

INDIVIDUAL DIFFERENCES IN THE BILINGUAL EXPERIENCE AND VARIATION IN
THE NEURAL CORRELATES OF EXECUTIVE FUNCTION: A SYSTEMATIC REVIEW

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Abstract

Research suggests that the experience of bilingualism might contribute to variation in executive function (EF) skills, however patterns of results reported in the literature are mixed. Many studies measure behavioural correlates of executive function, with less exploration of underlying neural mechanisms. Most studies also report “bilinguals” as a homogenous group, despite considerable variation in the experience of bilingualism across individuals. To address these limitations, a systematic review was conducted that explicitly explores and summarizes reported associations between individual differences in the bilingual experience and neural correlates of EF. Individual differences noted were found to predict neural correlates of executive function in a number of studies; however associations were not observed across all reviewed studies, relaying other variables that could be in play. Limitations, implications, and suggestions for future research are discussed.

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Introduction

Executive function (EF) is a term used to describe a combined set of higher cognitive skills pertinent to overall human development and functioning. This set of skills can include self-regulation of emotions, inhibition of behavioural and psychological output, attention/task switching, and successful use of working memory (Miyake et al., 2000). The neural processes of these cognitive skills are typically accomplished via frontal brain regions, particularly the pre-frontal cortex and associated networks (Miller & Cohen, 2001; Wiebe & Karbach, 2017).

EF skills facilitate humans' ability to perform a wide range of functions. From day-to-day functioning to future planning to occupational success, EF is a critical component for individuals to succeed across a variety of domains (e.g., O'Donnell et al., 2017; Taukari, 2002). Because of the importance of EF in daily functioning, research dedicated to understanding that which can affect or is affected by EF has burgeoned over the last few decades. Of the numerous domains that have empirically tested questions relating to EF, this thesis deals with a phenomenon discovered in the field of psycholinguistics. Namely, that exposure to and use of two (or more) languages (bilingualism) may influence domain general processes, such as executive functioning.

Bilingualism

The experience of bilingualism is prevalent worldwide, with reports estimating that two thirds of children are raised hearing and using more than one language (Bialystok et al., 2009; Crystal, 1997). The literature defines a person as bilingual in many ways, commonly conceptualized by the percentage of time (e.g., 30 %) that they hear or use a second language.

In the current study, bilingualism can be defined as the ability to read, write, or speak in two languages and the level of fluency with each language can vary. With its rising occurrence, a

body of psycholinguistic research has provided some evidence that the experience of bilingualism may confer an advantage in EF abilities. More specifically, several studies have demonstrated that individuals who speak more than one language perform better than their monolingual counterparts on behavioural tasks requiring alerting, orienting, and set shifting (Costa et al., 2008; Bialystok et al., 2004). This phenomenon has been termed the bilingual advantage (Bialystok & Martin, 2004). Multiple explanations have been provided to explain why these patterns might emerge, and explanations have evolved over time. Evidence suggests that use of two or more languages is facilitated by neural activation of both languages simultaneously (Martin et al., 2009; Kroll et al., 2006; Rodriguez-Fornells et al., 2002; Thierry & Wu, 2007). Early accounts therefore suggested that the requirement of bilingual speakers to regularly shift, inhibit, and monitor language use (e.g., to match the language context) results in a domain general enhancement of EF abilities (Bialystok & Martin, 2004; Carlson & Meltzoff, 2008). More specifically, this hypothesis suggests that daily practice of these EF skills during language use might transfer from the linguistic domain, leading to improvements in non-verbal EF abilities (Garbin et al., 2010). The experience of bilingualism might therefore confer benefit to EF via modulation to neural systems underlying EF. In contrast, but building from these earlier studies, more recent accounts suggest that the bilingual experience might not result in the transfer of these specific EF skills, per se. Instead, exposure to a bilingual language context might contribute to variation in attention patterns, even from infancy, which are required to facilitate separation of multiple languages (e.g., Arredondo et al., 2022). Such variation might lead developing systems to adapt to the language context in ways that facilitate development of broader EF skills such as attentional control, or effortful attention (Bialystok & Craik, 2022; Bialystok, 2017), as opposed to individual components of EF.

While behavioural and neural evidence supports the notion that there are differences in EF abilities between monolingual and bilingual speakers, some recent reviews have tempered the claim that a bilingual advantage exists (see Antoniou, 2019; Antoniou, 2023; Gunnerud et al., 2020; Lehtonen et al., 2018). Recent research has also described contexts in which an advantage is more likely to be observed (e.g., in studies of children and older adults compared to university students/young adults). The following sections review evidence for and against the bilingual advantage and propose how neuroscientific investigations can shed light on our understanding of EF abilities in bilingual and monolingual speakers.

Behavioural Evidence for a Bilingual Advantage

Many studies have reported behavioural effects in bilinguals that were indicative of and interpreted as a bilingual advantage in EF when compared against monolingual speakers (Antoniou, 2019). A recent review (Antoniou, 2019) describes the state of the evidence for and against the bilingual advantage and reports that given the complexity of the area under study, boiling down bilingualism into a single, fixed construct will most likely not contribute to a coherent explanation nor a unified understanding of the bilingual advantage, if it is present. Moreover, given that most of the discrepancy in results lies predominantly in the behavioural domain, inclusion of neuroscientific methodologies is pertinent. Antoniou reports that the bilingual advantage is most likely to be observed in studies testing older adults and children, as opposed to young adults/university students, where evidence for a bilingual advantage has been the weakest. Prevalent methodologies to test for a bilingual advantage had participants conduct a series of experimental tasks designed to challenge one or two aspects of EF (inhibition, monitoring, and/or task-switching). Tasks typically used, and those which have been most likely to show behavioural effects, include: 1) The Simon Task, Erikson Flanker Task, and Stroop Task

to test for inhibition and monitoring and 2) Dimensional Change Card Sort, Color-shape Switching Task, and the Task Switch Paradigm to test for set-shifting. Results in support of a bilingual advantage typically find that bilingual participants display faster reaction times and better accuracy on EF tasks compared to monolinguals (e.g., Bialystok et al., 2004; Costa et al., 2008; 2009).

As an example, Costa and colleagues (2008) conducted a study with bilingual and monolingual participants, aged between 19 to 32, who completed an altered 12-condition mixed trial Flanker task. To test for possible differences in EF between these groups, the 12 experimental conditions were presented in random order for each participant. Participants were required to answer as quickly and accurately as possible. Results revealed that bilingual participants have significantly faster reaction times and greater response accuracy in both congruent and incongruent trials in comparison to monolinguals. In a different study by this research group, Costa and colleagues (2009) hypothesized that bilinguals and monolinguals would not differ in reaction time for trials where conflict monitoring is low, such as consecutive similar trials. However, when participants are presented with trials erratic in order, the demand for conflict monitoring will increase with trial difficulty. Costa and colleagues further hypothesized that bilinguals would significantly outperform monolinguals in non-consecutive trials due to bilinguals having a more efficient monitoring system that is the result of the cognitive training that stems from hearing and using two languages. Testing a sample of university students/young adults, results robustly demonstrated that bilinguals had overall faster reaction times in both non-consecutive and consecutive trial types. Another behavioural study by Bialystok and colleagues (2004) had monolingual and bilingual participants (consisting of both middle-aged and older adults) complete the Simon task in three different studies. Bilingual

participants within all three studies outperformed monolingual participants, showing faster reaction times and greater accuracy as a smaller Simon effect was reported.

Behavioural Evidence Against a Bilingual Advantage

As significant evidence for a bilingual advantage became mainstream, many researchers sought to replicate these results. Null results in comparison of behavioural performance between bilingual and monolingual speakers, and different outcomes on tasks designed to assess the same behaviour (e.g., Stroop, Erikson Flanker, and Simon tasks) have led many to conclude that there is minimal support for a bilingual advantage in EF abilities (e.g., Paap & Greenberg, 2013).

For example, Paap and Greenberg (2013) conducted a behavioural study with 3 large groups of first year undergraduate students in which participants completed an array of tasks including modified versions of the Stroop, Simon, and Flanker tasks. Behavioural performance was measured through reaction times. Responses were calculated as mean reaction time per condition in each task. The results of the Simon tasks within the 3 studies revealed no significant differences in reaction time between monolingual and bilingual participants. The authors concluded that there was no evidence that bilingualism was positively associated with EF. In fact, a statistically significant “bilingual disadvantage” was observed in the third study, although this observation had a small effect size. From this series of studies, Paap and Greenberg concluded that no evidence was present to support enhanced inhibition or monitoring by bilinguals compared to monolingual speakers. Paap and Greenberg’s Flanker task was comparable to that used by Costa and colleagues, described previously (2008). The Flanker task was only tested on participants in the third study. To combat the missing comparison data from Studies 1 and 2, Paap and Greenberg explored Flanker task results from participants who were categorized as either high fluency bilinguals or extreme monolinguals. Authors reported that

their results were replicated even when using Costa and colleagues' (2008) design, as even these extremely different groups of participants did not differ in reaction times. Thus, even when classified as highly fluent, bilinguals were not observed to have enhanced inhibition, monitoring, and shifting skills. Similarly, Dick and colleagues (2019) conducted a large behavioural study in which 4524 middle school aged participants completed three EF tasks: a variation of the Flanker task, the Dimensional Change Card Sort task, and a Stop-signal task. This study found no statistically significant differences between monolingual and bilingual groups on any tasks administered. A study by Kousaie and Philips (2012) used a modified application of the Stroop task on young and older monolinguals and bilinguals, while controlling for confounding demographics including language type and immigrant status. Again, no differences in reaction time were observed between monolingual and bilingual groups. The authors concluded, similar to Costa and colleagues (2009), that monolingual and bilingual participants had similar conflict monitoring abilities. Many other studies have also reported no behavioural advantages for bilingual compared to monolingual speakers (e.g., see Antoniou, 2019 for a review).

As shown, inconsistencies have been observed in behavioural studies of EF abilities for monolingual compared to bilingual speakers. Discrepancies may be due to factors such as different task demands, different age groups (e.g., child, young adult, middle-aged adult, older adult), different language background and proficiency (Antoniou, 2019; Lehtonen et al., 2018), or other factors.

Inclusion of Neuroimaging Techniques

Evidence for a bilingual advantage in behavioural studies is clearly mixed. Another body of work has sought to test differences in neural structure and function between monolingual and bilingual speakers, to understand whether and how the brain adapts to the bilingual experience,

and whether this could explain differences in EF between groups seen in behavioural studies. Though EF abilities are demonstrated through behavioural performance, they are undeniably driven by neural mechanisms. As such, bilingualism research has extended beyond a sole reliance on behavioural methodologies to include neuroimaging as well. There are merits to using neurophysiological paradigms. For example, neurophysiological tools may provide more sensitive measures to detect fine-grained differences between groups. It is also possible that neural changes might be observed prior to any behavioural change in performance. Moreover, even in cases where behavioural performance between groups is similar, neurophysiological tools can provide an indication of whether different neural processes are used to facilitate comparable behavioural outcomes. For example, neuroimaging studies have observed denser gray matter volume (GMV) and white matter volume (WMV) for bilingual compared to monolingual speakers in regions that support EF. Using structural magnetic resonance imaging (MRI), Olulade et al. (2016) found denser GMV in the right and left dorsolateral prefrontal cortex, right parietal cortex, and left ventrolateral prefrontal cortex of adult bilingual participants compared to their monolingual counterparts; neural structures that have been implicated in EF abilities (e.g., Bunge et al., 2002; Derrfuss et al., 2004; Luk et al., 2012). Note that participants did not complete any EF tasks as a part of this study. Considering effects of lifelong bilingualism on EF in a sample of older adults, Olsen et al. (2015) had elderly bilingual and monolingual participants complete a battery of neurophysiological tasks, including tasks designed to test EF (e.g., Stroop), and return for MRI scanning 2 weeks after behavioural testing. Significantly greater WMV was observed for bilinguals compared to monolinguals in frontal and temporal regions. Furthermore, Stroop performance was positively correlated with WMV in frontal regions, but only within the bilingual group.

Neural processes underlying EF abilities have also been measured using event-related-potentials (ERPs). Differing latencies and amplitudes of ERP components associated with EF processes have been observed between bilinguals and monolinguals. For example, Fernandez and colleagues (2013) had bilingual and monolingual adults complete a Go/No-Go task, designed to measure inhibition, while recording EEG. Analyses of behavioural performance revealed no significant differences in accuracy or reaction times between bilingual and monolingual groups. However, although behavioural performance was similar between groups, neural activity differed. Namely, significantly larger N200 amplitudes, smaller P300 amplitudes, and faster P300 latencies, were observed for bilingual compared to monolingual participants. This pattern was interpreted to reflect a more efficient and stronger inhibitory response and attention allocation for bilingual participants, even when their behavioural performance was similar to that of monolinguals. Other studies such as Kousaie and Philips (2017) and Morales et al. (2015) have observed similar patterns. In these studies, which included adults/older adults, behavioural performance between bilingual and monolingual participants was, again, not significantly different. However, bilinguals consistently exhibited earlier peaks of N200 amplitudes, larger N2 amplitudes, larger P300 amplitudes and faster P300 latencies than monolinguals during tasks that measured conflict monitoring, allocation of resources, and response inhibition. A recent systematic review demonstrated weak evidence for a bilingual effect in which bilinguals presented with larger N2 and P3 amplitudes and shorter N2 and P3 latencies (Antoniou, 2023). Furthermore, the author indicated that with increasing bilingual experience, bilinguals presented with larger and faster N2 and P3 amplitudes and latencies.

Individual Differences in the Bilingual Experience

As reviewed in the prior section, evidence suggests that experiences associated with bilingualism contribute to variation in neural structure and function. It has been hypothesized that variation in the bilingual environment drives these changes in an experience-dependent manner (Antoniou, 2019) That is, experiences unique to a given individual shape neural circuitry in a manner that allows them to adapt to the demands of their specific context or environment. However, “bilingualism” is not a categorical experience. Bilinguals can differ in many ways, including the age at which they acquire their second language, their duration of exposure or relative use of each language, proficiency in each language, specific language pairs, clinical diagnoses that might affect EF, and more. Despite the considerable variability in the bilingual experience, a relatively small amount of research has explored the role of these kinds of individual differences in our understanding of the neural correlates of executive function in bilinguals. Understanding the role that individual differences play is important because it can a) help to provide an explanation for the mixed results observed in the body of research to date, and b) aid in revealing mechanistic pathways by which different facets of the bilingual experience might shape domain general processes such as EF. Therefore, the goal of this systematic review is to summarize the literature to systematically ask a) which individual differences related to the bilingual experience have been most frequently explored in research addressing the neural correlates of EF, and b) whether common individual differences are associated with variation in neural processes underlying EF. In addressing these aims, the review will discuss whether an understanding of individual differences helps to explain variation seen in the EF system between bilingual and monolingual individuals.

Methods

Design

This systematic review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. A systematic review aligned with the authors' aims in exploring the current literature to systematically ask if individual differences in the bilingual experience account for variation in neural structure and function underlying EF. This review was not preregistered.

Searched databases and search strategy

Identical searches were run on PubMed and PSYCINFO, and the search results were exported into Covidence, a web-based collaboration software that streamlines the production of systematic and other literature reviews (Veritas Health Innovation). Each abstract and full-text review had two reviewers take part in the screening process, and a narrative synthesis approach was adapted to facilitate summarization of the extracted studies. The search was run on both databases on May 31, 2024.

Eligibility criteria

Based on the search strategy, articles including terms related to bilingualism, executive function, and neural structure and function were included. Specifically, the search across the two databases was as follows: (bilingual*) AND (executive function*) AND (neur*). The search run on PubMed did not include filters, while the search run on PSYCINFO filtered for articles in English, peer-reviewed articles, and excluded dissertations/theses and books. Studies were considered eligible and were included if they met the following criteria: i) included at least one group of bilingual participants, ii) measured and reported an individual difference in the bilingual experience (e.g., age of acquisition), and either iii) tested associations between at least one individual difference associated with bilingualism and a neural correlate of executive function, or

iv) compared two groups that differed on one or more individual difference, or v) did not directly compare groups or test associations but considered and described an individual difference in the bilingual experience in the context of the broader literature on the bilingual advantage (e.g., tested *only* a group of high proficiency bilinguals, which were not directly compared to a group of low proficiency bilinguals, however patterns of results were interpreted in the context of the broader literature on variation in proficiency. Or, considered age of participants as a relevant difference in the bilingual experience, beyond simply reporting age as a demographic variable). Articles were excluded if they i) only tested monolinguals, ii) tested only behavioural outcomes, or iii) were meta-analyses or reviews. Neural correlates of EF were either explicitly described as such, or an outcome measure was a brain area that has been reported in the literature to be implicated in EF (i.e., frontoparietal regions).

Screening procedure

After the search results were imported into Covidence, the software automatically excluded duplicates. Each abstract and full-text article was independently screened by two reviewers, with the lead author (YO) resolving any conflicts. Those that appeared eligible for the study based on the title and abstract screening then received a full-text review. At this stage, articles were excluded based on the above-specified exclusion criteria. Conflicts at every stage were resolved by YO, and eligible studies continued to proceed to the final stage of extraction (i.e., Figure 1).

Data collection and management

Data for the systematic review, including study and participant characteristics, were extracted independently by trained research staff, with a final review conducted independently by YO. All conflicts were resolved by YO. Study characteristics included the individual difference(s)

explored, language pair, evaluation of language abilities, executive function measure(s), the neural tool(s) used, and the key findings. Participant characteristics included the country of the study, which groups were included in each study, sample size, age mean and standard deviation, and sex via percentage of female participants (i.e., Table 1)

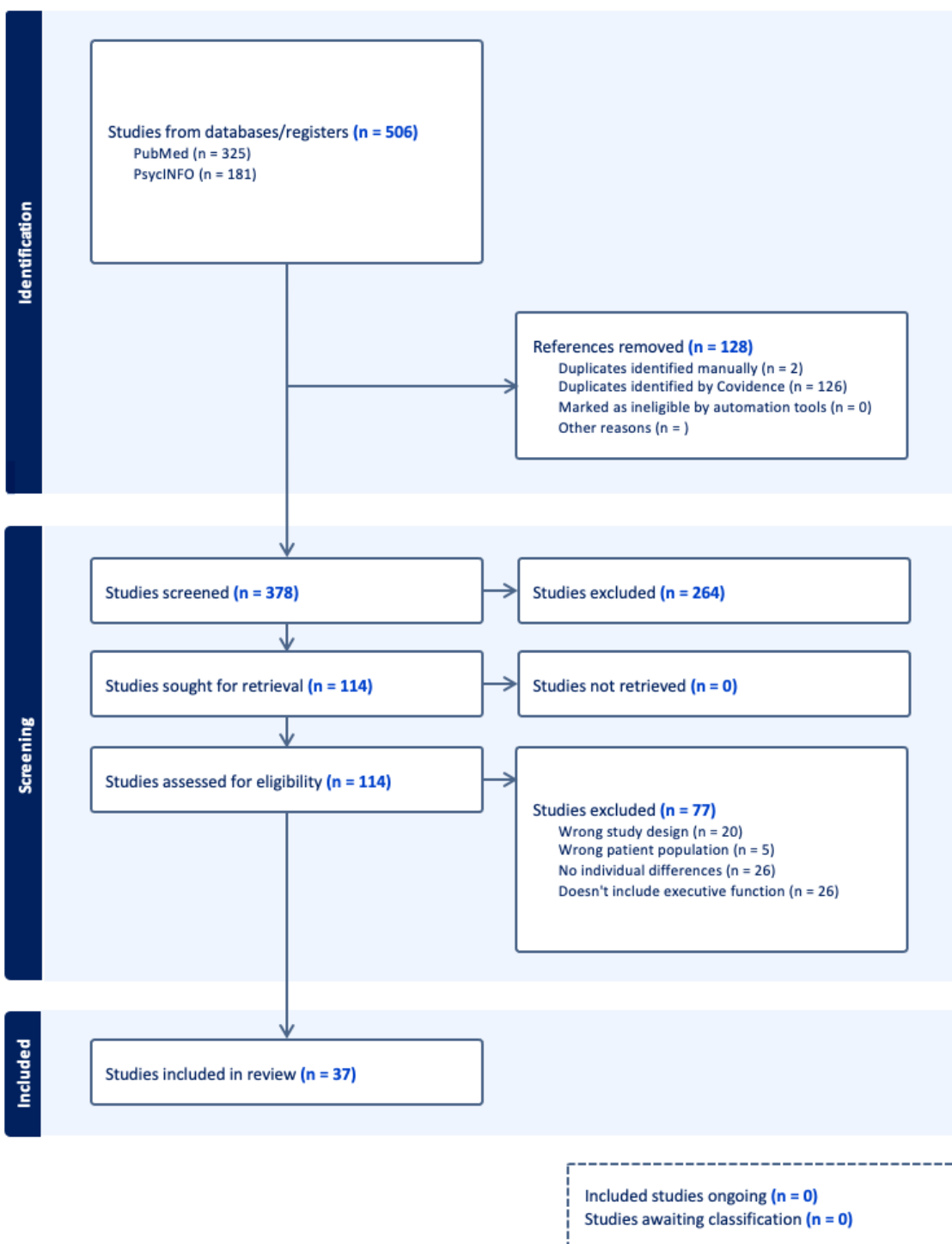
Results

The results of the searches run on PubMed and PsycINFO generated a total of 506 results, where 128 duplicates were automatically identified and removed on Covidence. Out of the remaining 378 studies eligible for title and abstract screening, 114 met the eligibility criteria and proceeded to the full-text screening stage, where a final of 37 articles were identified and extracted based on the eligibility criteria for study inclusion. A flow chart generated through Covidence is shown in Figure 1 to highlight this process as per PRISMA guidelines.

Figure 1

Flowchart of Study Inclusion and Exclusion Decisions (PRISMA flowchart)

Pierce Lab - bilingualism, EF systematic review



Characteristics of included studies

Out of the 37 articles that met inclusion criteria, all individual differences identified in the review included age as a relevant individual difference (11 articles), L2 age of acquisition (17 articles), L2 usage (6 articles), L2 exposure (1 article), L2 proficiency (9 articles), language switching (1 article), and language diversity (2 articles). The most common languages spoken (when reported) were English, French, Spanish, Cantonese, Mandarin, and Russian. Neuroimaging tools most often included a variation of MRI (including fMRI, rs-fMRI, rs-MRI, and others), EEG, fNIRS or a combination of other neural tools. A detailed breakdown of individual differences, language pairs, evaluation of language abilities, executive function measures, neural tool(s), and key results reported in each study can be found in Table 1.

Participant characteristics

Out of the 37 articles, 12 were completed in Canada, 4 in China, 1 in France, 1 with participants from Hong Kong, 3 in Italy, 1 in New Zealand, 1 in Russia, 1 in Singapore, 4 in Spain, 2 in the United Kingdom, 7 in the United States, and 1 in Germany. Therefore, reported results span many countries and language pairs. The sample size ranged from 7 participants in a given group, to 93 participants, with a mean of approximately 26, and a median of approximately 20 participants. The percentage of females within each group in a study ranged from 16% to 100% female when reported, with the mean being approximately 58% and a median of 59%.

Participant mean age ranged from approximately 50 months (or roughly 4 years of age) to approximately 74 years of age. A detailed breakdown of each of these participant characteristics can be found in Table 2.

Table 1*Main Characteristics of Studies Included in the Review*

Authors	Individual difference	Language pair	Tasks	Results		
			Evaluation of language abilities	Executive function measure	Neural tool	
Abutalebi et al. (2011)	AoA, L2 proficiency, language switching, SES	German-Italian	Translation tasks for proficiency	Naming paradigm, Snodgrass battery, Flanker task, language switching, conflict monitoring	er-fMRI	Bilinguals resolved cognitive difficulties with fewer neural resources and adapted better to conflicting situations
Anderson et al. (2021)	AoA, L2 proficiency	Mixed	LSBQ	MMSE, N-Back task, WM tasks, item-associative task, item/associative memory: task PLS	fMRI	Gray matter volume and white matter integrity (fractional anisotropy) lower in bilinguals, bilinguals had better white matter integrity in select regions. Negative association of age and brain structure in bilinguals with increased performance associated with better brains structure

Ansaldo et al. (2015)	Age	French-English	LEAP-Q	Simon task	fMRI	No differences in behavioural results between elderly bilinguals vs elderly monolinguals. Neural results indicate that monolinguals had significant activity in the prefrontal cortex, while bilinguals had significant activation of the left inferior parietal lobule.
Arredondo et al. (2022)	Age	Spanish-English	Parent-report questionnaire , KBIT-2 verbal knowledge subtest, CELF-4 word structure subtest, Woodcock reading mastery tests revised 2nd edition word identification subtest, CTOPP elision subtest, Rapid automatized naming numbers subtest, Receptive one-word picture vocabulary	Neuroimaging attentional network task	fNIRS	No behavioural differences between bilinguals and monolinguals. Bilinguals presented with greater brain activity in the left frontal and parietal regions

			test Spanish bilingual edition			
Ballarini et al. (2023)	AoA, L2 usage	German-Mixed	German version of Lifetime of Experiences Questionnaire	Extensive battery of cognitive tests including learning and memory, working memory, EF, visuo-spatial abilities, and language	MRI	Overall lifelong bilingualism vs lifelong monolingualism did not show any significant differences in gray matter volume. There was a trend for early bilinguals to have greater gray matter volume right basal ganglia.
Cai et al. (2021)	AoA	Mandarin-Cantonese	Self-reported proficiency scale, LBSQ, College English Test	Stroop color and word task, Go/no-go task, Color-shape switch paradigm, Wechsler-IV Adult intelligence Scale-Revised Chinese version	rs-fMRI	Bilinguals exhibited stronger functional connectivity in the Cingulo-opercular area than monolinguals. No differences seen in the Fronto-parietal region.

Costumero et al. (2015)	AoA	Catalan-Spanish	Preliminary interview of languages, self-reported linguistic competence questionnaire for proficiency	Go/no-go task modified version	fMRI	Use of salience and left fronto-parietal networks more common in bilinguals for go infrequent and no-go cues. Modulation had opposite correlations for performance in bilinguals than monolinguals
Dash et al. (2019)	Participant age; L2 usage; L2 proficiency	French-English	LEAP-Q, percent of L2 speaking and reading usage, reported L2 speaking and reading proficiency, Boston Naming Test, Western Aphasia Battery and Boston Diagnostic Aphasia Examination, YAA-R, LexTale test.	MoCA, TMT A and B, OBT, and digit span task (through MoCA)	fMRI	No significant brain-behaviour associations for executive function nor significant activation for executive control brain regions. Individual differences such as L2 proficiency especially among older adults was associated with decreased BOLD activity for alerting. Identified bilingual advantage especially for alerting ability within attention

Dash et al. (2022)	AoA, L2 exposure, L2 proficiency	French-English	LEAP-Q, Boston Naming Test, Western Aphasia Battery and Boston Diagnostic Aphasia Examination, YAA-R.	TMT A and B, Attention Network Task, OBT	fMRI	Executive functioning did not significantly predict neural processing; L2 age of acquisition and task proficiency were significantly related to rsFC within attention networks, including stronger rsFC in Alerting and Orienting Networks and between certain regions such as right superior temporal gyrus and occipital regions for those with higher L2 proficiency
Del Maschio et al. (2018)	AoA	Cantonese English; Cantonese-Mandarin	L1 and L2 proficiency measured through picture-naming task through the Snodgrass and Vanderwart picture set, and oral translation task switching from L1 to L2	Flanker Task, MMSE	MRI	Identified that lifelong bilingualism is correlated positively with neural and cognitive reserve for healthy aging

AoA	Cantonese-English	L1 and L2 proficiency measured through picture-naming task through the Snodgrass and Vanderwart picture set, and oral translation task switching from L1 to L2	Flanker Task	MRI	Identified that lifelong bilingualism is correlated positively with neural and cognitive reserve for healthy aging
AoA	n.r.	n.r	Flanker Task, MMSE	MRI	Identified that lifelong bilingualism is correlated positively with neural and cognitive reserve for healthy aging

DeLuca et al. (2020)	AoA, L2 usage, L2 proficiency	English-Mixed	LSBQ, QPT	Raven's Standard Progressive Matrices, Flanker task	fMRI, EBF	Flanker task behavioural results show no modulation by language experience, and language experience impacted neural recruitment and differed for each task
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DeLuca et al. (2024)	L2 usage and language switching	Mixed	LSBQ, amended version of SEEQ, OQPT, NART, and verbal fluency tasks	n.r.	EEG, MRI	Intensity of L2 usage was positively associated with GMV. Significant association identified for GMV in the right posterior MTG, left posterior MTG, and left AG.
Fernandez et al. (2013)	L2 proficiency	English-Spanish	Language questionnaire, Bilingual Verbal Ability Test	Auditory Go/no-go task	EEG, ERP	Highly proficient bilinguals exhibited significantly larger N2 amplitudes on No-go trials than monolinguals, even when behavioural results were inconclusive. even though behavioural results were inconclusive.
Fernandez et al. (2023)	L2 use, Language switching	Spanish-English	Language questionnaire, The Bilingual Verbal Ability Test, Raven's Standard Progressive Matrices	Go/No-Go task, <i>n</i> back test	ERP	Higher balanced bilinguals demonstrated greater N2 and P3 amplitude and behavioural inhibition in bilinguals on the Go/No-Go task. Stronger inhibition in bilinguals led to poorer behavioural performance on Go trials. Greater

degree of balance associated with greater N2 amplitude and higher switch costs. No differences on *n* back test.

Gallo et al. (2021)	AoA, L2 exposure, L2 proficiency, SES	Russian-English	L2 vocabulary task, Russian version of LEAP-Q	Raven's Matrices, Flanker task	MRI	L2 proficiency positively correlated with executive performance. Neuroplasticity peaked at certain stages within bilingual experience, with an eventual revert.
Garbin et al. (2010)	AoA	Spanish-Catalan	Questionnaire for language history, perfect command for both languages through comprehension, expression, writing, and reading, used both languages throughout their lives	Non-verbal task-switching paradigm	MRI, fMRI	Activation among right inferior frontal cortex and anterior cingulate for monolinguals. Bilinguals had reduced switching cost, activated left inferior frontal cortex and left striatum for language control. Concluded early training in language switching helps with brain regions for language control with non-

with regular
switching

verbal cognitive
tasks

Grady et al. (2015)	AoA	English; Mixed	Shipley vocabulary scores	Simon task, MMSE	fMRI	Identified how bilinguals had improved network activity, mainly through stronger functional connectivity in networks influencing cognitive control, and stronger links of connectivity with brain dynamic measures
Gullifer et al. (2018)	AoA, L2 usage	French-English	Language history and demographic questionnaire	AX-Continuous Performance Task	rs-fMRI	Early bilinguals exhibited stronger functional connectivity in left and right prefrontal regions. Greater language entropy correlated with increased functional connectivity in the ACC, bilateral putamen, left

						caudate, and bilateral STG.
Jasinska & Petitto (2013)	AoA	English-Mixed	BLBUQ	Sentence judgment task	fNIRS	Adults had faster reaction times and higher accuracy. Bilinguals especially later-exposed, had higher neural activation in the left inferior frontal gyrus
Jia (2022)	L2 usage, L2 proficiency	Chinese-English	English word reading test for L2 proficiency	Simon task	fMRI	Those with higher L2 vocabulary proficiency did better with the Simon task, with weaker activation in regions supporting cognitive control
Köpke et al. (2021)	AoA and L2 proficiency	French-English	Sociolinguistic questionnaire for language learning, proficiency, and use for each language, ELAO	Language switching picture-naming task	fMRI, MRI	Language switching in highly proficient bilinguals showed increased activation in regions related to domain-general inhibitory processes

Kousaie et al. (2017)	AoA	French-English	Letter fluency, category fluency, sentence repetition tasks for both languages for proficiency	Simon task	rs-fMRI	Simultaneous bilinguals had stronger associations between attention network and DMN, and enhanced cognitive control
Kousaie et al. (2021)	AoA	English-French	Language and Health History Questionnaire, L1 and L2 proficiency, letter fluency, and category fluency	Matrix Reasoning subtest from WAIS-IV, N-back task, non-verbal working memory task	fMRI, MRI	Identified group differences among neural recruitment for phonological working memory task
Kousaie & Phillips (2017)	AoA, L2 proficiency	English-French	Animacy judgment task for proficiency	MoCA, Stroop, Flanker, and Simon tasks	EEG, ERP	Group differences evident for Stroop task where bilinguals had better performance. Simon and Flanker tasks showed electrophysiological differences but no behavioural differences.
Li et al. (2021)	AoA, L2 usage, L2 proficiency	Mixed	Language background questionnaire	Raven's Standard Progressive Matrices, color-shape switching task, numeric Stroop task	fMRI, MRI	Increased language diversity in place of balanced bilingualism was positively associated with brain network segregation and specialization for default mode and

						executive control networks, with lower signal variability
Malik-Moraleda et al. (2021)	L2 proficiency	Mixed	Proficiency questionnaire	Spatial working memory task	fMRI	Bilinguals had stronger neural responses to spatial working memory task with a larger difference between easier and harder conditions of said task
Nayak et al. (2020)	Age	Mixed	Interview of Parents for L2 assessment	Nonverbal Stroop task	EEG, ERP, LRP	No behavioural differences between bilingual children and monolingual children. Regarding neural results, bilinguals exhibited longer positive-peak-cessation latencies, longer negative-peak-onset latencies, and shorter negative-peak latencies compared to monolinguals on the Stroop task.

Nayak & Tarullo (2020)	Age, AoA, SES	English-Mixed	TPVT for receptive vocabulary	Cool Dimensional Change Card Sort Task, Hot Dimensional Change Card Sort Task, NIH Toolbox Picture Vocabulary Test	EEG, ERP, ERN	Behavioural results highlight a bilingual advantage for reaction time, electrophysiological results highlight lower ERN amplitudes in bilingual participants
Olsen et al. (2015)	Age, L2 proficiency	English-Mixed	Shipley vocabulary scores, verbal fluency tasks	MMSE, Trail-making response time, Stroop response time	MRI	Bilinguals had greater frontal lobe white matter, increasing age was associated with decreasing temporal pole cortical thickness among monolinguals but not among bilinguals, and Stroop task positively associated with frontal lobe white matter.
Olulade et al. (2016)	AoA	Spanish-English-American Sign Language	Woodcock-Johnson III Basic Reading Composite Cluster, self-reporting for language history, exposure, use, and proficiency	n.r	MRI	Greater gray matter volume for early bilinguals in right DLPFC, parietal cortex, left DLPFC, and VLPFC. The authors further state these areas are inclusive of the EF network.

Rodríguez-Pujadas et al. (2013)	AoA	Catalan-Spanish	Interview for language use and language history, self-reporting for proficiency	Non-linguistic switching task	fMRI	Concluded early bilingualism affects neural circuitry for executive control
Rodríguez-Pujadas et al. (2014)	AoA, L2 usage, L2 proficiency	Catalan-Spanish	Preliminary interview of languages	Scan test, stop-signal task	fMRI	More activation of anterior cingulate cortex in bilinguals during stop-signal task, no significant differences behaviourally
Stevens et al. (2023)	L2 proficiency	English-Mixed	LSBQ	Trail Making task, Shipley Composite score, Stroop task	fMRI, resting state functional connectivity	Higher L2 proficiency correlated with decreased gray matter volume in the default mode network. Higher L2 proficiency was also correlated with higher intrinsic functional network integrity.
Sulpizio et al. (2020)	AoA, L2 proficiency, L2 usage, Language Entropy, and language switching habits	Italian-English	Online Cambridge test for adult learners, Shannon Entropy (H), BSWQ for bilingual experience and switching habits, Test Breve di Intelligenza (TIB) as Italian	Translation task, Raven's Matrices	fMRI	Bilingualism affected brain plasticity, modulated functional connectivity within and between control networks and language. Effect of age of acquisition modulated through usage and proficiency

equivalent of
NART

Sun et al. (2019)	L1 and L2 proficiency in listening, speaking, reading, writing; language switching; AoA L2 usage; SES	Mandarin-English	LHQ 2.0, CET, TEM-4, BSWQ	Non-verbal IQ through Raven's Matrices	rs-MRI	Proficiency affected components of cognitive control systems. For switching, rsFC in high proficiency bilinguals was weaker with no differences for WM, and negative association with behavioural performance among all participants
Waldie et al. (2009)	L2 proficiency, AoA	Macedonian-English	QPT	Stroop color-word interference task	fMRI	Monolinguals had greater activation during Stroop task, showed more posterior brain activation during the task, and greater activation in the anterior cingulate and prefrontal regions for response conflict. Among bilinguals, English activated more neural substrates

Wu et al. (2016)	Language and dialect proficiency, SES	Standard Mandarin-Southern Min Nan; Standard Mandarin-Hakka	n.r.	Flanker task, Raven's Matrices, Operational Span Task	EEG, ERP	No significant behavioural differences
Wu et al. (2019)	L2 proficiency	Chinese-English	CET-4, self-rated proficiency	Raven's matrices, 48 line drawings of common objects from Snodgrass and Wandersman (1980) database, language switching task, nonverbal switching task	fMRI	Language control composed of cooperative brain network, recruited more subcortical areas and connections from the frontal to the subcortical areas. Reconfiguration efficiency of brain network was mainly affected through general cognition and mediated by L2 proficiency

n.r., Not reported; *B*, Bilingual; *M*, Monolingual; *AoA*, Age of acquisition; *L2*, Language 2;

LEAP-Q, Language Experience and Proficiency Questionnaire; *YAA-R*, York Adult Assessment

Battery-Revised; *TMT*, Trail Making Test; *OBT*, One Back Test; *MoCA*, Montreal Cognitive

Assessment; *L1*, Language 1; *MMSE*, Mini Mental State Examination; *LSBQ*, Language and

Social Background Questionnaire; *SEEQ*, Switching Experience and Environments

Questionnaire; *OQPT*, Oxford Quick Placement Test; *NART*, National Adult Reading Test;

BLBUQ, Bilingual Language Background and Use Questionnaire; *ELAO*, Efficient Language

Assessment Online; *WAIS-IV*, Wechsler Adult Intelligence Scale Fourth Edition; *SES*,

socioeconomic status; *TPVT*, Toolbox Picture Vocabulary Test; *BSWQ*, Bilingual Switching

Questionnaire; *LHQ*, Language History Questionnaire; *CET*, College English Test; *TEM*, Test

for English Majors; IQ, Intelligence Quotient; QPT, Quick Placement Test; WM, working memory; PLS, partial-least squares; CET-4, College English Test Band 4; fMRI, Functional Magnetic Resonance Imaging; MRI, Magnetic Resonance Imaging; EEG, electroencephalogram; fNIRS, Functional Near-Infrared Spectroscopy; rs-fMRI, resting-state functional Magnetic Resonance Imaging; ERP, Event Related Potential; ERN, error-related negativity; EBF, experience based factors; er-fMRI, event-related functional Magnetic Resonance Imaging; LRP, Lateralized Readiness Potentials.

Table 2

Participant Characteristics of Studies Included in the Review

Authors	Country	Participants			
		Group	N	Age mean (SD)	Sex (% female)
Abutalebi et al. (2011)	Italy	B	17	23.35 (4.59)	100
		M	14	26.55 (4.15)	100
Anderson et al. (2021)	Canada	B	39	73.9 (4.03)	62
		M	37	74.3 (3.38)	73
Ansaldi et al. (2015)	Canada	B	10	74.50 (7.10)	n.r
		M	10	74.20 (7.40)	n.t
Arredondo et al. (2022)	USA	B	26	n.r (n.r)	46
		M	26	n.r (n.r)	46
Ballarini et al. (2023)	Germany	B, lifelong	23	72.40 (4.90)	57
		M, lifelong	185	72.40 (5.20)	53
		B, early life stage	99	70.50 (5.80)	62

		M, early life stage	284	71.10 (5.90)	53
		B, middle life stage	99	70.80 (6.10)	38
		M, middle life stage	294	70.90 (5.80)	53
		B, late life stage	36	72.78 (4.80)	42
		M, late life stage	313	72.10 (5.30)	49
Cai et al. (2021)	China	B,	31	21.1 (1.97)	77
		M	31	21.4 (2.03)	71
Costumero et al. (2015)	Spain	B	20	21.1 (1.4)	60
		M	19	20.5 (2.9)	53
Dash et al. (2019)	Canada	B, young adults	20	32.6 (3.1)	45
		B, old adults	18	73.94 (2.8)	61
Dash et al. (2022)	Canada	B	50	65.9 (n.r.)	72
Del Maschio et al. (2018)	Hong Kong	B, old adults, Hong Kong	22	62.32 (5.73)	50
	Hong Kong	B, young adults, Hong Kong	22	20.5 (1.74)	50
	Italy	M, old adults, Italy	22	62.05 (5.88)	67
	Italy	M, young adults, Italy	22	20.86 (1.64)	55
DeLuca et al. (2024)	United Kingdom	B	92	23.80 (3.8)	73
		M	42	20.90 (2.9)	60
Fernandez et al. (2013)	USA	B	13	20.46 (1.51)	93
		M	15	22.67 (4.73)	92
Fernandez et al. (2023)	USA	B	152	n.r (n.r)	70
		M	109	n.r (n.r)	75

Gallo et al. (2021)	Russia	B	22	22.95 (4.38)	55
Garbin et al. (2010)	Spain	B	19	22.55 (4.84)	58
		M	21	20.9 (3.64)	48
Grady et al. (2015)	Canada	M; B	28	70.5 (3.0)	54
Gullifer et al. (2018)	Canada	B	27	23.30 (3.7)	63
Jasinska & Petitto (2013)	Canada	B, children, early exposure	10	8.90 (n.r.)	30
		B, children, later exposure	10	9.00 (n.r.)	60
		M, children	20	8.92 (n.r.)	65
		B, adults	10	19.90 (n.r.)	70
		M, adults	9	19.00 (n.r.)	89
Jia (2022)	China	B	28	41.1 (n.r.)	39
Köpke et al. (2021)	France	B, early	10	24.7 (n.r.)	30
		B, late	10	28.7 (n.r.)	50
Kousaie et al. (2017)	Canada	B, simultaneously	11	n.r.	n.r.
		B, later exposure	10	n.r.	n.r.
Kousaie et al. (2021)	Canada	B, simultaneously	10	22.80 (2.3)	60
		B, early exposure	11	24.10 (4.0)	82
		B, later exposure	10	24.80 (3.6)	60
Kousaie & Phillips (2017)	Canada	B	22	68.70 (5.2)	68

		M	21	71.70 (6.8)	86
Li et al. (2021)	Singapore	B	35	21.40 (n.r.)	60
Malik-Moraleda et al. (2021)	USA	B	55	25.47 (4.87)	44
		M	54	25.42 (5.81)	48
Nayak et al. (2020)	USA	B	51	6.85 (0.62)	51
		M	61	6.98 (0.57)	47.5
Nayak & Tarullo (2020)	USA	B	19	49.74 (4.02) in months	24
		M	21	50.20 (3.01) in months	16
Olsen et al. (2015)	Canada	B	14	70.40 (3.7)	57
		M	14	70.60 (3.0)	50
Olulade et al. (2016)	USA	B, early	15	22.30 (3.2)	60
		M	15	25.90 (6.0)	47
Rodríguez-Pujadas et al. (2013)	Spain	B, early and highly proficient	18	23.06 (3.04)	61
		M	18	23.67 (4.28)	50
Rodríguez-Pujadas et al. (2014)	Spain	B, early and highly proficient	17	21.41 (1.54)	41
		M	16	21.00 (2.49)	50
Stevens et al. (2023)	Canada	B	39	73.87 (4.00)	23
		M	39	73.51 (3.25)	30
Sulpizio et al. (2020)	Italy	B	50	25.78 (4.8)	60

Sun et al. (2019)	China	B, low proficiency	93	n.r.	n.r. 85 females from total sample of 144
		B, high proficiency	51	n.r.	n.r.^
Waldie et al. (2009)	New Zealand	B, later exposure	7	24.87 (2.7)	43
		M, later exposure	10	28.40 (7.4)	50
Wu et al. (2016)	United Kingdom	B, bi-dialect	19	20.37 (2.06)	68
		M, mono-dialect	20	20.90 (2.22)	85
Wu et al. (2019)	China	B	63	22.57 (2.17)	51

n.r., Not reported; B, Bilingual; M, Monolingual

Discussion

The present systematic review identified 8 individual differences in the bilingual experience and discussed or explicitly tested an association between these individual differences and neural correlates of EF – both neural structure and function. While 8 individual differences were reported within the reviewed studies, the current discussion will narrow the focus to the top four: L2 proficiency, age of acquisition, age of the participant (when considered as an individual difference and not simply reported demographically), and L2 usage. Additional individual differences identified (L2 exposure, language switching, language diversity, and SES) are not included because too few studies report these differences to draw meaningful conclusions. Each individual difference is discussed in a separate subsection, which is further subdivided by neuroimaging measure used.

Age of Acquisition

The most frequently reported individual difference in the studies reviewed was age of acquisition, which was reported in 17 out of the 37 articles identified.

Resting state fMRI. In a study by Dash et al. (2022), bilingualism was explored as a continuum of factors including age of acquisition, L2 proficiency, and L2 exposure. Associations with other variables (L2 proficiency & exposure) are reported in subsequent sections. Dash and colleagues scanned adult bilingual participants using fMRI and measured resting state functional connectivity. They found a negative association between age of L2 acquisition and connectivity patterns, such that participants who learned an L2 earlier in life had stronger connectivity between right thalamus, inferior parietal lobe, right middle frontal gyrus, precentral gyrus, and right supramarginal gyrus. Connectivity between these brain regions is thought to reflect activity in the attention network.

Sulpizio and colleagues (2020) had bilingual participants undergo fMRI and recorded resting state functional connectivity. They found that later age of L2 acquisition was correlated with greater connectivity between left parietal superior temporal gyrus and left precuneus. Furthermore, an interaction was observed between age of acquisition and language entropy (i.e., a value representing level of integration of the L2 in the language environment, L1 versus L2 usage), such that increased connectivity between the left putamen, left supplementary motor area, and left caudate was observed only for bilinguals who attained their L2 later in life and had higher language entropy. Higher language entropy is thought to relate to development of connections between language control regions in the brain.

Using resting state functional connectivity, Cai et al. (2021) explored differences in functional connectivity underlying EF in long-term bilingualism compared to monolinguals, measuring both age of acquisition and length of exposure. All bilingual participants had acquired

their L2 after the age of 3, classifying them as late bilinguals. Compared to monolinguals, bilinguals had stronger functional connectivity in the cingulo-opercular region, a network known to house the anterior insula, dorsal anterior cingulate cortex, and thalamus. No differences were seen between groups in connectivity between fronto-parietal regions.

In a study by the Gullifer et al. (2018), resting state functional connectivity was measured to test whether age of L2 acquisition is associated with connectivity in brain regions that are related to language and EF. The authors found that, compared to late bilinguals, early bilinguals exhibited greater functional connectivity in the left and right prefrontal regions, namely the left and right inferior frontal gyrus.

Kousaie and colleagues (2017) explicitly tested whether age of L2 acquisition in adult bilingual participants was associated with either resting state connectivity or behavioural performance on a cognitive control task (Simon task) performed outside the scanner. Participants were divided into simultaneous/early bilinguals (L2 attained from birth) or sequential/late bilinguals (L2 attained after age 6). Simultaneous bilinguals had greater anticorrelations compared to sequential bilinguals between the precuneus, posterior cingulate cortex, bilateral temporal regions, bilateral angular gyrus, bilateral inferior frontal gyrus, dorsal lateral prefrontal cortex, superior parietal lobule, and left inferior parietal lobule.

Functional MRI (fMRI). Garbin et al. (2010) recorded fMRI from early bilinguals and monolinguals while they completed a non-linguistic switching task. Both behavioural and neurophysiological differences were observed between these groups. Bilinguals were faster and more accurate on the switching task than monolinguals. Within the monolingual group, higher activation was observed in the right inferior frontal gyrus, left inferior parietal lobe, and anterior cingulate cortex during switch compared to non-switch trials. This pattern was not observed for

the early bilingual group. Because these structures support monitoring and inhibition processes, the authors infer that – for monolinguals – greater effort was required to successfully complete switch compared to non-switch trials. In contrast, greater activation in switch compared to non-switch trials was only observed in the left striatum and left inferior frontal gyrus for bilinguals. Some measure of caution should be taken with the results as indicative of early bilingualism attributing to differing behavioural performances and neural structures, as there was no late bilingual group to measure against the early bilingual group.

Utilizing a sample of highly proficient bilinguals, Köpke et al. (2021) grouped highly proficient bilingual participants into early/simultaneous or late/sequential L2 learners. Participants performed an overt picture naming switch task while neural activity was recorded using fMRI. Functionally, no differences in neural activation were observed between early and late bilinguals while completing the task. The authors posit that once a bilingual individual reaches a high level of fluency, age of acquisition becomes irrelevant, and bilingual and monolingual groups perform similarly. This interpretation contrasts with what others who support a bilingual advantage might predict.

In a different study by Kousaie et al. (2021), neural correlates of both phonological and non-verbal working memory (important features of EF) were compared between different adult bilingual groups. Bilingual participants were divided into three groups: simultaneous bilinguals who learned their L2 from birth, early bilinguals who learned their L2 before the age of 5, and late bilinguals who learned their L2 after the age of 5. Kousaie and colleagues found that during the phonological working memory task different patterns of neural activity were observed across the bilingual groups. Namely, greater activity was observed in simultaneous and late bilinguals

compared to early bilinguals in regions associated with EF. Regions included left superior temporal gyrus, anterior insula, dorsolateral prefrontal cortex, and anterior cingulate cortex.

Rodríguez-Pujadas and colleagues (2013) had bilingual and monolingual adults perform a non-linguistic switching task while undergoing fMRI. Participants reported L2 proficiency and age of L2 acquisition. All bilingual participants reported a high level of proficiency, and all participants attained their L2 at an early age, by 4 years. They found that the early bilingual group, compared to the monolingual group, had greater activation of the left caudate and left inferior frontal gyrus during switch trials. However, again there is some caution to be taken when interpreting these results, as they did not compare to a late bilingual population.

Waldie et al. (2009) recorded fMRI from adult bilingual and monolingual participants while they completed a manual Stroop task. All participants indicated that their L2 was attained later in life (age 9 or older). In comparison to these late bilingual participants, monolingual participants displayed greater activation in left cingulate and fusiform gyrus, which the researchers interpreted as a greater degree of attention allocated to the Stroop stimuli. They suggest that lower activation in bilinguals, compared to monolinguals, could be due to the fact that bilinguals required less effort when processing word-forms during this task. Additionally, bilinguals had increased activation in the left inferior frontal gyrus compared to monolinguals, which the authors interpret as arising from more practice for bilinguals who are required to use two languages, compared to monolinguals. Finally, monolinguals had greater activation of the anterior cingulate cortex, right inferior superior frontal gyrus and insula compared to these late bilingual participants. While patterns differ between the monolingual and bilingual groups, caution must be taken in interpreting age of acquisition effects as there was no early bilingual comparison group.

DeLuca and colleagues (2020) scanned a diverse set of bilingual participants (e.g. variation in L2, ethnic and cultural backgrounds, age range) using fMRI while they completed a version of the Flanker task. They found that earlier age of L2 acquisition was correlated with increased activation of inferior frontal gyrus, anterior cingulate cortex, and inferior parietal lobule, suggesting that as the bilingual training starts early, there is a stable level in the degree of use of these brain regions in events where there are EF demands.

Rodríguez-Pujadas and colleagues (2014) recruited a group of early bilinguals (L2 acquired by age 4) and monolinguals to complete a non-linguistic Stop-signal task while fMRI was recorded. Though no significant behavioural differences were observed between the groups, monolinguals had increased activation of the anterior cingulate cortex compared to bilinguals. The authors also observed comparable behavioural performance (reaction time and accuracy) between the two groups, despite less activation in the anterior cingulate cortex in the bilingual group. This suggests that less effort was required for the bilingual group to reach the same degree of accuracy and/or same speed in performance.

Costumero and colleagues (2015) recorded fMRI from early bilinguals (L2 acquired in infancy) and monolinguals while they completed a non-linguistic Go/No-go task. The study found that bilinguals had increased activation of regions within left fronto-parietal networks as well as the inferior frontal gyrus, insula, and dorsal anterior cingulate during task performance compared to monolingual participants. Authors speculate that observed differences between groups might reflect increased connectivity in these EF-relevant networks for bilingual compared to monolingual participants. The authors further state that different activations in these networks between language groups might be due to bilinguals' consistent use of language control that helps to shape brain functions. Again, there was no comparison with a late bilingual group.

Structural MRI. Returning to Köpke et al. (2021), though no differences were found functionally, structurally they found that simultaneous bilinguals, who learned their L2 early in life (before the age of 3 years), had greater cortical thickness in right inferior frontal gyrus than sequential bilinguals. Additionally, they found a plasticity effect regarding the left temporal pole with simultaneous bilinguals exhibiting a thicker cortex. This supports prior evidence demonstrating that bilinguals have a thicker cortex in this region than monolinguals, and extends prior work to show graded effects depending on the age of L2 acquisition (Abutalebi et al., 2014).

To test for lifelong differences in EF of bilinguals compared to monolinguals, Olulade et al. (2016) scanned bilingual and monolingual participants using MRI to test for gray matter volume differences between groups. Early bilinguals (before the age of 6 years) exhibited greater gray matter volumes than monolinguals in the right dorsolateral prefrontal cortex and parietal cortex, and the left dorsolateral prefrontal cortex and ventrolateral prefrontal cortex.

Ballarini et al. (2023) tested whether acquiring an L2 at different stages of the lifespan was associated with cognition and brain structure in later adulthood. The authors tested groups with early L2 acquisition (13-30 years), middle-age L2 acquisition (30-65 years), and late L2 acquisition (over 65 years) and compared these groups to a group of monolingual participants. Using MRI to measure differences in gray matter volume between groups, results indicated no significant differences between lifelong bilingual or monolingual groups. However, a trend was observed between lifelong bilingual and monolingual groups, suggesting more gray matter volume in the basal ganglia for the bilingual group.

fNIRS. Jasinka and Petitto (2013) had bilingual children, bilingual adults, monolingual children and monolingual adults complete a sentence judgement task while recording brain

activity using fNIRS. The authors tested whether age of acquisition was associated with neural activity supporting both language and cognitive control. In this study, age of acquisition was divided into early (L2 attained from birth) or late (L2 attained between age 4-6). Higher levels of blood oxygenation were observed in bilinguals of any age compared to monolinguals in left and right hemisphere language regions. Furthermore, when comparing neural activity between early and late L2 participants, late bilingual children showed greater neural activity than early bilinguals in brain areas involved in language processing (i.e., left inferior frontal gyrus, Broca's area, superior temporal gyrus) and areas related to cognitive control (i.e., dorsolateral prefrontal cortex).

Summary. Studies reviewed tested whether L2 age of acquisition was associated with differences in resting state connectivity – specifically networks supporting alerting, orienting, and executive control. Two studies (Dash et al., 2022; Sulpizio et al. 2020) found evidence that L2 age of acquisition was associated with variation in these networks, such that a) earlier age of acquisition was associated with increased functional connectivity between the right thalamus, inferior parietal lobule, right middle frontal gyrus, precentral gyrus, and right supramarginal gyrus and b) later age of acquisition was associated with increased functional connectivity between the left parietal superior temporal gyrus and left precuneus. These studies suggest a) individuals that acquire their L2 early in life have stronger connectivity in EF networks compared to late L2 bilinguals and b) that individuals who acquire an L2 later in life are more likely to resemble monolingual speakers in terms of connectivity in EF networks.

Studies measuring neural activity during EF tasks demonstrate a more complicated pattern. On the one hand, 2 studies (Garbin et al., 2010; Kousaie et al., 2017) found that early bilinguals compared to monolinguals and late bilinguals showed decreased activation in areas

related to EF. On the other hand, 4 studies (Costumero et al., 2015; DeLuca et al., 2020; Kousaie et al. 2021; Rodríguez-Pujadas et al., 2013) found that early bilinguals actually had *increased* activation in areas related to EF compared to both monolinguals and late bilinguals. At the same time, 2 studies (Kousaie et al., 2021; Jasinka and Petitto, 2013) found that late bilinguals displayed increased activity in areas related to EF compared to both monolinguals and early bilinguals. One study (Waldie et al., 2009) found that late bilinguals displayed decreased activation in areas relative to EF compared to monolinguals. To note, differences observed between studies may result from differences in tasks, such as the Go/No-go task, a variety of different switching tasks, the Stroop task, and the Flanker task. These tasks range on different aspects of the EF measured, from switching to inhibition. At the same time, some studies (e.g., Costumero et al., 2015; DeLuca et al., 2020; Kousaie et al. 2021; Rodríguez-Pujadas et al., 2013) measured activation of similar regions (i.e., inferior frontal gyrus and anterior cingulate cortex), and generally showed increased activity in early bilinguals compared to monolinguals and late bilinguals. In contrast, other studies measured a variety of different regions and patterns varied. This might suggest that differences between groups depend on the specific dimension of EF measured, as well as reported brain region.

When considering structural differences between monolingual and bilingual speakers, 3 studies observed differences between these groups. Differences were also observed within bilinguals, with differences in the structure (volume and cortical thickness) of right inferior frontal gyrus between early/simultaneous and late/sequential bilinguals. This suggests that the experience of bilingualism might shape the structure of the brain in areas that have been implicated in EF, such that the earlier the L2 was acquired the more likely structural differences are to be observed. The observation that age of acquisition was associated with these structural

differences supports this point. Köpke and colleagues (2021) observed that the cortex in the right inferior frontal gyrus region was thicker the earlier the L2 was acquired. This is consistent with patterns observed between early/late bilinguals and suggests that age of L2 acquisition uniquely contributes to structural variation in the brain. Additionally, in other studies, early bilinguals exhibited increased gray matter volumes the right dorsolateral prefrontal cortex and parietal cortex, and the left dorsolateral prefrontal cortex and ventrolateral prefrontal cortex, with a trend to for greater volume of the basal ganglia as well.

In summary, across studies reviewed, neural correlates of EF in early bilinguals appeared similar to that of monolinguals, while in others neural correlates of EF in late bilinguals appeared more similar to monolinguals. Differences may arise from different task demands and different brain regions reported.

Age of Participant

Age of participant at time of testing was another individual difference assessed in the reviewed studies. While age of participant is reported across all studies as a demographic variable, it was discussed as an individual difference relevant for neural correlates of EF in 11 out of the 37 articles.

Resting State fMRI. Grady et al. (2015) hypothesized that proficient older adult bilinguals would exhibit greater functional connectivity of EF related networks when compared to age-matched monolingual participants. They found that older bilinguals had greater resting state functional connectivity in the frontoparietal control network and default mode network than monolingual participants. Note that effects of age were not directly assessed, since there was no younger comparison group.

Functional MRI. In the study by Dash et al. (2019) reviewed previously, bilingual participants were asked to complete the Attention Network Test while fMRI was recorded. Bilingual participants were divided into young and older aged groups. While matched on behavioural outcomes, results indicated differences in neurophysiological function between age groups in alerting and orienting trials. Namely, elderly bilinguals, when compared to their younger counterparts, had significantly greater activation of the left ventrolateral prefrontal cortex when completing alerting trials and of the right superior parietal gyrus when completing orienting trials. This suggests that elderly bilinguals were relying more heavily on these structures to obtain similar accuracy rates and reaction times than the young bilingual group.

In a study that focused on working memory, Anderson et al. (2021) compared older adult bilinguals and monolinguals on the n-back test, an EF task, while scanning using fMRI. A few results emerged. First, bilinguals presented with faster reaction times in the n-back task than monolinguals. Furthermore, bilinguals had decreased activity in the dorsolateral prefrontal cortex and the anterior cingulate cortex as compared to monolinguals when completing the n-back task; two areas that the authors cite as critical to the EF system.

A study by Ansaldo et al. (2015) had elderly bilingual and monolingual participants complete the Simon task while scanning using fMRI. Behavioural results demonstrated no significant differences in accuracy or reaction time between groups, however neural differences were exhibited. Monolinguals had significantly greater activity in the prefrontal cortex than bilinguals, while bilinguals had significantly greater activity in the left inferior parietal lobule than monolinguals. Some caution is needed to interpret these results, as there were no younger bilingual and monolingual comparison groups.

Structural MRI. Del Maschio and colleagues (2018) conducted a study on a sample of young adult and elderly bilinguals and monolinguals to test whether bilingualism protects against age-related cognitive decline. Relevant to the current systematic review, Del Maschio et al. (2018) specifically focused on the EF system. To measure the efficiency of the EF network, they had their participants complete the Flanker Task after undergoing MRI. When compared to similar aged monolinguals, elderly bilinguals presented with better accuracy and faster reaction times. Furthermore, neural results show greater gray matter volume in the prefrontal cortex, inferior parietal lobule, and anterior cingulate cortex, leading to the hypothesis that bilingualism does protect against age-related cognitive decline. Young adult bilinguals, when compared to young adult monolinguals, did not show any difference in behaviour (accuracy or reaction time). However, the young bilingual participant group did have greater gray matter volume than their monolingual counterparts. Finally, though elderly bilinguals had less gray matter volume than young bilinguals, behavioural differences between groups were not significant.

Interested in the structural differences between older adult bilinguals and monolinguals, Olsen et al. (2015) examined differences in gray and white matter volume as well as differences in volume and cortical thickness of the temporal pole, entorhinal cortex, and hippocampus using MRI. The older adult bilingual group exhibited significantly greater white matter volume of the frontal lobe and marginally greater white matter volume of the temporal lobes compared to the monolingual group. Furthermore, cortical thickness differences were observed between language groups, with bilinguals having greater thickness in frontal regions than monolinguals. It should be noted that there was no younger adult comparison group.

Back to the Anderson et al. (2021) study, of particular note is that older adult bilinguals overall had decreased levels of gray matter and white matter volume than monolinguals throughout the

whole brain. While that may be the case, bilingual participants interestingly still exhibited a) more gray matter volumes in the left superior temporal gyrus and inferior frontal gyrus, and b) more white matter volume in the bilateral superior corona radiata compared to monolingual participants.

EEG. Using a sample of bilingual versus monolingual older adults, Kousaie and Phillips (2017) had participants complete three EF tasks (Stroop, Simon, Flanker) while undergoing event-related potential analysis. ERPs of interest to the study were the N2 and P3, ERPs associated with conflict monitoring and stimulus evaluation/resource allocation respectively (For a detailed explanation of these ERP components see: Kappenman & Luck, 2012; Sur & Sinha, 2009; Woodman, 2010.) For the Stroop task, Kousaie and Phillips (2017) found their bilingual groups when compared to the monolingual group, presented with earlier latencies of the N2 and larger amplitudes of the P3, which they suggest might indicate that bilinguals have better conflict detection skills and need to allocate fewer resources to perform the task. In addition, behavioural results lined up with the neural results, with bilinguals showing higher accuracy and faster reaction times than monolinguals. In the Simon task, the N2 amplitude was larger for bilinguals but only in the incongruent trials. However, overall amplitude of the N2 was larger for the monolingual participants to which Kousaie and Phillips (2017) suggest that conflict monitoring demands placed a greater toll on monolinguals than bilinguals. Regarding the P3, earlier latencies and larger amplitudes were seen in bilinguals compared to monolinguals suggesting better allocation of resources. Behavioural results appeared inconclusive as no significant differences in accuracy or reaction time were demonstrated between language groups. In the Flanker task, the N2 amplitudes did peak earlier for bilinguals compared to monolinguals, however this was only the case when they were completing incongruent trials. The authors

suggest that bilinguals had faster conflict monitoring skills on incongruent trials compared to monolinguals. Their bilingual group exhibited earlier peaks of the P3 to which the authors suggest possible processing differences that might favour bilinguals. Behavioural results again appeared inconclusive as no behavioural differences were observed between language groups.

Nayak and Tarullo (2020) sought to expand reliance on behavioural methodologies to test the EF of bilingual children and conducted a study on preschool bilingual and monolingual children (age 3.5 to 4.5 years of age) while recording event-related potentials. Specifically, they measured the error-related negativity event-related potential in order to test mechanisms of error-awareness underlying performance on tasks. The EF tasks they used were the Cool Dimensional Change Card Sort Task and Hot Dimensional Change Card Sort Task. Results indicated the bilingual preschool children had smaller error-related negativity peak amplitudes than monolingual preschool children on error-related trials in the Cool Dimensional Change Card Sort Task. The smaller error-related negativity peak amplitudes were seen in the frontal and frontocentral midline brain regions, leading to the hypothesis that bilingual children process error in a different way than monolingual children. However, the authors discuss issues with their interpretation as larger error-related negativities are also correlated with higher anxiety and older age; two outcomes that were not adjusted for which also may have differed between groups.

In a different study by Nayak et al. (2020), they once more tested bilingual and monolingual children, this time between the ages of 6 and 8 years while recording lateralized readiness potentials (LRP). LRPs are centroparietal ERPs that monitor responses between presentation of a stimulus and the consequent behavioural responses. Behaviourally, no differences were seen between bilinguals and monolinguals in inhibition skills. However, neurally, bilingual children presented with longer positive-peak-cessation latencies, longer

negative-peak-onset latencies, and shorter negative-peak latencies compared to monolinguals when conducting a version of the Stroop task. Though no overall differences were seen in inhibition, the authors state that there was a trend for bilinguals to be more prepared and were able to inhibit incorrect motor responses prior to making the correct responses.

To test for inhibitory responses on an EF task, Fernandez et al. (2013) recruited bilinguals and monolinguals to perform the Go-/No-Go task while undergoing EEG. Behaviourally, there were no apparent differences between monolinguals and bilinguals. However, when tested neurally, the more proficient a bilingual was, the more likely they would exhibit larger N2 amplitudes on No-Go trials than monolinguals.

fNIRS. Using fNIRS, Arredondo et al. (2022) wanted to expand their previous research and tested on bilingual and monolingual school age children (7-9 years) on a version of the Attention Network Task with age as the dependent variable. No behavioural differences were observed between bilingual and monolingual children. Neurally, bilingual children compared to monolingual children presented with increased brain activity in the left frontal and parietal areas.

Summary. The study measuring resting state functional connectivity demonstrates a pattern in which older adult bilinguals exhibited greater functional connectivity of the frontoparietal control network and default mode network compared to monolinguals (Grady et al., 2015). Importantly, there was no comparison between older adult bilinguals and younger bilinguals; the differences presented are found within an older group only. Thus, it cannot be ascertained whether age of participant has an effect on resting state functional connectivity.

Studies measuring neural activity during EF tasks demonstrate a similar pattern. In fMRI research, one study (Dash et al., 2019) found that older bilingual participants had increased

activation of the left ventrolateral prefrontal cortex and right superior parietal gyrus compared to younger bilinguals. Another study showed that older bilinguals presented with decreased activation of the dorsolateral prefrontal cortex and anterior cingulate cortex compared to monolinguals only (Anderson et al., 2021). Ansaldi et al. (2015) found that older bilinguals compared to monolinguals had significantly greater activity of the left inferior parietal lobule. Within ERP research, one study presented results in which older bilinguals compared to monolinguals exhibited earlier latencies of the N2 and larger amplitudes of the P3 when completing EF tasks (Kousaie and Phillips, 2017). Another study found that young bilingual children exhibited smaller error-related negativity amplitudes than monolingual children in areas such as the frontal and frontocentral midline brain (Nayak and Tarullo, 2020). Therefore, age of participant appears to be associated with neural correlates of EF across tasks and measures.

In studies comparing structural differences between bilinguals and monolinguals, differences were observed between older bilinguals compared to younger bilinguals, younger monolinguals, and older monolinguals. This suggests that participant age might influence the degree to which structural brain differences are observed in areas that have been implicated in EF. Participant age was also, in some cases, linearly associated with structural changes. In one study, both older and younger bilinguals had overall greater gray matter volumes compared to monolinguals (Del Maschio et al., 2018) with younger bilinguals additionally presenting with even greater gray matter volumes than older bilinguals. In another study, older bilinguals had significantly greater white matter volumes in frontal and temporal regions compared to monolinguals (Olsen et al., 2015). In addition, older bilinguals presented with thicker cortices of the frontal and temporal lobes. However, in one study (Anderson et al., 2021) results differed in that older bilinguals compared to similar aged monolinguals had overall lower gray and white

matter volumes except for 3 areas (left superior temporal gyrus, inferior frontal gyrus, and bilateral superior corona radiata). Therefore, differences in brain structure between bilingual and monolingual groups may be more likely to be observed as age of the participant increases.

To conclude, age of participant appears to be a likely factor in determining whether neural correlates of EF differ between monolinguals and bilinguals.

L2 Proficiency

The third most frequently reported individual difference amongst the articles reviewed was L2 Proficiency, which was reported in 9 out of the 37 articles.

Resting State fMRI. Using resting state functional connectivity, Dash and colleagues (2022) (as reported in the age of acquisition section) observed that adult bilingual participants who reported low, compared to high L2 proficiency had stronger negative functional connectivity in the EF network, namely the left superior frontal gyrus connecting to other regions including the left occipital pole and lingual gyrus. From this pattern of results the authors infer that with increased L2 proficiency, connectivity within the EF network decreases in strength, indicating greater efficiency within that network.

Sulpizio and colleagues (2020) conceptualize bilingualism as complex and dynamic phenomenon that embodies both what they term static factors (such as L2 age of acquisition) and dynamic factors (such as L2 proficiency and L2 usage). Using this framework, they measured resting state functional connectivity from a group of adult bilingual participants. They observed an interaction between age of acquisition and L2 proficiency, such that greater inter-hemispheric connectivity of the left bilateral posterior superior temporal gyrus to the right precuneus and right temporal pole was observed for late bilinguals who also demonstrated high L2 proficiency.

Sulpizio et al., hypothesize that higher L2 proficiency reinforces clusters of information that are segregated within the EF network, implying a greater utility of local information processing. Lastly, an interaction between age of acquisition and L2 proficiency was observed, such that there was weaker neural connectivity between the left caudate and right cerebellum the earlier participants learned their L2. The authors use these patterns of results to posit that the earlier an L2 is learned, the more likely a high level of L2 proficiency will be achieved, and that level of L2 proficiency is the variable associated with connectivity patterns.

In a study by Sun et al. (2019), bilingual participants were divided into low versus high levels of L2 proficiency based on scores of an accredited exam and self-report questionnaires. Participants completed tasks assessing different domains of EF (i.e. inhibition and switching), while fMRI was recorded. During the inhibition task, high proficiency bilinguals exhibited significantly weaker resting state functional connectivity between regions in the right middle frontal gyrus compared to participants who reported low L2 proficiency. The authors suggest that neural processes supporting inhibition are modulated by L2 proficiency. During the switching task, high L2 proficiency participants exhibited weaker resting state functional connectivity compared to low L2 proficiency participants within the anterior cingulate cortex, an area known to play an important role in task switching (Paus et al., 1993).

Stevens et al. (2023) used resting state functional connectivity to explore brain function differences between an older bilingual and older monolingual population. They found that higher L2 proficiency was correlated with higher intrinsic functional network integrity in the default mode network.

Functional MRI. Jia and colleagues (2022) recorded fMRI from adult participants while they completed a Simon task. L2 proficiency was measured on a self-report questionnaire. They

found a positive correlation between performance on the Simon task and degree of L2 proficiency, such that more proficient bilinguals performed with higher accuracy and faster reaction times on the Simon task. Higher L2 proficiency was also correlated with decreased activity in regions that support EF, including right anterior cingulate cortex, left insula, and left superior temporal gyrus.

Dash and colleagues (2019) used an event related fMRI paradigm while participants of different ages (between 32 to 74 years old) completed an Attention Network Test, which is a combination of EF tasks that assess alerting, orienting, and conflict monitoring. Similar to results observed in the previous study, here L2 proficiency was negatively correlated with activation in frontal regions. Associations varied depending on the age of the participants, as effects were stronger in older patients. Dash et al., (2019) infer from their results that increased L2 proficiency contributes to greater neural efficiency during tasks that require EF.

Waldie and colleagues (2009) had a group of high proficiency bilinguals complete a Stroop task while fMRI was recorded. They found that bilingual, compared to monolingual participants, exhibited decreased activation in anterior cingulate cortex and prefrontal regions. They infer that decreased activation during this task indicates more efficient conflict detection or conflict monitoring. While associations between proficiency and neural activity were not directly tested, authors collected data on proficiency and reported that this was a highly proficient group. Because differences were observed between these high proficiency bilinguals and monolingual participants, it may suggest that proficiency is a variable that increases the likelihood that differences between monolinguals and bilinguals will be observed.

In another study comparing highly proficient bilinguals and monolingual participants, Abutalebi et al. (2012) had their participants undergo fMRI scanning while completing a version

of the Flanker task. Results indicated that during the task, bilinguals had more activity in dorsal anterior cingulate cortex than monolinguals.

Structural MRI. Furthermore, in the study by Abutalebi et al. (2012), they also reported that highly proficient bilinguals had more gray matter volume in the dorsal anterior cingulate cortex region. The authors suggest that bilinguals might use the anterior cingulate cortex more efficiently than monolinguals in order to monitor domain general EF conflicts, outside the language domain. As there is no comparison group for L2 proficiency in bilinguals, it cannot be concluded that proficiency drove these effects.

Gallo and colleagues (2021) tested adult Russian-English bilingual participants using fMRI while they completed a Flanker task. An interaction was observed between L2 proficiency and L2 exposure, such that a higher level of L2 proficiency was associated with increased gray matter volume of the anterior cingulate cortex, while lower proficiency was associated with less gray matter volume in this region. Additionally, proficiency was marginally positively correlated with greater gray matter volume in the prefrontal cortex as well.

In a study testing predictors of cognitive reserve, Stevens et al. (2023) used structural MRI to explore brain structure differences between an older bilingual and older monolingual population. They found that as L2 proficiency increases, gray matter volume decreases in the default mode network.

Summary. In studies measuring resting state functional connectivity, the studies reviewed tested whether L2 proficiency was associated with differences in resting state networks in brain areas that support EF. Three studies found evidence that L2 proficiency was associated with variation in these networks. In one study, low L2 proficiency bilinguals had stronger

functional connectivity in the left superior frontal gyrus, left occipital pole, and lingual gyrus (Dash et al., 2022). In another study by Sun et al. (2019), high L2 proficiency participants had weaker resting state functional connectivity in the right middle frontal gyrus when completing an inhibition task and weaker resting state functional connectivity of the anterior cingulate cortex when completing a switching task. Both studies infer that increased L2 proficiency leads to weaker connectivity in these resting state networks. However, in the last study by Sulpizio et al. (2020), results differed in that high L2 proficiency participants had stronger connectivity between the bilateral superior temporal gyrus and the right precuneus and right temporal lobe compared to low L2 proficiency bilinguals. From what can be seen, increased L2 proficiency might lead to weaker connectivity in some networks and stronger connectivity in others.

Studies measuring neural activity while participants completed EF tasks followed a similar pattern of results. Two studies found that high proficiency bilinguals compared to low proficiency bilinguals exhibited decreased activation in frontal regions including the right anterior cingulate cortex, left insula, and left superior temporal gyrus (Dash et al., 2019; Jia et al., 2022). In one study by Abutalebi et al. (2012), high proficiency bilinguals presented with increased activity of the dorsal anterior cingulate cortex, however these bilinguals were only compared to monolinguals. Overall, studies suggest that it is more likely to observe differences in neural correlates of EF between monolingual and bilingual groups when L2 proficiency is high, however the direction of effects might vary based on task and region. It is also important to note that several studies that reported proficiency did not include a low L2 proficiency comparison group, making it difficult to conclude whether monolingual/bilingual differences would also be observed at lower levels of proficiency.

Several studies observed differences in brain structure between low- and high-L2 proficiency bilinguals and monolinguals. These studies suggest that the level of proficiency of the bilingual individual might shape the structure of the brain in areas relative to EF. In the studies examining structural differences, proficiency was positively correlated with gray matter volume such that as proficiency of the L2 increased, the likelihood of larger gray matter volume increased as well (Abutalebi et al., 2012; Gallo et al., 2021). Additionally, high proficiency bilinguals who learned their L2 earlier in life had thicker cortices in the right inferior frontal gyrus region the earlier the L2 was acquired than high proficiency bilinguals who learned their L2 later on (Köpke et al. 2021). However, in one study decreased gray matter volume was seen in highly proficient bilinguals in the default mode network (Stevens et al., 2023). Therefore, differences in brain structure between bilingual and monolingual groups in regions that support EF may be more likely to be observed at higher levels of L2 proficiency.

To conclude, L2 proficiency appears to be a likely factor in determining whether neural correlates of EF differ between monolinguals and bilinguals.

L2 Usage

Another individual difference reported in the articles reviewed was L2 usage. L2 usage can be defined as the amount of daily use in speech and writing and/or the difference in usage between the L1 and L2. Associations between L2 usage and neural correlates of EF were reported in 6 of the 37 articles.

Resting State fMRI. In the study by Sulpizio and colleagues (2020) reported earlier, resting state functional connectivity was measured. Associations between L2 usage and connectivity patterns were tested for bilingual participants. Though L2 usage by itself was not

associated with connectivity patterns, the interaction between age of acquisition and L2 usage was found to modulate connectivity between the left putamen, left supplementary motor area, and left caudate. Specifically, greater L2 usage was correlated with greater connectivity between these areas, but only for late bilinguals.

Going back to the study by Gullifer et al. (2018), in which they tested how the bilingual experience relates to resting state functional connectivity within language and EF networks, they also tested for language entropy/usage or the social diversity of language use. Authors found that with greater language entropy/usage, there was an increase in functional connectivity in the anterior cingulate cortex, bilateral putamen, left caudate, and bilateral superior temporal gyrus.

Functional MRI. As reviewed in a prior section, Dash et al. (2019) recruited young and elderly bilinguals to perform an Attention Network Task while undergoing fMRI. While they tested whether L2 usage was associated with neural activity during this task, no significant associations were observed between L2 usage and either behavioural or neural outcomes. The authors speculated that L2 usage and L2 proficiency might interact, however this was not directly tested in this study.

Finally, returning to DeLuca et al.'s (2020) study in which adult bilinguals performed the Flanker task while undergoing fMRI, increased usage of the L2 correlated with increased activation of the anterior cingulate cortex, middle frontal gyrus, and the inferior parietal lobule.

Structural MRI. In a later study, DeLuca and colleagues (2024) utilized the Unifying the Bilingual Experience Trajectories framework, a framework that focuses on how individual bilingual experiences lead to neural and cognitive adaptations. With this framework in mind, DeLuca and colleagues scanned monolingual and bilingual participants using MRI and had

participants complete demographic questionnaires to collect information about language and socio-demographic background. Results indicated that greater use of the L2 in day-to-day life was associated with larger gray matter volume in the right inferior frontal gyrus, right medial frontal gyrus, right angular gyrus, and medial temporal gyrus. The authors describe the role of these regions in supporting EF abilities, and processing during EF tasks.

EEG. Due to the inconsistency of results seen within the bilingual advantage field, a study by Fernandez et al. (2023) tested a large population of bilinguals and monolinguals on a variety of behavioural and neural measures of different aspects of EF (inhibition, shifting, updating). Furthermore, tested whether the degree of language use of the L1 compared to the L2 predicted performance or neural activity. Overall, results indicated that behavioural performance in EF tasks was lower for bilinguals compared to monolinguals. Neurally, a higher balance of language use in bilinguals was associated with greater N2 and P3 amplitudes in behavioural inhibition on the Go/No-Go task. A stronger case of inhibiting behavioural responses led to poorer behavioural performances on Go trials for bilinguals. Additionally, a greater degree of balance between L1 and L2 use was associated with increased N2 amplitudes and higher switch costs. No differences in ERPs were seen in the updating EF aspect.

Summary. To summarize, some evidence suggests that L2 usage is positively associated with structural differences in regions known to support EF. Namely, increased L2 usage was correlated with larger gray matter volumes of the right inferior frontal gyrus, right medial frontal gyrus, right angular gyrus, and medial temporal gyrus. This suggests that the experience of L2 usage might shape the structure of the brain in areas that have been implicated in EF. In contrast, associations between L2 usage and resting state functional connectivity in EF-relevant networks were mixed. Sulpizio et al. (2020) when testing for L2 usage and age of acquisition together,

found that greater L2 usage was associated with stronger connectivity between left putamen, left supplementary motor area, and left caudate in late but not early bilinguals. In a study by Gullifer et al. (2015), higher L2 usage correlated with increased functional connectivity in the anterior cingulate cortex, bilateral putamen, left caudate, and bilateral superior temporal gyrus. Results appear mixed when testing whether L2-Usage predicts activation of EF-relevant regions during tasks. While DeLuca et al. (2020) found that greater L2 usage was correlated with increased activation of the anterior cingulate cortex, middle frontal gyrus, and inferior parietal lobule, Dash et al. (2019), found no associations between L2 usage and neural activity. Differences could be attributed to the different tasks used and the different brain region areas measured. Therefore, it is difficult to attest to whether L2 usage is associated with neural correlates of EF as the research lays divided across neural measures.

Conclusion

The current systematic review asked whether individual differences in the bilingual experience explain variation in structural or functional neural correlates underlying domain general executive function. As studies reporting effects of bilingualism on EF abilities are mixed, this study aimed to a) identify individual differences that might contribute to variation in neural correlates underlying EF, and b) describe relationships between individual differences in the bilingual experience and neural correlates of EF. This review focused on neural as opposed to behavioural correlates because neural measures may be more sensitive to revealing experience driven effects of variation in language experience. Moreover, experience-driven neural differences may precede behavioural change or may reflect adaptation of the brain to the bilingual context, despite similarities in behavioural responses.

Individual differences identified through this review include age of acquisition, age of participant, L2 proficiency, and L2 usage. While other individual differences in the bilingual experience certainly exist (e.g., clinical diagnoses such as ADHD, socioeconomic status, duration of exposure to each language), these four variables emerged most frequently in the literature. Each of these individual differences were also associated with patterns of neural structure and function, across different studies and populations. For example, earlier age of acquisition tended to be associated with increased activity and thicker cortices of the right inferior frontal gyrus, left fronto-parietal networks, insula, anterior cingulate cortex, inferior parietal lobule, and dorsal anterior cingulate region in bilinguals compared to monolinguals. At the same time, higher L2 proficiency was correlated with decreased activation and larger gray matter volume of the prefrontal cortex and areas relative to it when completing EF tasks (such as the Stroop task, Simon task, Attention Network Task), which authors suggest indicates more efficient EF processing as proficiency increases. Moreover, this body of research mostly suggests that the older a bilingual participant is, a) the more likely they will have greater activation of the left ventrolateral prefrontal cortex and right superior parietal gyrus, b) the more likely they will have decreased activation of the dorsolateral prefrontal cortex and anterior cingulate cortex. In contrast, young bilinguals presented with greater gray matter volume compared to monolinguals and older bilinguals in regions such as the prefrontal cortex, inferior parietal lobule, and anterior cingulate cortex. Notably, however, not all studies found significant associations between individual differences and neural correlates of EF. Specifically with regards to L2 usage, evidence was divided. In one study, greater L2 usage was associated with greater activity in areas supporting EF. However, in other studies, L2 usage was not significantly correlated with brain activity in any region. Indeed, L2 usage was typically observed to interact with other

variables, such as proficiency and age of acquisition, when predicting neural structure and function. A reason could be that L2 usage is only relevant to EF when seen in conjunction with another individual difference.

Despite some mixed patterns, overall, most studies identified associations between individual differences in the bilingual experience and neural structure and function, even in cases when behavioural results (accuracy or reaction time) did not differ between groups. Therefore, future research should consider how specific experiences associated with bilingualism might lead to experience-driven changes in the brain.

This study provides insight into whether individual differences can help us to understand whether experiences of bilingualism contribute to variation in domain general EF by comprehensively reviewing the literature to date and describing patterns of neural correlates associated with the individual differences identified.

Limitations of results

While the articles reviewed provide important insight into the potential role of individual differences in the bilingual experience in shaping neural structure and function that supports EF, several limitations should be noted. In studies that reported effects of age of acquisition, there was some inconsistency in terms of how early and late bilinguals were categorized. For example, the study by Kousaie and colleagues (2017) classified early bilinguals as simultaneous bilinguals; those who obtained/had been introduced to their L2 starting from birth. However, in another study by Kousaie et al. (2021), simultaneous and early bilinguals were classified differently. Simultaneous bilinguals were those who learnt their L2 from birth, while early bilinguals may have learned their L2 anytime before the age of 5. In other studies, such as that by

Rodríguez-Pujadas and colleagues (2014), early bilinguals were those who obtained their L2 by age 4. When different studies report these categories in different ways, a level of caution is required when interpreting the results as certain patterns might be obscured. For example, simultaneous learners could have experienced a delay in learning the L2 or if classified as an early bilingual, they may have been exposed to the L2 from birth which would identify them as simultaneous rather than just early or sequential bilinguals. Future research should aim to find an agreement on how early, simultaneous, sequential, and late learners are classified or could test age of acquisition as a continuous variable rather than in fixed groups. Addressing these limitations might help to clarify the patterns in events where results are mixed such as the study Rodríguez-Pujadas et al. (2013) in which early bilinguals had increased activation of EF-relevant brain areas compared to a study such as Kousaie et al. (2021) in which early bilinguals showed decreased activity of EF-relevant brain areas.

Secondly, in studies that report L2 proficiency, it was frequently the case that only highly proficient bilinguals were included, and a group with lower levels of proficiency was not included for comparison. From the final 8 articles included within the review, only 3 of them had included a low L2 proficiency bilingual group (Sun et al., 2019). Caution must therefore be taken when interpreting the results of these studies. While differences between bilinguals and monolinguals might emerge at high levels of L2 proficiency, and associations might be observed between proficiency and neural correlates of EF when L2 proficiency is relatively high, there is limited evidence for these relationships at lower levels of L2 proficiency.

Another issue that is made evident through this review is that the interpretations of patterns of brain activity vary across studies. For example, studies such as that by Dash and colleagues (2022) found that bilingual participants had greater brain activity than monolinguals

in prefrontal regions. This pattern was interpreted as reflecting better, or more efficient, performance of the EF system. In contrast, other studies, such as Kousaie et al. (2017), demonstrated that bilinguals had lower brain activity in the prefrontal cortex compared to monolingual participants. However, in this case, patterns were interpreted as indicative of better execution of the EF system even in events where the tasks used, the brain regions that activated, and neuroimaging tools were similar. Without being grounded in behavioural performance, interpreting these different neurophysiological patterns can be challenging or problematic. While evidence suggests that the bilingual experience might contribute to variation in neural correlates of EF, the degree to which variation reflects an “advantage” per se, is less clear.

An additional limitation that appears in the review and is worth mentioning is the current sample size of the review’s articles. In total, only 37 studies were under review, making the current study size small compared to the extensive literature seen within the bilingual advantage field. I interpret the small sample size as an indication that relatively few studies have directly tested the effects of individual differences on neural correlates of EF. However, it is additionally possible that some references were missed due to the sensitivity of search strategy and databases employed. More empirical studies directly testing associations between individual differences in the bilingual experience and neural correlates underlying EF would create a clearer picture of whether and how certain individual factors such as age of acquisition and L2 usage (in which the research lays divided) might contribute to variation in EF in bilinguals compared to monolinguals.

Lastly, a limitation to be noted is the challenges testing unique effects of individual differences when they are often highly integrated with each other. For example, considering the section on L2 usage, out of the 4 studies described, 2 found null results. However, when tested in

conjunction with another individual difference such as L2 proficiency and age of acquisition, significant differences between groups were observed. This leads to a bit of dilemma as to whether future studies should find methodologies to separate individual differences to test them individually or to study individual differences together with enough statistical power to isolate unique effects of interacting and highly correlated variables. Given that these differences are highly interrelated, it seems that studies either need to find novel ways to isolate features, or to collect large samples with enough statistical power to begin to identify unique effects.

Implications and Future Directions

Patterns of results in the reviewed studies have demonstrated, with some exceptions, that individual differences in the bilingual experience are related to neural correlates of EF. From this, a few implications emerge. Associations between bilingualism and EF have been historically highly variable, leading to disagreements in how this phenomenon is understood. One goal of this systematic review was to shed light on our understanding of some of the sources of individual differences in the bilingual experience that might contribute to variable patterns in the literature. A better understanding of associations between individual differences and neural correlates of EF might contribute to a better understanding of when and for whom EF might be affected by the bilingual experience – and in what ways. Understanding individual differences also helps to provide evidence for how neural systems are shaped by different kinds of bilingual experiences, regardless of whether behavioural differences between bilingual and monolingual participants emerge. It might be the case that bilingual and monolingual brains accomplish similar tasks in different ways. Neural measures might also provide a more sensitive test than many of the behavioural assessments that require explicit responses that can be influenced by many factors. This review hopefully also helps to demonstrate that the bilingual experience is

rich and varied. Future research should move past understanding the phenomenon of bilingualism as a static experience. Rather, bilingualism should be seen as a continuum, to which different experiences might shape neural processes in unique experience-driven ways. There are a few ways that the field can move forward in future studies. First, even if not a primary goal of a study, the study in question should measure and report individual differences in the bilingual experience either descriptively or as a secondary analysis. Future studies should report at the very least, the most common individual differences in the bilingual experience, such as age of acquisition, L2 proficiency, and L2 usage in addition to current age of participant which is always reported. Secondly, as there are pros and cons to each neuroimaging method, studies would do well to use tools such as magnetoencephalography. As an example, combining spatial and temporal imaging devices such as magnetoencephalography to further understand functionality of the brain when taxed on EF abilities. Third, I suggest there be an aim to unify specific uses of certain EF aspects. Namely, determining which EF networks are considered most relevant or likely to give a significant results and then assess them in different ways using different tools. Lastly, the field should strive to test more than one aspect of EF before making statements that indicate the whole system of EF is taxed when only one aspect is tested. As an example, many studies mentioned in this review have only tested their participants on one EF task, usually measuring one aspect of EF (i.e., inhibition or switching). Future studies should include more than one EF task that tests for different aspects of EF such as shifting and working memory or a task that combines multiple aspects of EF as this might affect the results of the study, leading to either inconclusive results or a bilingual advantage being seen. It could be that there are truly differences in EF between bilinguals and monolinguals, however only in one or two aspects rather than general effects across all facets of EF. Or, it could truly be that there are

no ultimate behavioural differences between monolinguals and bilinguals on EF even in the event of the neural results suggesting otherwise. Studies should work to align measures in some way by the type of EF task used, brain regions/networks that are assessed across studies in order to provide a clearer understanding of how and if bilingualism has an effect on the EF network.

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