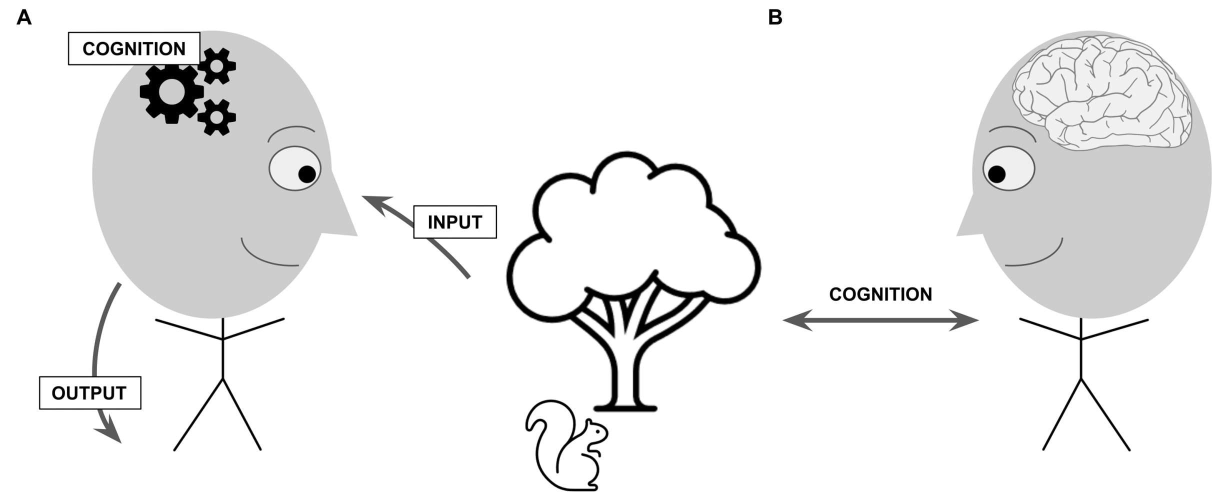

FIGURE 5
An illustration of competing views of "cognition," **(A)** understood computationally in terms of representational states and procedures internal to the organism, or **(B)** understood in epistemic terms as a relation of acquaintance or familiarity that holds between an individual and the world. Depending on the particular computational model, the states and processes posited may be understood more or less abstractly, and more or less in connection to neurophysiological descriptions, and so on. In the relational perspective, although the organismic contribution is crucial (including perception-action in all its bodily and neurophysiological dimensions), cognition is not understood to exist "in the head" but rather as a feature of the organism-environment system as a whole.

knowledge because it requires the existence of prior knowledge (i.e., internal knowledge structures) against which incoming sensory inputs are matched—that is, instead of explaining knowledge, it requires that we already have knowledge in the first place.

In contrast, in the radical embodied conception, knowledge (and, by extension, the "cognitive") is understood, most fundamentally, as a relation rather than a thing.

Generally speaking, relations aren't reducible to the properties of any one of the things between which the relation holds. Consider, for instance, family relations: you cannot be a cousin or a parent on your own; the roles cannot be reduced to anything about you, because the relation entails the existence of someone else you are related to in that way—put differently, the relation itself exists between the two people rather than inside any one of them. The physical concept of "gravity" provides another example: the fact that a stone, when dropped, falls to the ground is explained not by reference to anything internal and intrinsic to the stone on its own, but rather to the relation between the stone's mass and the Earth's, a relation that exists at the interface of the two rather than inside either of them.

Knowledge, then, rather than being an object contained within the mind, is a relation between mind and world: James talks about the "relation of knowing" (James, 1890/1983, p. 212), a relation of "intimacy" or "acquaintance" with some object, a relation that may be more or less articulate—more or less entangled with concepts and language—but whose existence always leads to a transformation in the knower, leaving her changed in her abilities to act in the world as a result of what and how she knows or is familiar with. In the following subsections we draw from two independent but mutually supporting lines of research to further illustrate this embodied, relational epistemic conception of cognition (thereby also illustrating concrete ways to understand the bidirectional arrow shown in Figure 5B).

Computational "cognitive (dis)advantage" is problematic because it neglects the relational, ecological nature of information

The conceptualization of the "cognitive" in terms of epistemic relations is at the foundation of the research tradition in ecological psychology started by James J. Gibson (Gibson, 1966, 1979; see also, e.g., Richardson et al., 2008; Chemero, 2009, 2013; Turvey, 2018). To illustrate what this relational perspective looks like in more concrete terms, we will consider here Gibson's claim that "Locomotion and manipulation are neither triggered nor commanded but *controlled,*" to which he added that "they are controlled not by the brain but by information" and, further, that "control lies in the animal-environment system" (Gibson, 1979, p. 225).

Let us flesh out Gibson's claim. A strictly behaviorist perspective might be to think that locomotion in space and manipulation of some object are elicited ("triggered," as in Gibson's quote) from the outside by some stimulus. In contrast, an internalist perspective (e.g., computationalism) would try to explain locomotion and manipulation as caused from within ("commanded," as Gibson put it), controlled by some motor program. Gibson's alternative is "ecological" in the same way that ecology as a branch of biological science explains life not at the molecular level (i.e., the level of cells, genes, biochemistry, and so on), but at the "molar" level of the relations between organisms

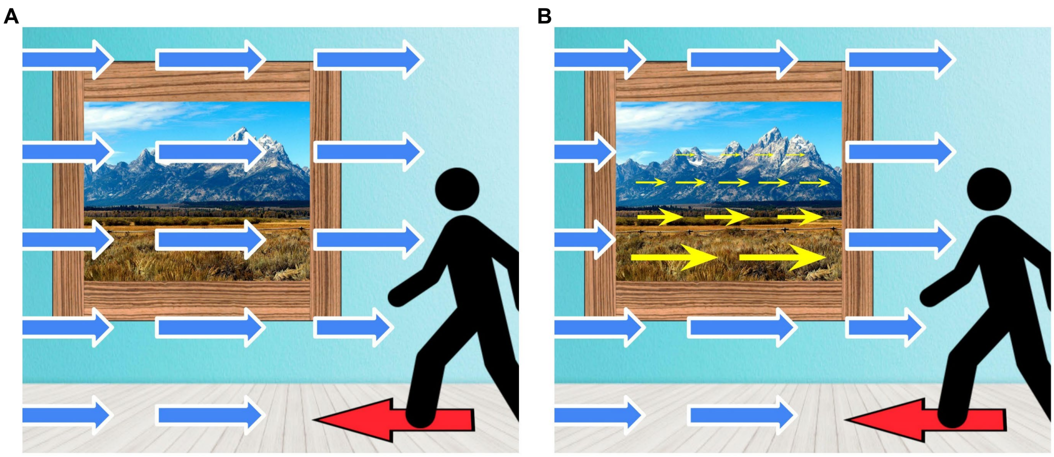

FIGURE 6
Locomotion generates optic flow, a visual pattern that is directly informative to the agent of her direction of movement. The two images provided here illustrate the optic flow (arrows pointing to the right) that gets generated as a person walks to the left side of the room (red arrow on floor). The specific character of the optic flow can be informative of whether the mountainous landscape is a picture hanging on the wall or an actual scene viewed through a window: if, as you move forward, the optic flow generated is the same everywhere, then what you see is a picture **(A)**, whereas the rate and quality of visual change for the real scene is specific to a space with depth **(B)**. In the computational conception of cognition, locomotion is the *output* of cognition (e.g., the execution of a motor plan) and what you perceive becomes the *input* for further cognitive processing. In contrast, in the ecological view, insofar as it generates optic flow, locomotion is itself cognitive: it is a process through which an agent gains epistemic access to (i.e., comes to know) aspects of the environment and of the agent's relation to it.

and the environment. Analogously, the explanatory strategy in ecological psychology is to "ask not what's inside your head, but what your head's inside of," as Mace (1977) famously put it: that is, in order to explain an organism's behavior we need to understand the entire organism-environment system (see, e.g., Reed, 1996; Heft, 2001).[3]

A good example of how, as Gibson put it, locomotion can be controlled *by information* and how control can lie *in the animal-environment system*—rather than controlled by the brain from within the organism—is optic flow (see Figure 6). Optic flow has been described as "the visual streaming or outflow of environmental features that one experiences when moving forward, and inversely, the convergence or inflow of environmental features in the direction from which one is traveling" (Heft, 2001, p. 119). As a pattern of visual displacement, optic flow is a *dynamic* pattern—that is, a pattern of change over time—and it is also an *ecological* pattern—that is, one that emerges from the relation between an organism and the environment as this relation unfolds in space and time. Crucially, optic flow is related to information not because the organism receives and processes bits of information from a supposed visual input: rather, as the organism moves (e.g., by walking) or gets moved (e.g., is carried by others or is transported by a car) the dynamic relational pattern that this movement generates is itself *informative* to the organism of how it is moving with regard to its surroundings, whether forward or backward, for instance. The organism's task, then, is to *detect* the information (or better, to detect the informative pattern) rather than to internalize and process bits of information. As Bill Warren (2021) puts it in the title of a recent article, "information is where you find it": that is, "information is available within the constraints of a particular ecological niche" (p. 3) and we just need to *adapt* to it (p. 19). At this point, this idea is no longer speculative, but is a conclusion drawn from decades of research on the role of optic flow in the control of locomotion, yielding ecological explanations of how we steer toward goals and away from obstacles (Warren, 1998; Warren et al., 2001; Fajen and Warren, 2003; Warren, 2006).

Ecological psychology as articulated by Gibson is "a theory of how animals come to *know* their environments—a theory of cognition" (Reed, 1991a, p. 142; see also Reed, 1991b, 1997). In this ecological framing, locomotion controlled by optic flow is a cognitive process in the specific sense that it is a process of coming to know (or coming to be acquainted with) one's environment and one's relation to that environment. But it's not a process of *processing* information: rather, it is one of generating information through movement and detecting information where it is and adapting to it, that is, a process of resonating to informative patterns that arise in the organism-environment relation. The example of locomotion might seem too "bodily" to be relevant for discussions about mind and language, but the point in the ecological approach is precisely that mind and language are always bodily in this way: the goal in the ecological approach is to explain how "mental" things like meaning and the

3 To be sure, approaching psychological phenomena through an ecological lens does not amount to "blackboxing" the brain, but it does call for rethinking the way we understand how the brain works and, in particular, how what the brain does contributes to the organism-environment system (see, e.g., Van Orden et al., 2012; Dotov 2014; Bruineberg and Rietveld 2019).

appreciation of meaning are grounded in organism-environment relations as they unfold dynamically through embodied perception-action and as they change through development—see, for instance, ecological views on how people engage with complex and inherently social structures such as the postal system (Gibson, 1979; Heft, 2020).

The ecological way of thinking has implications for a number of debates far beyond the scope of this article. Given our interest in the research question of bilingualism's cognitive advantages or disadvantages, for present purposes it suffices to indicate how different views of *what* cognition is lead to different interpretations of what the research question is and can be. If we assume cognition to be information processing, then to ask whether or not bilingualism is cognitively advantageous is to ask whether bilingualism contributes to or hinders the processing of information. In contrast, in the radical embodied, ecological perspective "cognitive" is synonymous with "epistemic," and cognition is understood relationally: as a result, "cognitive" processes are processes at the scale of organism-environment relations through which an agent becomes acquainted with aspects of the environment and those aspects come to guide or steer behavior. From this conception, it follows that to ask whether bilingualism is cognitively advantageous or not is to ask whether bilingualism contributes to or hinders a person's coming to know the world. Here it might be important to consider individual differences in sensitivity to information (i.e., to the relational informative patterns arising through interaction with the world), but this has very little, if anything, to do with how quickly and efficiently one internalizes and processes bits of information—if that's even something that people do at all. As this subsection's title suggests, the computational interpretation of "cognitive" advantages and disadvantages is problematic because it neglects the relational, ecological nature of information: information is not in the head, information does not get processed, and information is never only about the world, but also about the agent's relation to the world.

Computational "cognitive (dis)advantage" is problematic because it neglects the relational, situated nature of cognitive processes such as problem solving

Another useful illustration of a relational epistemic view of cognition comes from the distinct but allied tradition of research on "situated cognition" (see, e.g., Suchman, 1987; Lave, 1988; Kirsh, 1991, 2009; Clancey, 1997, 2009; Kirshner and Whitson, 1997, Robbins and Aydede, 2009). To begin, consider how in the classical computationalist perspective it's assumed that cognitive procedures get implemented in some *context* or other (much like it's taken for granted that cognition will be implemented by some body or other), yet the cognitive processing itself is thought to be fundamentally neutral with regard to the agent's situation (much like the processing is supposed to be neutral with regard to the body). In contrast, relational thinking leads to seeing the situation as constitutive of cognition itself: as Clancey (1997) puts it, "every human thought and action is adapted to the environment, that is, *situated*, because what people *perceive*, how they *conceive of their activity*, and what they *physically do* develop together" (pp. 1–2). Here we focus on the implications of this perspective for understanding problem solving.

Since the early days of computational cognitive science, "problem solving" was assumed to be a general cognitive ability or process, perhaps even a foundational one that could explain a wide range of mental and behavioral phenomena (see, e.g., Newell et al., 1958, 1958/1962; Simon and Newell, 1962). But, as Kirsh (2009) points out, "problem solving" cannot be a general cognitive ability or process because "problems" are not general categories independent from particular contexts:

> Problems are not regarded to be a distinct category for empirical and computational analysis because what counts as a problem varies from activity to activity. (…) Each problem is tied to a concrete setting and is resolved by reasoning in situation-specific ways, making use of the material and cultural resources locally available. What is called a problem, therefore, depends on the discourse of that activity, and so in a sense, is socially constructed. There is no natural kind called "problem" and no natural kind process called "problem solving" for psychologists to study. Problem solving is merely a form of reasoning that, like all reasoning, is deeply bound up with the activities and context in which it takes place (Kirsh, 2009, pp. 264–265).

In describing cognition as being fundamentally shaped by the situation, Kirsh emphasizes the interactive nature of problem solving. When trying to solve a problem people typically do not first *think* and then *implement* the solution they came up with. Rather, they interact with the elements in their environment throughout the problem solving process, exploring not only possible solutions but even the problem itself: "If it is a word problem (John is half as tall as Mary…), they mutter, they write things down, and they check the question several times. If they are solving an assembly task (here are the parts of a bicycle, assemble it), they will typically feel the pieces, try out trial assemblies, and incrementally work toward a solution" (Kirsh, 2009, pp. 277–278). Through interactive exploration we aren't simply testing hypotheses about potential solutions, but we are manipulating the environment in ways that test possibilities even before we had contemplated what those possibilities would be. Sometimes we do this by adding structure to the environment, such as when we use physical reminders with sticky notes, or when we rearrange the layout of resources (e.g., books, cooking ingredients, building materials, desktop icons, etc), or when we talk to others as a way to organize our thoughts and actions (Kirsh, 2009, p. 281). Some of these interventions constitute what Kirsh calls "epistemic actions," as in the example of rotating Tetris pieces as soon as they appear on the screen instead of thinking before implementing a move (see, e.g., Kirsh and Maglio, 1994; Maglio and Kirsh, 1996): these are physical

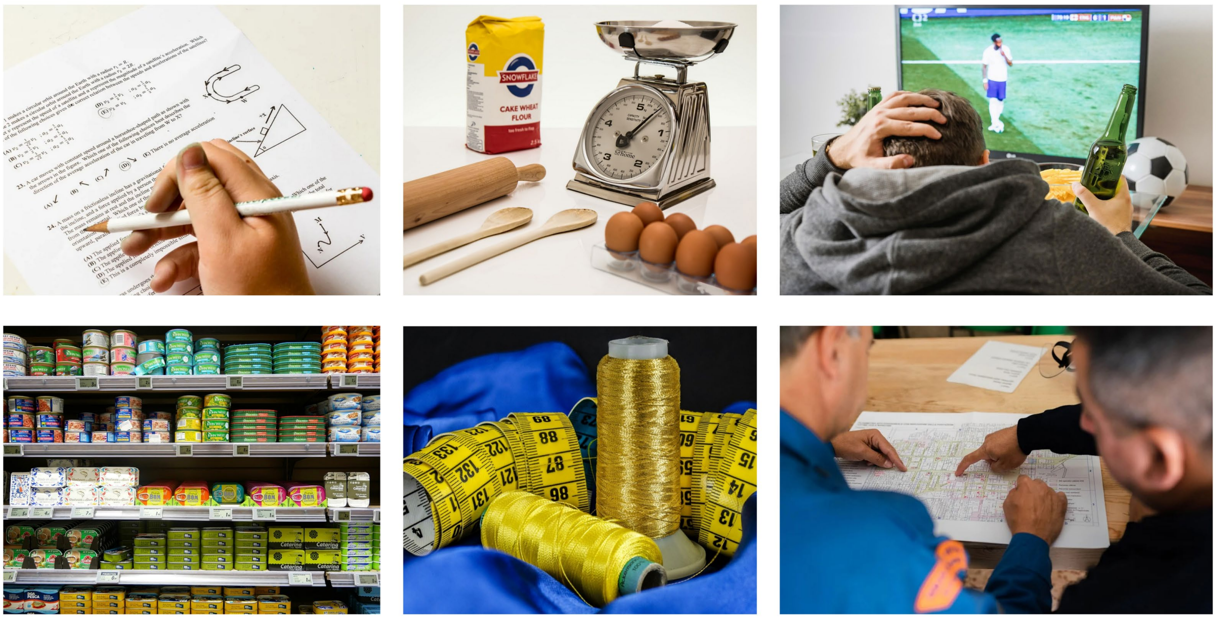

FIGURE 7
Given the situated nature of cognition, there is no "problem solving in general" because in real life there is no "problem in general" either: problems and solutions are always situation-specific. This is illustrated here with instances in which problem solving is paired to "mathematical reasoning": rather than a discrete generic ability that merely gets implemented in some context or other, our use of quantity, numbers and their relations always involves local adaptations to situation-specific circumstances that shape the "problem" we are trying to address, for instance at school (top left), when baking (top center), when trying to assess your soccer team's odds of overcoming an adverse aggregate score where home and away goals are weighted differently (top right), when shopping on a tight budget (bottom left), when sewing (bottom center), and at work as a civil engineer (bottom right).

actions that accomplish cognitive work for the agent, revealing and addressing aspects of the situation so that the agent does not have to figure them out reflectively. We solve problems through interaction in and with the world, and what counts as a "problem" and as a "solution" is specific to the situation, which also makes the process of solving a problem inherently situation-specific.

The examples considered so far emphasize the crucial role of what people *do*, in particular circumstances, to provide structure to the problematic situation they are faced with, so as to solve the problem in question. But it's important to emphasize that, when we do this, we aren't giving structure to something that lacked structure altogether: rather, we work with the resources and constraints already present and shape them in new ways, but there were resources and constraints already there even before we approached the problem.

To illustrate this, consider another classical example from the situated cognition literature—that of going through the checkout line in a supermarket. Anyone who does grocery shopping knows that there are better and worse ways of bagging what you buy: cans and heavy items go first; bread, bananas, tomatoes, eggs and other delicate items go toward the top; but you also need to ensure that bags do not get too heavy, and that the weight is more or less evenly distributed between bags, and so on. As with the previous examples, this kind of scenario has been used to illustrate how cognition is shaped by the ways people act in the environment, exploiting the existing structure, and interactively and iteratively adapting it: as the cashier rings up some items, people commonly use the buffer zone to separate items into distinct categories, to assess how to bag them and in what order (see, e.g., Kirsh, 1995; Solomon, 2007). But to really emphasize the specificity of situations, we think it's useful to consider a dimension of this example that's usually left unacknowledged. As we can attest from personal experience, the checkout process at supermarkets in Germany is notoriously fast, surprisingly so for newcomers who have immigrated from North America. Here, the cashier rings up everything as quickly as possible, but in many stores the space past the cash register is minimal, with no buffer zone for sorting and bagging items—instead, there is a separate table or surface nearby where people more calmly organize and pack their groceries after having paid for them. This means that the task here is different: as soon as an item gets scanned, you try to quickly determine where to place it *back in the shopping cart* so that you have an easier time bagging your groceries afterward; of course, you can make your life even easier by organizing items properly on the conveyor belt even before they reach the cashier. The point of this example is that, not only is "problem solving" always a different kind of cognitive process in specific situations (rather than a general process that is merely implemented in different situations), but even a seemingly well-defined situation such as the often-cited "grocery store checkout situation" is not one and the same everywhere—it varies in different contexts depending on what people do and the way the environment is structured (see Figure 7 for additional examples).

So, does bilingualism contribute to or hinder cognition? The upshot of the preceding discussion is that, given the inherently relational, situated nature of cognition, we cannot talk about "cognitive" advantages and disadvantages in general, without accounting for the ways in which cognition in every case is fundamentally shaped by the situation. Here, understanding cognition relationally motivates thinking that cognition is not a single thing, and even problem solving is not a single thing: these are always specific to some situation or other, which also means that they are specific to some agent-environment relation or other. Strategies for coping in some situations can, of course, come to be useful, to varying degrees, for succeeding in other situations. Still, in the perspective outlined here, what counts as success or failure is always going to be situation-specific, such that what counts as an advantage or disadvantage cognitively speaking is not necessarily going to be the same across situations. As suggested by this subsection's title, the computational interpretation of "cognitive" advantages and disadvantages is problematic because it neglects the relational, situated nature of cognitive processes such as problem solving. Cognitive advantages and disadvantages cannot be reduced to the level of the efficient processing of bits of information supposedly internal to an agent, but must take into account the complexities of how embodied agents relate to resources and constraints in particular real-world situations.

Discussion

In the introduction we saw how the research question of whether bilingualism is cognitively advantageous or disadvantageous is well established, having guided research at least since the 1960s. But that's a positive way to think about this. With less of a positive spin, it is interesting to note that, despite all of the developments in research on bilingualism over the years, the progress has not been sufficient to promote a shift in paradigm and we are still guided by a research question as posed more than half a century ago.

In the previous sections we were concerned with sketching how ideas in fields studying language and cognition, and in particular research in sociolinguistics and embodied cognitive science, pose challenges for the usual way of thinking about bilingualism and cognitive advantages or disadvantages. Having done this, we can now more clearly articulate what the research question means given the dominant assumptions about "language" and "cognition." In the computationalist conception, *cognition* is internal information processing. From this picture of what the mind is and how it works, *language knowledge* comes to be understood as internal representations of linguistic units (e.g., written symbols, sounds) and algorithms or rules about how those units work together (see, e.g., Bucholtz and Hall, 2016). *Bilingualism*, in turn, amounts to the internalization of two or more systems of linguistic units+rules, especially to a level of proficiency in each system equivalent to the proficiency of people who have internalized only one system (i.e., the view of bilingualism as a plurality of monolingualisms within the same person). As a combination of these conceptions, the *research question* can then be interpreted as asking: does having internalized knowledge of more than one system of linguistic units+rules contribute to efficient internal information processing, does it hinder it (i.e., does it pose a burden, for instance, slowing down information processing), or is it neutral in this regard? (see, e.g., Ross and Melinger, 2017; DeLuca et al., 2019, 2020).

In the previous sections we provided a number of different reasons for seeing the research question in this and similar formulations as being deeply problematic and misguided. As we have suggested, ideas from sociolinguistics and embodied cognitive science challenge the essentialist and internalist way of thinking that underlies and motivates the question. But so far we have explored these ideas in separation from one another. Accordingly, our goal in this concluding section is to spell out how the different ideas from the different fields and research traditions come together to motivate a view of cognition, language and linguistic knowledge as embodied, situated, and inherently social.

Language, cognition, and the social

To make it clearer why—in light of the ideas discussed in the previous sections—the research question of bilingualism's cognitive advantages and disadvantages is problematic, consider the following related but different question:

> Is being "lingual" cognitively advantageous, disadvantageous or neutral? That is, is having some linguistic knowledge and ability (as opposed to lacking any and all linguistic knowledge and ability) a cognitive boon?

Although it might sound far-fetched, this new question could be applied to the case of a feral child raised by non-human animals in the wild: in comparison, is a person who grows up in human environments and develops some communication skills better off—and not only better off socially, for instance, or in terms of well-being, or chance of surviving to old age, but better off *cognitively*?

Would this question be a reasonable and fruitful starting point for research, one that would lead to decades of work trying to find evidence of advantage, disadvantage, or neutrality? It does not seem like it. Our intuition is that this is not a great research question because the answer is obvious: regardless of how you conceptualize "language" and "cognition," having some linguistic communicative ability is, for humans, always cognitively better than not having any. But why is that? We think the ideas from sociolinguistics and embodied cognitive science reviewed in the previous sections provide some useful guidance. Those ideas give us a way to make sense of *what we come to know when* *we learn language*, and *what it means to know it*—or, put differently, they give us a particular conceptualization of the nature and object of linguistic knowledge. In clarifying what we mean by this, we will be building upon Jean Lave's view of learning as not "a process of socially shared cognition that results in the end in the internalization of knowledge by individuals, but as a process of becoming a member of a sustained community of practice" (Lave, 1991, p. 65). This is a claim Lave makes about learning in general that we think is especially helpful for thinking about language.

First, *what we come to know when we learn language*: we come to know the *world*—though not in the abstract and in general, but in the concrete way in which it is experienced in some community of practice or other. In particular, when we learn language we come to know a way of relating to things, to people, and to events—some of which are named, categorized, described and evaluated, referred to in marked and unmarked ways, and ultimately (or, in the first place) noticed, while others aren't. Learning language, we propose, is developing a way of *being* in the world: for Martin Heidegger (1927/2001) being and world are inseparable because being human is always "being-in-the-world"; and as Merleau-Ponty (1945) emphasizes, "being-in-the-world" is inherently social, interpersonal, relational (see also, e.g., Gallagher, 2012; Käufer and Chemero, 2021).

Following from this, and second, *what it means to know language*: it means to have skill in *participating* in the relevant community of practice. This includes, for instance, having skill in coordinating with others and contributing to shared activities, but it's not limited to interpersonal action. Even when we are acting individually and in supposed isolation from others, we cannot help but do so in certain ways that are informed by, and recognizable in light of, a socially-shared frame of reference. In the limit case, even the actions of a hermit who fled civilization as an adult would likely continue to be *intelligible* to a hypothetical observer from the society the hermit fled, however deplorable the hermit's actions might be—a radically unintelligible action, by contrast, could not be deplorable.

Skill in participating in a community of practice can look different in different communities of practice. It often involves participation in particular practices of codifying behavior, including, in some cases, ability to engage in explicit meta-linguistic talk about correct and incorrect ways of speaking and writing, and about why X is right but Y is wrong, and so on. An intuitive example of this phenomenon concerns developing skill in navigating expectations around dominant, prestige varieties in a given language—for instance, coming to be able to discuss the correct use of standard expressions or the pronunciation of technical terms within a particular disciplinary academic circle in Standard American English. But the same can be present in any community of practice: practices of codifying behavior and of discussing those codifications can arise around anything that gets used to form social groups, be it around profession, religious membership, racial identity, and so on.

Still, meta-linguistic skill is arguably *not* necessary for linguistic skill. This is a point in which the relational embodied perspective we are sketching differs from the traditional essentialist and internalist perspective in which linguistic knowledge is precisely the internalization of meta-linguistic rules. In our view, it's possible to succeed in participating in a community of (communicative) practice without being able to articulate the patterns that make up participation in the community, that is, without being able to put your finger on precisely why this is right and that is wrong in the way of speaking, for instance. Developing the ability to engage in meta-linguistic coordination (especially when this is already part of the community of practice) is a case of expansion in linguistic skill rather than acquisition of a separate, distinct, and supposedly more fundamental, skill. And crucially, like all other expansions of linguistic skill (including, e.g., "learning a new language"), developing the ability to engage in meta-linguistic coordination is *necessarily cognitively advantageous*. This is because expansions in linguistic skill always broaden the scope of what and how we can know: new aspects of the world are unveiled and can be confronted and can come to be understood and made sense of, resulting in activity that is more sensitive to the particularities of the situation. Recognition of the centrality of the social in language through participation in communities of practice calls for further consideration of how power and political interests come into play.

Language, social construction, and power

In the section titled "What is 'bilingualism' such that it may be cognitively advantageous or disadvantageous?" we talked about how the boundaries between languages and within languages are used politically as a means of creating division as well as uniting people groups. But it's not just that languages exist out there and are sometimes used politically. The existence of languages as distinct bounded entities was not the origin of their political use: rather, their coming to be conceptualized as distinct bounded entities is an outcome of their (social, political) history.

Named languages are socially constructed in more than one sense. First, they are socially constructed in that terms like "Spanish," "Russian," "Indonesian," and "Quechua" do not capture natural kinds, but reflect a convention to name a complex set of practices (and not others) as a single thing. Many of these names are the legacy of historical processes of European nation building (Blommaert and Verschueren, 1992; Irvine et al., 2009) and of European colonialism (Makoni and Pennycook, 2007). So, "English" as an idea or concept exists because people made it up. This does not entail, however, that named languages are *not real*. Socially-constructed or made-up things are very real: e.g., money, weeks, national borders, etc.

In another sense, named languages are socially constructed in that, at specific points in time and space, people in interaction with one another developed shared communicative behaviors that solidified certain patterns that they came to identify as *their* language, even if they may not have used the term "language" to refer to those practices or to separate them from other practices in their culture. Put another way, languages came to be conceptualized as distinct bounded entities, and through this, they came to *be* distinct bounded entities. Blackledge and Creese (2014) caution that, "[t]he idea of 'a language' therefore may be important as a social construct, but it is not suited as an analytical lens through which to view language practice" (p. 1). As socially constructed in the ways just identified, named languages are still real, and understanding the socially-constructed categorization schemes that people are subjected to as speakers of single or multiple named languages can still help shed light on real phenomena.

Discrimination is not a bug, but a feature.

> If we view bilingualism only in additive and cognitive terms (speaking more than one language brings benefits), we miss the point that bilingualism is more usefully understood in terms of "resources which circulate in unequal ways in social networks and discursive spaces" (Pennycook, 2019, p. 169, quoting Heller, 2007, p. 2).

A discussion of bilingualism would not be minimally adequate without acknowledging the role of language status and speaker status to support prejudice and justify processes of social stratification (Piller, 2015). Woolard (2020) affirms that beliefs about languages "endow some linguistic features or varieties with greater value than others, for some circumstances and some speakers" (p. 2). Not all language practices are treated equally, and double standards abound, such that bilingualism is inconsistently and unequally defined and valued (Piller, 2012). To illustrate, consider the case of two people who could be labeled bilingual in Spanish and English: an Anglo-American teenager who studies Spanish in school and a Mexican-American peer who is proficient in English and Spanish as a result of bi-cultural life experiences. While the white English speaker is praised for acquiring valuable ("marketable") additional language skills, the Mexican-American student faces linguistic discrimination and is denied access to a host of opportunities. Bilingualism even in the same languages will not be treated equally if the speakers' status is not equal (Piller, 2012). This means that being bilingual will confer different advantages and disadvantages to different people, even *cognitive* advantages and disadvantages—being denied access to experiences limits possibilities to learn and come to know the world, which is a kind of epistemic deprivation.

The example of the two teenagers connects to Politzer's (1981) description of the influence of class difference on bilingualism: "Within the upper ranges of socioeconomic status, bilingualism tends to be associated with some additional educational advantages; within the lower ranges, it often appears to result in an additional handicap" (p. 3). Social factors such as race (see, e.g., Rosa and Flores, 2017), class (see, e.g., Block, 2013), and immigration status (see, e.g., Piller, 2001) are central in understanding how value is unequally accorded to (bilingual) language practices. And this same double standard in bilingualism applies within monolingual contexts too. Not all monolinguals are created equal, which is clear, for instance, in cases of discrimination against the English of various racialized people groups in the US (see, e.g., Milroy and Milroy, 1985/2012; Lippi-Green, 2012). As Blommaert (2001) points out, "people can be 'majority' members (e.g., they can speak the language of the ruling groups in society) yet they can be thoroughly disenfranchised because of a lack of access to status *varieties* of the so-called 'power-language'" (p. 136, emphasis added). All language practices are connected to power, and unequal treatment of language users occurs both for those considered bilingual and for those considered monolingual. Classification of people according to their language practices is not neutral and cannot be properly understood apart from processes of social differentiation for the maintenance of hierarchy.

The idea that languages are discrete, natural objects that are used by distinct speech communities is common, and perhaps still the dominant understanding of language today. Under this ideology, even victims of linguistic discrimination might recognize that the discrimination they suffer is of sociopolitical basis, but might still not realize that the criterion used in this particular form of discrimination (i.e., language) is itself of sociopolitical origin as well. That is, while acknowledging the arbitrariness of the fact of discrimination, they might still assume languages to be real, natural, and objective categories rather than socially-constructed objects that are inherently instrumentalized precisely in the service of social discrimination.

In line with this, and as we suggested previously, rather than uncritically embracing essentialism about bounded languages (e.g., thinking that there is such a thing as "the English language"), it is better to think of languages as goals, projects. This applies to large dominant languages, such as in the promotion of Swahili as a regional *lingua franca* (Amidu, 1995); it also applies to projects in minority language revitalization, such as, for instance, in the teaching of the Irish language in schools in Ireland (Ceallaigh and Dhonnabhain, 2015). Whether majority or minority, languages are aspirational, ideal (Costa, 2020). Languages are what some people want the world to be like (which includes human activity, and aspects of interpersonal relations). From this perspective, "language"—as a collective pattern of coordination and joint activity—is only properly understood *relationally*: this is clear, for instance, in the way standard varieties can only be defined in contrast with what are considered nonstandard varieties (Auer, 2005b); accordingly, attempts to distinguish between varieties are always a move to solidify difference, and through this, to "realize" (i.e., "make real") a sociopolitical state of affairs.

An analogous point applies to "language" at the personal level too. With regard to real languaging practices, rather than focusing on the named languages that people speak, it is perhaps better to think in terms of idiolects, namely unique assemblages of bits of language that make up the linguistic repertoire of an individual speaker (Blommaert, 2009). Individuals speak idiolects that work in some contexts, for some ends, because they at least partially overlap with the idiolects of others participating in those contexts and activities. So people who can speak "English" participate in a complex pattern of multiple partly-overlapping idiolects. As such, relational thinking also applies to "language" understood at the personal level: after all, a person's languaging is what it is because of, and in interaction with, others—and this includes many different "others," that is, both "others" who are seen as interlocutors and co-participants, on the one hand, and, on the other hand, those 'radically other' others, who aren't interlocutors and co-participants, not even remotely.

Relational thinking thus motivates shifting the focus away from rigid classifications of people and people groups solely on the basis of named languages and of categories like "bilingual" and "monolingual": instead, the relational nature of language at both the collective and personal levels calls for careful attention to how both individuals and groups forge their unique linguistic profile in specific contexts and activities. This involves taking seriously how both individual repertoires and collective patterns of interpersonal overlaps are defined relationally, through participation in communities of practices, and distinction between communities of practice. And it also involves taking seriously the relational *cognitive* dimension of these practices: we cannot properly make sense of what cognitive advantages or disadvantages bilingualism might provide without considering how opportunities for learning and growing in our knowledge of the world (including contributing to shared knowledge production) are mediated by language and by the way linguistic ability is interwoven with particular practices, group membership and sociopolitical projects of world-making.

What now?

The ideas examined in the previous sections motivate a radical departure from usual interpretations of the research question of whether bilingualism is cognitively advantageous or not. On the one hand, as we have seen "bilingualism" is a complicated category, and describing someone as "bilingual" is not as straightforward as ascribing a trait such as "being X centimeters tall," but is instead more like describing them as "tall enough to play this game" or "too tall to stand up here" or "too short to be able to see us from there"—in other words, it's a relational feature, a characteristic not of people on their own but of the different ways people can relate to their environment and participate in different activities. This emphasis on the multifaceted nature of bilingualism is in line with the work mentioned earlier that takes into account multiple, dynamically changing variables to define the potentially very different linguistic profiles of different bilinguals (e.g., Hartanto and Yang, 2016, 2020; Gullifer et al., 2018; DeLuca et al., 2019, 2020; Gullifer and Titone, 2020, 2021a; Sulpizio et al., 2020; Kremin and Byers-Heinlein, 2021). By blurring the boundaries between "bilingual" and "monolingual," these multivariate accounts are also promising starting points for understanding any and all linguistic profiles, including those of people typically described as monolinguals but who may differ widely from other monolinguals in their range of experiences and skills. On the other hand, however, even these more sophisticated and fine-grained multivariate measures of bilingualism aren't enough to support conclusions about the cognitive benefits or drawbacks of bilingualism without further consideration of what "cognitive" advantages and disadvantages are in the first place.

As traditionally construed, the cognitive advantage/disadvantage question is a question about whether knowledge of multiple languages (understood as internalized representations of multiple linguistic systems or codes) enhances the efficiency of, or poses a burden to, information processing. But work in radical embodied cognitive science like that explored earlier in the paper challenges this view of cognition as information processing, instead understanding the "cognitive" in terms of an epistemic relation constituted by embodied, situated interaction. In this view, as we saw, even walking is a "cognitive" process, yet this is not because it involves information processing, but rather because it's an epistemically enriching act—by moving around and exploring the environment agents can change how and what they know, for instance, revealing or occluding different aspects of the environment (as illustrated in Figure 6).

So, consider how, as cited earlier in the paper, bilingualism is often linked to enhanced executive control and executive function as shown in tasks involving self-monitoring and the inhibition of irrelevant information, as well as slower lexical access and retrieval (e.g., Bialystok et al., 2008; Festman et al., 2010; Pelham and Abrams, 2014). In line with traditional computational thinking, these effects are often considered "cognitive" because they are construed as changes in information processing speed and accuracy as managed by a "master subsystem, the central executive" that "controls and coordinates the resources of the cognitive system" (Anastas et al., 2014, p. 263). Here, reaction time or response time is a common measure of information load and processing efficiency: whatever imposes a "cognitive" burden tends to lead to a slowing down of performance, because "the executive could only operate as quickly as the slowest component" that it gets inputs from (Anastas et al., 2014, p. 268; see also, e.g., West, 2001; Diamond, 2013; Karbach and Unger, 2014; Vasquez et al., 2018). Although common, this way to construe "executive function" is neither theoretically-neutral nor unproblematic. As some researchers in embodied cognitive science have put it, the "deeply rooted acceptance that behavior's organization reflects entirely internal, locally defined, representational processes has made the dependence of standard theory on executive function so pervasive as to be almost invisible" (Richardson et al., 2008, p. 163). By rejecting such internalist, localist and computationalist assumptions about cognition, authors like these also challenge the usual understanding of what the label "executive function" is supposed to capture. For instance, some have proposed that, rather than amounting to the output of an internal master component that oversees and *organizes* the flow of data, the phenomena falling under the label of "executive function" are instead *self-organized*, emerging dynamically through the interaction of system activity at different timescales (Anastas et al., 2014; Kelty-Stephen et al., 2016). The implication of views like these is that "executive function" is not cognitive because it entails information processing (in particular, a process of "managing" and "organizing" data flow), but rather because, understood properly, it is an epistemic enrichment of embodied, situated perception-action. If the "cognitive" is not operationalized in terms of the internal storage and processing of information but is instead understood in terms of the behavioral implications of what and how one knows, then speed is no longer obviously a crucial factor. If after learning something you come to know to slow down and pay closer attention to a given task you are confronted with, then this is a cognitive boon compared to lacking this sensitivity to the situation and proceeding quickly as you might have done before. Sometimes knowing more (or differently) means taking your time to do something that demands more attention or precision. Taking longer is not necessarily a cognitive deficit (nor symptomatic of a cognitive deficit), and sometimes it might even be cognitively (i.e., epistemically) advantageous. Ultimately, then, a shift in how we understand not only "bilingualism" but also "cognition" has to be taken into account if we are to make sense of how speaking two or more languages has cognitive implications for embodied, situated agents—that is, implications for what and how they know.

These points suggest that the research question we are focusing on in this paper is weird in that it rests on strange assumptions about human communication and our mental lives, assumptions that neglect the situated and embodied nature of our experience. But the research question is also "WEIRD" in that it is characteristic of a way of thinking typical of "Western, Educated, Industrialized, Rich and Democratic" societies (Henrich et al., 2010). Monolingualism is not the norm in most of the world today nor has it been the norm in most of human history. And yet, monolingualism is the presumed reality in the most influential centers of knowledge production today, such that studies tend to take bilingualism as an exotic phenomenon to be explained, while monolingualism is the default for normal people (this is evidenced by the common reference to "bilingualism" as synonymous with knowledge of "additional" languages—a description that erroneously presupposes monolingualism to be the normal starting point upon which something may be added or not). Because of this monolingual bias in WEIRD science, although Figures 1–4 were not meant to depict a temporal relation between monolingualism and bilingualism, we would not be surprised if some readers saw those figures as illustrating a chronological progression where you start out as a monolingual and later move in the direction of learning additional languages. Of course, the reality is that there are plenty of individuals in many places today and throughout history for whom monolingualism is not the starting point (see, e.g., Grosjean, 2010 for a nuanced look at the experiences of contemporary bilinguals, and Canagarajah and Liyanage, 2012 for a discussion of multilingual practices in the pre-colonial southern hemisphere). Citing Doerr's (2009) work, Lovrits and de Bres (2021) assert that "the ideological prerequisite of innate monolingualism in a standard language exerts a strong influence on constructions of linguistic legitimacy and competence" (p. 400). Along these lines, some psycholinguists acknowledge the danger of taking for granted, and reinforcing, the "dominant ideology of monolingualism as a gold standard" (Tiv et al., 2021): given its prevalence globally, it's inadequate to treat bilingualism as the exceptional case (Gullifer and Titone, 2021b). And in a provocative hypothetical scenario, Pennycook and Makoni (2020) suggest that, if the dominant centers of knowledge production today were located in the Global South, bilingualism (rather than monolingualism) would be assumed to be the norm, and researchers might be interested in understanding the rare, exotic peoples who are so limited in their communicative abilities that they can only speak a single language—though perhaps these researchers would not even think of languages as countable entities analyzable in separation from other aspects of human life.

Given these reflections and how they cast doubt on the research question of bilingualism's cognitive advantages or disadvantages, we want to conclude with a few suggestions of potentially helpful guides for future research.

A first practical and foundational implication of the preceding discussion is that we need to be extremely careful in experimental design and how we delineate the target population and choose participants. The ways we see some people as monolingual, bilingual, "native" speakers, and so on are permeated with philosophically-loaded assumptions. It's crucial that researchers address these assumptions head on: rather than uncritically importing the procedures and groupings others have used previously, results cannot properly count as findings if they do not specify which assumptions the research presupposes.

Second, ideas like the ones explored in this paper motivate moving away from research that takes for granted *named languages* as if they are the only natural way, or even a necessary way, of partitioning phenomena of linguistic communication. Once we get over the bias toward named languages and move toward partitioning linguistic communication around *activities*, a related shift makes sense, away from focusing on speech communities and toward focusing on communities of practice, which encompass patterns of speech and communication, but where those are only understood as grounded in the real-world activities of, and relations between, co-practitioners.

Third, besides moving away from partitioning communication around named languages, the ideas explored in this paper also support the related but distinct shift away from a focus on languages as countable entities (many of which would supposedly coexist inside a person) toward the study of an individual's idiolect (or total languaging repertoire) as a social, embodied meaning-making practice. As in the previous point, this fits nicely with attention to activities and communities of practice, as it is in these that "languaging" gets molded through behaviors of codification and interpersonal coordination. But the move away from languages as countable entities also invites re-consideration of how we understand all that individuals are capable of, how we qualify and quantify their skill, and the ways in which people are more or less well equipped for thriving in different circumstances. Instead of asking how many languages someone can speak, a better question is what they can get done, and what they can participate in, and in what contexts.

Here we think researchers interested in bilingualism would have much to profit from theoretical and methodological developments in recent work on languaging practices in embodied cognitive science. This includes studies of language through the lens of embodied interactivity (see, e.g., Steffensen, 2017; Steffensen and Harvey, 2018; Li et al., 2020), studies focusing on the tuning of multimodal embodied interaction over developmental timescales (see, e.g., Rączaszek-Leonardi et al., 2013, 2018; Nomikou et al., 2016; Rohlfing et al., 2019), as well as studies using nonlinear analysis methods to quantify the dynamics of coupling and complexity matching in interpersonal coordination (see, e.g., Richardson and Dale, 2005; Abney et al., 2014; Coey et al., 2016). Examples such as these tend to focus on embodied dimensions of interaction in only one language, but, even in light of the caveats above, we see promise in using similar conceptual frameworks and methodological tools for investigating diverse multilingual practices while taking seriously the complex embodied and relational nature of languaging.

Lastly, we think it's important to understand what this different way of thinking of language and cognition means for elucidating the role that technology can play in human embodied activity. "In the wild" people use whatever resources are available to them in order to be able to get by. Is using one's phone to translate something necessarily a crutch, something external and distinct from the individual's language, language knowledge and cognition "themselves"? Views of cognition as distributed and extended and as a feature of the organism-environment relation motivate moving away from these conclusions. The smartphone in this case can be seen as a resource that is both linguistic and cognitive, a resource that supports and partly constitutes the person's ability to coordinate with others or to solve a problem and through this to achieve cognitive ends, making sense of the world and continuing moving forward more successfully than before. This example illustrates the more general upshot: understanding language requires understanding what resources people rely on, when, where, and why, and what their use leads to.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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References

Abney, D. H., Paxton, A., Dale, R., and Kello, C. T. (2014). Complexity matching in dyadic conversation. *J. Exp. Psychol. Gen.* 143, 2304–2315. doi: 10.1037/xge0000021

Amidu, A. A. (1995). Kiswahili: people, language, literature and lingua Franca. *Nord. J. Afr. Stud.* 4:20.

Anastas, J. R., Kelty-Stephen, D. G., and Dixon, J. A. (2014). Executive function as an interaction-dominant process. *Ecol. Psychol.* 26, 262–282. doi: 10.1080/10407413.2014.957985

Anisfeld, M. (1964). A comparison of the cognitive functioning of monolinguals and bilinguals. Doctoral dissertation, Montreal, QC: McGill University.

Antoniou, K., Grohmann, K. K., Kambanaros, M., and Katsos, N. (2016). The effect of childhood bilectalism and multilingualism on executive control. *Cognition* 149, 18–30. doi: 10.1016/j.cognition.2015.12.002

Auer, P. (2005a). "The construction of linguistic borders and the linguistic construction of borders," in *Dialects Across Borders: Selected Papers from the 11th International Conference on Methods in Dialectology* (Netherlands: John Benjamins), 3–30.

Auer, P. (2005b). Europe's sociolinguistic unity, or: a typology of European dialect/standard constellations. *Perspect. Var.* 7, 7–42. doi: 10.1515/9783110909579.7

Barsalou, L. W. (1999). Perceptual symbol systems. *Behav. Brain Sci.* 22, 577–660. doi: 10.1017/S0140525X99002149

Barsalou, L. W., Simmons, W. K., Barbey, A. K., and Wilson, C. D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends Cogn. Sci.* 7, 84–91. doi: 10.1016/S1364-6613(02)00029-3

Bialystok, E. (2007). Cognitive effects of bilingualism: how linguistic experience leads to cognitive change. *Int. J. Biling. Educ. Biling.* 10, 210–223. doi: 10.2167/beb441.0

Bialystok, E. (2021). Bilingualism as a slice of Swiss cheese. *Front. Psychol.* 12:769323. doi: 10.3389/fpsyg.2021.769323

Bialystok, E., Craik, F., and Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *J. Exp. Psychol. Learn. Mem. Cogn.* 34, 859–873. doi: 10.1037/0278-7393.34.4.859

Biber, D. (2009). "38. Multi-dimensional approaches," in *Corpus Linguistics: An International Handbook*, *Vol. 2*. (Berlin: De Gruyter Mouton), 822–855.

Biber, D., and Conrad, S. (2019). *Register, Genre, and Style*. Cambridge: Cambridge University Press.

Bice, K., and Kroll, J. F. (2019). English only? Monolinguals in linguistically diverse contexts have an edge in language learning. *Brain Lang.* 196:104644. doi: 10.1016/j.bandl.2019.104644

Blackledge, A., and Creese, A. (2014). "Heteroglossia as practice and pedagogy" in *Heteroglossia as Practice and Pedagogy. Educational Linguistics*. eds. A. Blackledge and A. Creese (Dordrecht: Springer), 1–20.

Block, D. (2013). *Social Class in Applied Linguistics*. London: Routledge.

Blommaert, J. (2001). The Asmara Declaration as a sociolinguistic problem: reflections on scholarship and linguistic rights. *J. Socioling.* 5, 131–142. doi: 10.1111/1467-9481.00142

Blommaert, J. (2009). Language, asylum, and the national order. *Curr. Anthropol.* 50, 415–441. doi: 10.1086/600131

Blommaert, J. (2010). *The Sociolinguistics of Globalization*. Cambridge: Cambridge University Press.

Blommaert, J., and Backus, A. (2013). "Superdiverse repertoires and the individual," in *Multilingualism and Multimodality*. eds. I. Saint-Georges and J.-J. Weber (Leiden: Brill Sense), 9–32.

Blommaert, J., and Verschueren, J. (1992). The role of language in European nationalist ideologies. *Pragmatics* 2, 355–375.

Bourdieu, P. (1991). *Language and Symbolic Power*. Cambridge, MA: Harvard University Press.

Bowcher, W. (2019). "Context and register," in *The Cambridge Handbook of Systemic Functional Linguistics* (Cambridge: Cambridge University Press), 142–170.

Bruineberg, J., and Rietveld, E. (2019). What's inside your head once you've figured out what your head's inside of. *Ecol. Psychol.* 31, 198–217. doi: 10.1080/10407413.2019.1615204

Brunstad, E. (2003). Standard language and linguistic purism. *Sociolinguistica* 17, 52–70. doi: 10.1515/9783110245226.52

Bucholtz, M., and Hall, K. (2016). Embodied sociolinguistics. *Sociolinguistics* 1, 173–200. doi: 10.1017/CBO9781107449787.009

Canagarajah, S., and Liyanage, I. (2012). "Lessons from pre-colonial multilingualism," in *The Routledge Handbook of Multilingualism*. eds. M. Martin-Jones, A. Blackledge and A. Creese (London: Routledge), 67–83.

Castro, S., Wodniecka, Z., and Timmer, K. (2022). Am I truly monolingual? Exploring foreign language experiences in monolinguals. *PLoS One* 17:e0265563. doi: 10.1371/journal.pone.0265563

Ceallaigh, T. Ó., and Dhonnabhain, Á. N. (2015). Reawakening the Irish language through the ırish education system: challenges and priorities. *Int. Electr. J. Element. Educ.* 8, 179–198. Available at: https://www.iejee.com/index.php/IEJEE/article/view/107

Chemero, A. (2009). *Radical Embodied Cognitive Science*. Cambridge, MA: MIT press.

Chemero, A. (2013). Radical embodied cognitive science. *Rev. Gen. Psychol.* 17, 145–150. doi: 10.1037/a0032923

Clancey, W. J. (1997). *Situated Cognition: On human Knowledge and Computer Representations*. New York, NY: Cambridge University Press.

Clancey, W. J. (2009). "Scientific antecedents of situated cognition," in *The Cambridge Handbook of Situated Cognition*. eds. P. Robbins and M. Aydede (New York, NY: Cambridge University Press), 11–34.

Coey, C. A., Washburn, A., Hassebrock, J., and Richardson, M. J. (2016). Complexity matching effects in bimanual and interpersonal syncopated finger tapping. *Neurosci. Lett.* 616, 204–210. doi: 10.1016/j.neulet.2016.01.066

Costa, J. (2020). Standard language(s). in *The International Encyclopedia of Linguistic Anthropology*. ed. J. Stanlaw.

Costall, A. (2007). How cognitive psychology highjacked thinking. *Anthropol. Psychol.* 18, 21–23. Available at: http://psy.au.dk/fileadmin/Psykologi/Forskning/Forskningsenheder/Journal_of_Anthropological_Psychology/Volume_18/alan_costall.pdf

Crippen, M., and Schulkin, J. (2020). *Mind Ecologies: Body, brain, and World*. New York, NY: Columbia University Press.

Dąbrowska, E. (2012). Different speakers, different grammars: individual differences in native language attainment. *Linguistic Approaches Biling.* 2, 219–253. doi: 10.1075/lab.2.3.01dab

Dąbrowska, E. (2018). Experience, aptitude and individual differences in native language ultimate attainment. *Cognition* 178, 222–235. doi: 10.1016/j.cognition.2018.05.018

Dąbrowska, E. (2019). Experience, aptitude, and individual differences in linguistic attainment: A comparison of native and nonnative speakers. *Lang. Learn.* 69, 72–100. doi: 10.1111/lang.12323

Davies, N. F. (1976). Receptive versus productive skills in foreign language learning. *Mod. Lang. J.* 60, 440–443. doi: 10.1111/j.1540-4781.1976.tb03667.x

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U. S. A.* 116, 7565–7574. doi: 10.1073/pnas.1811513116

DeLuca, V., Rothman, J., Bialystok, E., and Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage* 204:116222. doi: 10.1016/j.neuroimage.2019.116222

Dennett, D. C. (1984). "Cognitive wheels: the frame problem of AI" in *Minds, machines and evolution: Philosophical Studies*. ed. C. Hookway (Cambridge: Cambridge University Press), 129–151.

Di Paolo, E., Buhrmann, T., and Barandiaran, X. (2017). *Sensorimotor Life: An Enactive Proposal*. Oxford: Oxford University Press.

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Diebold, A. R. (1968). "The consequences of early bilingualism on cognitive development and personality formation" in *The Study of Personality: An Inter-Disciplinary Appraisal*. eds. E. Norbeck, D. Price-Williams and W. M. McCord (New York, NY: Hold, Rinehard, & Winston), 218–245.

Doerr, N. M. (Ed.). (2009). *The native Speaker concept*. Berlin: De Gruyter Mouton.

Dotov, D. G. (2014). Putting reins on the brain. How the body and environment use it. *Front. Hum. Neurosci.* 8:795. doi: 10.3389/fnhum.2014.00795

Dreyfus, H. L. (1972). *What Computers Can't Do: A Critique of Artificial Reason*. New York, NY: Harper & Row.

Dreyfus, H. L. (1992). *What Computers Still Can't Do: A Critique of Artificial Reason*. Cambridge, MA: MIT Press.

Faarlund, J. T., and Haugen, E. (2007). Scandinavian languages. Encyclopedia Britannica. Available at: https://www.britannica.com/topic/Scandinavian-languages

Fajen, B. R., and Warren, W. H. (2003). Behavioral dynamics of steering, obstable avoidance, and route selection. *J. Exp. Psychol. Hum. Percept. Perform.* 29, 343–362. doi: 10.1037/0096-1523.29.2.343

Festman, J., Rodriguez-Fornells, A., and Münte, T. F. (2010). Individual differences in control of language interference in late bilinguals are mainly related to general executive abilities. *Behav. Brain Funct.* 6, 5–12. doi: 10.1186/1744-9081-6-5

Fodor, J. A., and Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: a critical analysis. *Cognition* 28, 3–71. doi: 10.1016/0010-0277(88)90031-5

Folke, T., Ouzia, J., Bright, P., De Martino, B., and Filippi, R. (2016). A bilingual disadvantage in metacognitive processing. *Cognition* 150, 119–132. doi: 10.1016/j.cognition.2016.02.008

Fox, R., Corretjer, O., and Webb, K. (2019). Benefits of foreign language learning and bilingualism: an analysis of published empirical research 2012–2019. *Foreign Lang. Ann.* 52, 699–726. doi: 10.1111/flan.12424

Gal, S. (2016). "Sociolinguistic differentiation," in *Sociolinguistics: Theoretical Debates*. ed. N. Coupland (Cambridge: Cambridge University Press), 113–136.

Gal, S., and Irvine, J. T. (1995). The boundaries of languages and disciplines: how ideologies construct difference. *Soc. Res.* 62, 967–1001. Available at: http://www.jstor.org/stable/40971131

Gallagher, S. (2012). *Phenomenology*, New York, NY: Palgrave Macmillan.

Gallese, V. (1999). "From grasping to language: mirror neurons and the origin of social communication," in *Towards a Science of Consciousness*. eds. S. Hameroff, A. Kazniak and D. Chalmers (Cambridge, MA: MIT Press), 165–178.

Gallese, V., Fadiga, L., Fogassi, L., and Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain* 119, 593–609. doi: 10.1093/brain/119.2.593

Gallese, V., and Lakoff, G. (2005). The brain's concepts: the role of the sensory-motor system in conceptual knowledge. *Cogn. Neuropsychol.* 22, 455–479. doi: 10.1080/02643290442000310

Gentner, D. (2019). Cognitive science is and should be pluralistic. *Top. Cogn. Sci.* 11, 884–891. doi: 10.1111/tops.12459

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston, MA: Houghton Mifflin.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Boston, MA: Houghton Mifflin.

Grapin, S. E. (2017). "Language for specific purposes testing: a historical review," in *Teachers College, Columbia University Working Papers in Applied Linguistics & TESOL*.

Green, C. D. (1996). Where did the word "cognitive" come from anyway? *Can. Psychol.* 37, 31–39. doi: 10.1037/0708-5591.37.1.31

Grosjean, F. (1985). The bilingual as a competent but specific speaker-hearer. *J. Multiling. Multicul. Dev.* 6, 467–477. doi: 10.1080/01434632.1985.9994221

Grosjean, F. (2010). *Bilingual*. Cambridge, MA: Harvard University Press

Grosjean, F., and Li, P. (2013). *The Psycholinguistics of Bilingualism*. Hoboken, NJ: John Wiley & Sons.

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., and Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Biling. Lang. Congn.* 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., and Titone, D. (2021a). Engaging proactive control: influences of diverse language experiences using insights from machine learning. *J. Exp. Psychol. Gen.* 150, 414–430. doi: 10.1037/xge0000933

Gullifer, J. W., and Titone, D. (2021b). Bilingualism: A neurocognitive exercise in managing uncertainty. *Neurobiol. Lang.* 2, 464–486. doi: 10.1162/nol_a_00044

Haeri, N. (2003). *Sacred Language, Ordinary People: Dilemmas of Culture and Politics in Egypt*. New York, NY: Springer.

Hartanto, A., and Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages: a diffusion-model analysis of the effects of interactional context on switch costs. *Cognition* 150, 10–19. doi: 10.1016/j.cognition.2016.01.016

Hartanto, A., and Yang, H. (2020). The role of bilingual interactional contexts in predicting interindividual variability in executive functions: a latent variable analysis. *J. Exp. Psychol. Gen.* 149, 609–633. doi: 10.1037/xge0000672

Hazen, K. (2001). An introductory investigation into bidialectalism. *Univ. Pa. Work. Pap. Linguist.* 7:8. Available at: https://repository.upenn.edu/pwpl/vol7/iss3/8

Heft, H. (2001). *Ecological Psychology in Context: James Gibson, Roger Barker, and the Legacy of William James's Radical Empiricism*. London: Psychology Press

Heft, H. (2020). Ecological psychology as social psychology? *Theory Psychol.* 30, 813–826. doi: 10.1177/0959354320934545

Heidegger, M. (1927/2001). *Being and Time*. Oxford: Blackwell Publishers Ltd.

Heller, M. (ed.) (2007). "Bilingualism as ideology and practice" in *Bilingualism: A Social Approach* (London: Palgrave Macmillan), 1–22.

Henrich, J., Heine, S. J., and Norenzayan, A. (2010). The weirdest people in the world? *Behav. Brain Sci.* 33, 61–83. doi: 10.1017/S0140525X0999152X

Hsu, L. (2014). Effectiveness of English for specific purposes courses for non-English speaking students of hospitality and tourism: a latent growth curve analysis. *J. Hosp. Leis. Sport Tour. Educ.* 15, 50–57. doi: 10.1016/j.jhlste.2014.05.001

Hurley, S. (2001). Perception and action: alternative views. *Synthese* 129, 3–40. doi: 10.1023/A:1012643006930

Irvine, J. T., Gal, S., and Kroskrity, P. V. (2009). "Language ideology and linguistic differentiation," in *Linguistic Anthropology: A Reader.* (Oxford: John Wiley & Sons), 402–434.

James, W. (1890/1983). *The Principles of Psychology*. Cambridge, MA; Harvard University Press.

Karbach, J., and Unger, K. (2014). Executive control training from middle childhood to adolescence. *Front. Psychol.* 5:390. doi: 10.3389/fpsyg.2014.00390

Käufer, S., and Chemero, A. (2021). *Phenomenology: an Introduction, 2nd Edn*. Hoboken, NJ: John Wiley & Sons.

Kelty-Stephen, D. G., Stirling, L. A., and Lipsitz, L. A. (2016). Multifractal temporal correlations in circle-tracing behaviors are associated with the executive function of rule-switching assessed by the Trail Making Test. *Psychol. Assess.* 28, 171–180. doi: 10.1037/pas0000177

Kirk, N. W., Fiala, L., Scott-Brown, K. C., and Kempe, V. (2014). No evidence for reduced Simon cost in elderly bilinguals and bidialectals. *J. Cogn. Psychol.* 26, 640–648. doi: 10.1080/20445911.2014.929580

Kirsh, D. (1991). Today the earwig, tomorrow man? *Artif. Intell.* 47, 161–184. doi: 10.1016/0004-3702(91)90054-N

Kirsh, D. (1995). The intelligent use of space. *Artif. Intell.* 73, 31–68. doi: 10.1016/0004-3702(94)00017-U

Kirsh, D. (2009). "Problem solving and situated cognition" in *The Cambridge Handbook of Situated Cognition*. eds. P. Robbins and M. Aydede (Cambridge: Cambridge University Press), 264–306.

Kirsh, D., and Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cogn. Sci.* 18, 513–549. doi: 10.1207/s15516709cog1804_1

Kirshner, D., and Whitson, J. A. (1997). *Situated Cognition: Social, Semiotic, and Psychological Perspectives*. London: Psychology Press.

Kremin, L. V., and Byers-Heinlein, K. (2021). Why not both? Rethinking categorical and continuous approaches to bilingualism. *Int. J. Biling.* 25, 1560–1575. doi: 10.1177/13670069211031986

Lähteenmäki, M. (2010). "Heteroglossia and voice: conceptualizing linguistic diversity from a Bakhtinian perspective" in *Language Ideologies in transition. Multilingualism in Russia and Finland*. (Frankfurt: Peter Lang), 17–34.

Lakoff, G., and Johnson, M. (1980a). The metaphorical structure of the human conceptual system. *Cogn. Sci.* 4, 195–208. doi: 10.1207/s15516709cog0402_4

Lakoff, G., and Johnson, M. (1980b). *Metaphors We Live By*. Chicago, IL: University of Chicago Press.

Lave, J. (1988). *Cognition in Practice: Mind, Mathematics and Culture in Everyday Life*. Cambridge: Cambridge University Press.

Lave, J. (1991). "Situating learning in communities of practice" in *Perspectives on Socially Shared Cognition*. eds. L. B. Resnick, J. M. Levine and S. D. Teasley (Washington, DC: American Psychological Association), 63–82.

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., De Bruin, A., and Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? *Meta Anal. Rev. Psychol. Bull.* 144, 394–425. doi: 10.1037/bul0000142

Li, J., Steffensen, S. V., and Huang, G. (2020). Rethinking ecolinguistics from a distributed language perspective. *Lang. Sci.* 80:101277. doi: 10.1016/j.langsci.2020.101277

Lippi-Green, R. (2012). *English with an accent: Language, Ideology, and Discrimination in the United States*. New York, NY: Routledge

Lovrits, V., and de Bres, J. (2021). Prestigious language, pigeonholed speakers: stances towards the 'native English speaker' in a multilingual European institution. *J. Socioling.* 25, 398–417. doi: 10.1111/josl.12431

Mace, W. M. (1977). *James J. Gibson's Strategy for Perceiving: Ask Not What's Inside Your Head, But What's Your Head Inside of. Perceiving, Acting, and Knowing: Towards an Ecological Psychology*. Hillsdale, NJ: Lawrence Earlbaum Associates.

Maglio, P. P., and Kirsh, D. (1996). Epistemic action increases with skill. in Proceedings of the Eighteenth Annual Conference of the Cognitive Science Society (Vol. 16, pp. 391–396). Hillsdale, NJ: Erlbaum.

Makoni, S., and Pennycook, A. (2007). *Disinventing and Reconstituting Languages*. (pp. 1–41). Buffalo, NY: Multilingual Matters.

Merleau-Ponty, M. (1945). *Phenomenology of Perception*. New York, NY: Routledge.

Milroy, J., and Milroy, L. (1985/2012). *Authority in Language: Investigating Standard English*. New York, NY: Routledge

Mordaunt, O. G. (2011). Bidialectalism in the classroom: the case of African-American English. *Lang. Cult. Curric.* 24, 77–87. doi: 10.1080/07908318.2010.546401

Neisser, U. (1967/2014). *Cognitive Psychology*: *Classic Edn*. London: Psychology Press.

Newell, A., Shaw, J. C., and Simon, H. A. (1958). Elements of a theory of human problem solving. *Psychol. Rev.* 65, 151–166. doi: 10.1037/h0048495

Newell, A., Shaw, J. C., and Simon, H. A. (1958/1962). "The processes of creative thinking" in *Contemporary Approaches to Creative Thinking: A Symposium Held at the University of Colorado*. eds. H. E. Gruber, G. Terrell and M. Wertheimer (New York, NY: Atherton Press), 63–119.

Noë, A. (2009). Out of our heads: Why you are not your brain, and other lessons from the biology of consciousness. Macmillan.

Nomikou, I., Leonardi, G., Rohlfing, K. J., and Rączaszek-Leonardi, J. (2016). Constructing interaction: the development of gaze dynamics. *Infant Child Dev.* 25, 277–295. doi: 10.1002/icd.1975

Orsi, L., and Orsi, P. (2002). "An ESP program for brewers." in *English for Specific Purposes.* (ed.) T. Orr (Alexandria, VA: TESOL), 175–188.

Oschwald, J., Schättin, A., Von Bastian, C. C., and Souza, A. S. (2018). Bidialectalism and bilingualism: exploring the role of language similarity as a link between linguistic ability and executive control. *Front. Psychol.* 9. doi: 10.3389/fpsyg.2018.01997

Otto, P. (2021). Choosing specialized vocabulary to teach with data-driven learning: an example from civil engineering. *Engl. Specif. Purp.* 61, 32–46. doi: 10.1016/j.esp.2020.08.003

Pelham, S. D., and Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *J. Exp. Psychol. Learn. Mem. Cogn.* 40, 313–325. doi: 10.1037/a0035224

Pennycook, A. (2010). Language as a local practice. Routledge.

Pennycook, A. (2019). "From translanguaging to translingual activism," in *Decolonizing Foreign Language Education*. ed. D. Macedo (New York, NY: Routledge), 169–185.

Pennycook, A., and Makoni, S. (2020). *Innovations and Challenges in Applied Linguistics from the Global South*. New York, NY: Routledge.

Piller, I. (2001). Naturalization language testing and its basis in ideologies of national identity and citizenship. *Int. J. Biling.* 5, 259–277. doi: 10.1177/13670069010050030201

Piller, I. (2012). Multilingualism and social exclusion. The Routledge handbook of multilingualism. (New York: Routledge), 281–296.

Piller, I. (2015). Language ideologies. The international encyclopedia of language and social interaction. (John Wiley & Sons), 1–10.

Pinker, S. (2005). So how does the mind work? *Mind Lang.* 20, 1–24. doi: 10.1111/j.0268-1064.2005.00274.x

Politzer, R. L. (1981). Social class and bilingual education: issues and contradictions. Evaluation, Dissemination and Assessment Center, California State University, Los Angeles.

Potts, M. H. (1965). *The Effect of French Instruction on the Reading Proficiency and General School Achievement of Primary-Grade Children*. Doctoral dissertation, State College, PA: The Pennsylvania State University.

Rączaszek-Leonardi, J., Nomikou, I., and Rohlfing, K. J. (2013). Young children's dialogical actions: the beginnings of purposeful intersubjectivity. *IEEE Trans. Auton. Ment. Dev.* 5, 210–221. doi: 10.1109/TAMD.2013.2273258

Rączaszek-Leonardi, J., Nomikou, I., Rohlfing, K. J., and Deacon, T. W. (2018). Language development from an ecological perspective: ecologically valid ways to abstract symbols. *Ecol. Psychol.* 30, 39–73. doi: 10.1080/10407413.2017.1410387

Reed, E. S. (1991a). "James Gibson's ecological approach to cognition" in *Against Cognitivism: Alternative Foundations for Cognitive Psychology*. eds. A. Still and A. Costall (New York, NY: Harvester Wheatsheaf).

Reed, E. S. (1991b). Cognition as the cooperative appropriation of affordances. *Ecol. Psychol.* 3, 135–158. doi: 10.1207/s15326969eco0302_5

Reed, E. S. (1996). *Encountering the World: Toward an Ecological Psychology*. Oxford: Oxford University Press.

Reed, E. S. (1997). "The cognitive revolution from an ecological point of view" in *The Future of the Cognitive Revolution*. ed. M. D. Johnson (New York, NY: Oxford University Press), 261–273.

Rey-Mermet, A., Gade, M., and Oberauer, K. (2018). Should we stop thinking about inhibition? Searching for individual and age differences in inhibition ability. *J. Exp. Psychol. Learn. Mem. Cogn.* 44, 501–526. doi: 10.1037/xlm0000450

Richardson, D. C., and Dale, R. (2005). Looking to understand: the coupling between speakers' and listeners' eye movements and its relationship to discourse comprehension. *Cogn. Sci.* 29, 1045–1060. doi: 10.1207/s15516709cog0000_29

Richardson, M. J., Shockley, K., Fajen, B. R., Riley, M. A., and Turvey, M. T. (2008). *Ecological Psychology: Six Principles for an Embodied–Embedded Approach to Behavior. In Handbook of Cognitive Science* (pp. 159–187). San Diego, CA: Elsevier

Robbins, P., and Aydede, M. (2009). "A short primer on situated cognition" in *The Cambridge Handbook of Situated Cognition*. eds. P. Robbins and M. Aydede (Cambridge: Cambridge University Press), 1–10.

Rohlfing, K. J., Leonardi, G., Nomikou, I., Rączaszek-Leonardi, J., and Hüllermeier, E. (2019). Multimodal turn-taking: motivations, methodological challenges, and novel approaches. *IEEE Trans. Cogn. Dev. Syst.* 12, 260–271. doi: 10.1109/TCDS.2019.2892991

Rosa, J., and Flores, N. (2017). Unsettling race and language: toward a raciolinguistic perspective. *Lang. Soc.* 46, 621–647. doi: 10.1017/S0047404517000562

Ross, J., and Melinger, A. (2017). Bilingual advantage, bidialectal advantage or neither? Comparing performance across three tests of executive function in middle childhood. *Dev. Sci.* 20:e12405. doi: 10.1111/desc.12405

Rowe, C., and Grohmann, K. K. (2013). Discrete bilectalism: towards co-overt prestige and diglossic shift in Cyprus. *Int. J. Sociol. Lang.* 2013, 119–142. doi: 10.1515/ijsl-2013-0058

Rumelhart, D., and McClelland, J.the PDP Research Group (1986). *Parallel Distributed Processing, Volumes 1 and 2*. Cambridge, MA: MIT Press

Sadat, J., Martin, C. D., Alario, F. X., and Costa, A. (2012). Characterizing the bilingual disadvantage in noun phrase production. *J. Psycholinguist. Res.* 41, 159–179. doi: 10.1007/s10936-011-9183-1

Schneider, B. (2019). Methodological nationalism in linguistics. *Lang. Sci.* 76:101169. doi: 10.1016/j.langsci.2018.05.006

Shardakova, M. (2022). "Testing sociolinguistic competence" in *The Routledge Handbook of Second Language Acquisition and Sociolinguistics*. ed. K. Geeslin (New York, NY: Routledge), 84–96.

Siegel, J. (2010). *Second Dialect Acquisition*. Cambridge: Cambridge University Press

Silverstein, M. (1998/2018). "Monoglot "standard" in America: standardization and metaphors of linguistic hegemony," in *The Matrix of Language*. eds. D. Brenneis and R. K. S. Macaulay (New York, NY: Routledge), 284–306.

Simon, H. A., and Newell, A. (1962). Computer simulation of human thinking and problem solving. *Monogr. Soc. Res. Child Dev.* 27, 137–150. doi: 10.2307/1165535

Solomon, M. (2007). "Situated cognition," in *Philosophy of Psychology and Cognitive Science* (Amsterdam: North-Holland), 413–428.

Steffensen, S. V. (2017). "Human interactivity: problem-finding, problem-solving, and verbal patterns in the wild," in *Cognition Beyond the Brain*. eds. S. Cowley and F. Vallée-Tourangeau (Cham: Springer).

Steffensen, S. V., and Harvey, M. I. (2018). Ecological meaning, linguistic meaning, and interactivity. *Cogn. Semiot.* 11, 1–21. doi: 10.1515/cogsem-2018-0005

Suchman, L. A. (1987). *Plans and Situated Actions: The Problem of Human-Machine Communication*. Cambridge: Cambridge University Press.

Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., and Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage* 205:116306. doi: 10.1016/j.neuroimage.2019.116306

Surrain, S., and Luk, G. (2019). Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005 and 2015. *Biling. Lang. Congn.* 22, 401–415. doi: 10.1017/S1366728917000682

Szmrecsanyi, B. (2019). Register in variationist linguistics. *Reg. Stud.* 1, 76–99. doi: 10.1075/rs.18006.szm

Thagard, P. (2005). *Mind: Introduction to Cognitive Science*. Cambridge, MA: MIT Press.

Thagard, P. (2019). *Brain-Mind: From Neurons to Consciousness and Creativity (Treatise on Mind and Society)*. Oxford: Oxford University Press.

Tiv, M., Kutlu, E., Gullifer, J. W., Feng, R. Y., Doucerain, M. M., and Titone, D. A. (2022). Bridging interpersonal and ecological dynamics of cognition through a systems framework of bilingualism. *J. Exp. Psychol. Gen.* doi: 10.1037/xge0001174

Tiv, M., O'Regan, E., and Titone, D. (2021). In a bilingual state of mind: investigating the continuous relationship between bilingual language experience and mentalizing. *Biling. Lang. Congn.* 24, 918–931. doi: 10.1017/S1366728921000225

Trentman, E., and Shiri, S. (2020). The mutual intelligibility of Arabic dialects. *Crit. Multiling. Stud.* 8, 104–134. Available at: https://cms.arizona.edu/index.php/multilingual/article/view/207

Turvey, M. T. (2018). *Lectures on Perception: An Ecological Perspective*. New York, NY: Routledge.

Van Orden, G., Hollis, G., and Wallot, S. (2012). The blue-collar brain. *Front. Physiol.* 3:207. doi: 10.3389/fphys.2012.00207

Varvaro, A. (2013). Latin and the making of the romance languages. *Camb. Hist. Roman. Lang.* 2, 6–56. doi: 10.1017/CHO9781139019996.002

Vasquez, B. P., Binns, M. A., and Anderson, N. D. (2018). Response time consistency is an indicator of executive control rather than global cognitive ability. *J. Int. Neuropsychol. Soc.* 24, 456–465. doi: 10.1017/S1355617717001266

Wagner, D., Bialystok, E., and Grundy, J. G. (2022). What is a language? Who is bilingual? Perceptions underlying self-assessment in studies of bilingualism. *Front. Psychol.* 13:863991. doi: 10.3389/fpsyg.2022.863991

Warren, W. H. (2006). The dynamics of perception and action. *Psychol. Rev.* 113, 358–389. doi: 10.1037/0033-295X.113.2.358

Warren, W. H. (2021). Information is where you find it: perception as an ecologically well-posed problem. *i-Perception* 12, 1–24. doi: 10.1177/20416695211000366

Warren, W. H. Jr. (1998). Visually controlled locomotion: 40 years later. *Ecol. Psychol.* 10, 177–219. doi: 10.1207/s15326969eco103&4_3

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., and Sahuc, S. (2001). Optic flow is used to control human walking. *Nat. Neurosci.* 4, 213–216. doi: 10.1038/84054

Weng, J. (2018). What is mandarin? The social project of language standardization in early republican China. *J. Asian Stud.* 77, 611–633. doi: 10.1017/S0021911818000487

West, R. (2001). The transient nature of executive control processes in younger and older adults. *Eur. J. Cogn. Psychol.* 13, 91–105. doi: 10.1080/09541440042000232

Woolard, K. A. (2020). "Language ideology," in *The International Encyclopedia of Linguistic Anthropology* (John Wiley & Sons), 1–21.

Wu, Y. J., Zhang, H., and Guo, T. (2016). *PLoS One* 11:e0150492, Does speaking two dialects in daily life affect executive functions? An event-related potential study. doi: 10.1371/journal.pone.0150492