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Multilingualism and Cognitive Control in the Brain

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Abstract

This chapter examines the impact of multilingual language experience on cognitive control in the brain. Converging evidence reveals that bilinguals' two languages are constantly active, even when only a single language is required. The need to control interference from co-activated languages places unique demands on the cognitive system, with consequences for performance as well as brain structure and function. Despite growing recognition within the scientific community of the variability among multilingual speakers, researchers often continue to designate individuals as monolingual or bilingual even though many speak more than two languages. Indeed, the bilingual designation is often used to encompass a variety of multilingual backgrounds and experiences. We begin with a brief overview of the neuroimaging literature on bilingualism and cognitive control, followed by a focus on three different groups who rely on varying degrees of language control to overcome competition from other languages: third-language learners, multilingual young adults, and simultaneous interpreters. Research on bilinguals who are in the process of acquiring a third language reveals that early stages of language learning produce neural changes in regions underlying cognitive control, whereas studies on multilingual young adults reveal that the effects of language experience may reflect a qualitative difference between monolingual and multilingual processing rather than a cumulative effect of increased linguistic knowledge. Finally, among simultaneous interpreters, changes in gray matter volume and white matter integrity have been found in brain areas associated with language selection and cognitive control, which may reflect increased neural efficiency due to experience with rapid translation. These findings are discussed in light of their potential implications for our understanding of multilingualism and the value of moving beyond the monolingual-bilingual dichotomy. Though the assessment of multilingualism can be challenging

due to significant variability in contextual (home, community, and school or work environment) and individual (proficiency, usage, age of acquisition, and language dominance) attributes, we propose that it is precisely this diversity in language experiences that warrants more directed research of how multilinguals differ, not only from monolinguals, but also among each other.

Multilingualism and Cognitive Control in the Brain

On the island of Aruba, most children become fluent in at least three languages by the time they finish school. Dutch is the official language because the island forms part of the Kingdom of the Netherlands. Spanish is taught in school because of the island's close proximity to Venezuela. English is taught in school due to its status as an international language. The locals of Aruba also speak Papiamento, which is a Portuguese-based creole that is used regularly in the media and government. In this way, multilingualism often emerges as a by-product of a country's history, regional ties, and socio-political context. These are only a few of the many reasons why individuals become multilingual. Other reasons include personal circumstances and relocations, family background and relationships, or individual preferences and interests. For example, a child may become trilingual if the mother speaks one language while the father speaks another, both of which differ from the language of the community. In the European Union, many countries have more than half of its students learning two or more foreign languages at school (Eurostat, 2017), and countries such as Belgium, Singapore, and South Africa have more than three official languages (in fact, South Africa has nine!). Given the prevalence of multilingualism in today's world, an important question that has emerged is whether fluency in additional languages yields effects above and beyond bilingualism alone.

In recent years, scientists and the public have become increasingly interested in the cognitive consequences of multilingualism. At the theoretical level, examining trilingualism contributes to a better understanding of whether the benefits associated with multilingualism emerge as a result of acquiring additional languages (i.e., a shift from monolingual to multilingual), or whether there are graded differences in cognitive function depending on the number of known languages (i.e., larger effects for trilinguals than bilinguals). In terms of practical implications, many individuals can converse fluently in two or more languages, and they often switch between languages within a single conversation. In addition, a number of countries have adopted dual-language programs or immersion programs to promote foreign-language learning. Therefore, research on the cognitive effects associated with learning three (or more) languages has practical implications for policymakers and the education system. We will begin our review with a general discussion of the cognitive consequences of bilingualism and trilingualism, followed by a brief overview of neural plasticity in the bilingual brain. The remainder of the chapter will focus on the structural, functional, and electrophysiological findings from three different groups of multilinguals: third-language learners, young adult multilinguals, and simultaneous interpreters.

Cognitive Consequences of Bilingualism and Trilingualism

A large body of research from language production to word recognition has shown that bilinguals (Blumenfeld & Marian, 2013; Marian & Spivey, 2003a, 2003b; Shook & Marian, 2019; see Kroll et al., 2012 for a review) and trilinguals (e.g., Poarch & van Hell, 2012a; 2014) simultaneously activate all of their languages, even when only a single language is required. When bilinguals encounter a spoken word, lexical entries from the competing non-target language are simultaneously activated. Marian and Spivey (2003a) used the visual-world paradigm to examine lexical competition in monolinguals and bilinguals. Russian-English bilinguals were instructed in English to identify a target (e.g., marker) from a display of four objects, which included a within-language competitor whose English name was phonologically similar to the target (e.g., marble), a cross-language competitor whose Russian name was similar to the target (e.g., *marka*, meaning stamp), and an unrelated object (e.g., spoon). When asked to

"Pick up the marker," Russian-English bilinguals made brief looks to both within-language (marble) and cross-language (stamp/*marka*) competitors even though they were irrelevant to the task, suggesting that multilinguals experience constant interference from their non-target language.

Despite the co-activation of multiple languages, bilinguals rarely commit cross-language errors when communicating (Gollan, Sandoval, & Salmon, 2011; Sandoval et al., 2010). It has been proposed that multilinguals achieve successful communication in the intended language through cognitive control mechanisms (Bialystok, Craik, & Luk, 2012), which are a set of higher-order processes that enable an individual to successfully monitor behaviors and accomplish a desired goal (Badre, 2000). Evidence for this claim comes from neuroimaging studies demonstrating that bilinguals recruit the same areas of the brain for language selection and domain-general executive control (Abutalebi & Green, 2008; Anderson et al., 2018a; Coderre et al., 2016; De Baene et al., 2015; see Luk et al., 2011a for a meta-analysis; see Pliatsikas, 2020; Pliatsikas & Luk, 2016 for reviews). Because of the continuous need to select between co-activated languages, bilinguals may develop a more efficient control system for non-verbal purposes as well (Bialystok et al., 2009). Previous research has shown that bilinguals typically perform better than monolinguals on nonverbal tasks that require inhibitory control, working memory, or attentional control (see Bialystok, 2017; Marian & Shook, 2012 for reviews). However, behavioral effects are less often observed in young adults who are operating at their peak efficiency on relatively simple tasks (e.g., see Paap & Greenberg, 2013; Paap & Sawi, 2014; von Bastian, Souza, & Gade, 2016 for null effects). Thus, in order to gain a clearer understanding of the conditions under which effects of bilingualism emerge, it is necessary to collect detailed information about individuals' demographic and language backgrounds, including experience with more than two languages.

Most studies that examine the impact of language experience on cognitive control continue to designate individuals dichotomously as monolingual or bilingual even though the bilinguals in the sample may speak additional languages. Moreover, the term *multilingualism* varies across studies (Cenoz, 2013). Some scholars refer to *multilingualism* as the ability to speak more than two languages, while others use the term *multilingualism* interchangeably with *bilingualism* in reference to the ability to speak and understand more than one language. Henceforth, the term *multilingualism* will be used in this chapter to refer to individuals who are fluent in more than two languages.

Despite the ubiquity of individuals who speak three or more languages, research on multilingualism (L3/Ln) and cognitive control is scarce. The main reason for this is because multilingualism is a multi-dimensional construct and language development is impacted by many factors, such as level of proficiency, exposure, usage, language typology, and the age of acquisition (Byers-Heinlein et al., 2019; Luk & Bialystok, 2013). The acquisition of each language can occur in different contexts (home, formal education, community), at different ages, and for a wide variety of reasons (personal, marriage, immigration, culture, etc.). Controlling for these variables is already challenging when studying two languages, and adding an additional language increases the complexity of the linguistic profile, especially given that proficiency, usage, and acquisition can also vary across languages. Variations along each factor can not only impact how a particular language is processed, but also the relationship among known languages. For example, a study by Heidlmayr et al. (2014) reported that frequent usage of a third language led to a smaller Stroop effect (i.e., better cognitive control) when using the first language, but not the second language. Refer to Figure 1a for an illustration of the Stroop task.

Research with children and young adults, though limited, suggests that trilinguals show similar advantages as bilinguals on executive function tasks when compared to monolinguals (see Schroeder & Marian, 2017 for a review). For example, Poarch and Van Hell (2012b) asked children between the ages of 5 and 8 who were German monolingual, German-English bilingual, or German-English-L3 trilingual to perform the Simon task (Figure 1b) and Attentional Network Test (Figure 1c). On both tasks, bilingual and trilingual children showed a smaller conflict effect (conflict effect = incongruent trials – congruent trials) than monolingual children, with no differences between the bilingual and trilingual groups. These findings have since been replicated with trilingual children of different ages (8–13 years; Poarch, 2018), learning different languages (e.g., French; Poarch & Bialystok, 2015), and in different contexts of acquisitions (e.g., French-immersion school; Chung-Fat-Yim, Sorge, & Bialystok, 2020). Similar to the effects observed with children, young adult trilinguals have been found to perform equivalently to young adult bilinguals (Madrazo & Bernardo, 2012; Vega-Mendoza et al., 2015). The preliminary behavioral evidence therefore suggests that the number of languages beyond monolingualism does not fundamentally alter cognitive control mechanisms. The gains attributed to multilingualism may be less associated with the number of words that need to be inhibited and more associated with a shift in the overall attentional system that changes as a result of managing at least two languages.

While there is substantial research on the cognitive consequences of bilingualism, there are very few studies that directly examine the relationship between trilingualism and cognitive control at the neural level. Therefore, functional and structural studies on language control are reviewed to make predictions about cognitive control. The degree of language control necessary to overcome lexical competitors from the other languages increases from bilinguals, who must control competition from one additional language, to simultaneous interpreters, who are actively switching back and forth between multiple languages in real time. The final section synthesizes the findings and provides suggestions for future research in the emerging field of trilingualism and cognitive control.

Figure 1 around here

Neural Plasticity in the Bilingual Brain

Neuroplasticity refers to our brains' remarkable ability to form new neural connections and re-organize its neural circuitry in response to the environment. Billions of pathways connecting different parts of the brain are formed every time you think, feel, or execute a response. Over time and through different types of experiences (e.g., learning a new task), these new pathways are strengthened to increase neural efficiency for learning, memory formation, and other forms of adaptation. Old pathways that are no longer used are weakened and eventually pruned. Several experiences have been implicated as factors that can boost cognition through neuroplasticity, including formal education (Kramer et al., 2004), aerobic exercise (Colcombe & Kramer, 2003), musical training (Gaser & Schlaug, 2003; Münte, Altenmüller, & Jäncke, 2002), and bilingualism (Baum & Titone, 2014; Bialystok, 2017). However, unlike other forms of experiences that can only be performed for a finite number of hours per day, bilingualism is unique in that it is a permanent state as we are constantly surrounded by language. Not only do we actively use language to communicate our thoughts and feelings, to read a book, or listen to someone speak, but we also passively use language every time we attach a label and representation to an object. By having to continuously select or deselect a language among other languages, bilinguals are engaging in a special form of mental exercise that has profound consequences for both brain function and structure.

A lifetime of managing attention between multiple languages has been shown to produce neuroplastic changes in brain structure (see Grundy, Anderson, & Bialystok, 2017; Hayakawa & Marian, 2019; Li, Legault, & Litcoftsky, 2014 for reviews). Studies that utilized voxel-based morphometry have found greater gray matter volume for bilinguals than monolinguals in parts of the fronto-parietal network, specifically in the anterior cingulate cortex (ACC) and parietal lobes (e.g., Abutalebi et al., 2012; Abutalebi et al., 2015; Del Maschio et al., 2018; Mechelli et al., 2004). The degree of structural re-organization in gray matter volume is further modulated by second-language age of acquisition and proficiency (e.g., Abutalebi et al., 2015; Mechelli et al., 2004). The primary role of the ACC is to detect instances of conflict and alert the dorsolateral prefrontal cortex to exert top-down control in order to reduce the amount of conflict (Botvinick et al., 1999; Botvinick et al., 2001). The parietal lobes serve as a major language area for comprehension and production by integrating multimodal sensory input from words to motor functions (Brownsett & Wise, 2010). Bilinguals recruit the ACC and the parietal lobes to manage interference from the unwanted language, leading to greater gray matter volume in these brain regions (Figure 2).

In addition to changes in gray matter volume, bilingualism impacts white matter integrity in children (Mohades et al., 2012, 2015), adults (Cummine & Boliek, 2012; Kuhl et al., 2016; Pliatsikas et al., 2015), and older adults (Anderson et al., 2018b; Berkes et al., 2021; Gold et al., 2013; Luk et al., 2011b). Using diffusion tensor imaging (DTI), researchers can measure the rate of water diffusion in the bundle of nerve fibres connecting different parts of the brain (Basser et al., 1994; Pierpaoli & Basser, 1996). One commonly used measure of microstructural integrity is fractional anisotropy (FA). Higher FA values signify faster and more efficient transmission of information between neurons, and thus better white matter integrity. Studies that use DTI have reported greater FA values in the association tracts of the corpus callosum (CC: major connection between the left and right hemisphere), inferior fronto-occipital fasciculus (IFOF: long range associative tract that connects the anterior temporal regions to the temporal-occipital regions of the brain), and the superior longitudinal fasciculus (SLF: associative tract that connects the frontal and parietal lobes) for bilinguals than monolinguals (Luk et al., 2011b; Mohades et al., 2015; Olsen et al., 2015; Pliatsikas et al., 2015; Schlegel et al., 2012). All three white matter tracts play an important role in language processing. While the IFOF has been associated with semantic processing (e.g., Almairac et al., 2015; Motomura et al., 2014), the SLF is thought to be involved in auditory comprehension and articulatory processing (Dick & Tremblay, 2012; Nakajima et al., 2020), as well as in visuospatial attention and working memory (e.g., Curtis, 2006; Kinoshita et al., 2016; Thiebaut de Schotten et al., 2005). The CC integrates information from both hemispheres, such that the additional processing from the right hemisphere leads to better verbal abilities in children (Bartha-Doering et al., 2020) and adults (Chiang et al., 2009; Dunst et al., 2014). However, this pattern of higher FA values for bilinguals than monolinguals is not consistently observed, with some studies reporting either no differences in FA values between language groups (Anderson et al., 2018b), lower FA values for bilinguals (Cummine & Boliek, 2012; Gold et al., 2013; Kuhl et al., 2016), or regional increases or decreases for bilinguals depending on the white matter tract (Mohades et al., 2012). For instance, simultaneous bilingual children who learned both languages from birth had higher FA values in the left IFOF, but lower FA values in the anterior CC that projects to the orbitofrontal cortex, compared to sequential bilingual children who acquired a second language after the age of 3, as well as compared to monolingual children (Mohades et al., 2012). Although some studies show that bilingualism promotes white matter integrity, research in this area is limited and direct comparisons between studies can be challenging due to the variability in approaches used to analyse white matter data.

Studies using functional magnetic resonance imaging have shown different patterns of activation for monolinguals and bilinguals performing a variety of nonverbal cognitive control tasks (Abutalebi et al., 2012; Garbin et al., 2010; Luk et al., 2010; see Pliatsikas & Luk, 2016 for a review). In the flanker task, participants respond to a target arrow that is surrounded by arrows on each side. The surrounding arrows point either in the same direction (congruent trials; ←←←←←) or in the opposite direction (incongruent trials; ←←→←←) as the central target arrow. Luk et al. (2010) found that on the incongruent trials, bilinguals and monolinguals activated different brain networks. Bilinguals relied more on the frontal, temporal, and subcortical regions, while monolinguals activated temporal and parietal regions. Furthermore, on the same task, Abutalebi et al. (2012) reported that bilinguals were more efficient at monitoring for conflict than monolinguals. In the bilingual group, there was a positive brain-behavior correlation, such that faster reaction times were associated with decreased activation in the dorsolateral anterior cingulate cortex. Hence, bilinguals may use fewer resources than monolinguals to achieve similar levels of performance when presented with conflict.

Another set of structures that has been shown to be impacted by language experience is the basal ganglia. The basal ganglia are a cluster of nuclei that include the caudate nucleus, putamen, globus pallidus, subthalamic nucleus, and substantia nigra (Figure 2). Relative to monolinguals, previous work has shown that bilinguals have greater gray matter volume in the caudate nucleus (Zou et al., 2012) and in the putamen (Burgaleta et al., 2016). Greater caudate engagement has been found during language and task-switching (Crinion et al., 2006), while the putamen is thought to be involved in articulatory and motor processes (Abutalebi et al., 2013a). Stocco and colleagues (2014) proposed that the striatum modulates prefrontal cortex activation for language control through feedback loops. The caudate acts as a gateway to the prefrontal cortex based on information from the environment, while the putamen connects to sensorimotor regions and plans for the initiation of a motor response as needed by the frontal regions. As these structures are modified by bilingualism through their repeated engagement with language control, it is possible that such increases in motor and perceptual processes allow the basal ganglia to rely less on top-down frontal regions, leading to more efficient, and thus better performance on cognitive tasks.

Figure 2 around here

Further evidence that bilingualism leads to more efficient use of neural resources comes from electrophysiological studies. Two ERP components that are commonly associated with cognitive control are the N2 and P3. The frontal N2 is often taken as an index of conflict monitoring (van Veen & Carter, 2002; Yeung, Botvinick, & Cohen, 2004) and attentional control processes (Bartholow et al., 2005). Through source localization, the N2 has been previously linked to the anterior cingulate cortex (van Veen & Carter, 2002). The P3 has been proposed to reflect attentional resource allocation during stimulus evaluation (Polich, 2007). For example, on a working memory task, as task difficulty increased, the P3 decreased in amplitude (Kok, 2001). Relative to monolinguals, bilinguals tend to elicit a larger N2 (Fernandez et al., 2013; Moreno et al., 2014; Morales et al., 2015a) and P3 (Barac, Moreno, & Bialystok, 2016; Morales et al., 2015a; Moreno et al., 2014) on various cognitive control tasks. Furthermore, both components tend to occur earlier for bilinguals than monolinguals (Barac et al., 2016; Chung-Fat-Yim et al., 2021). These findings suggest that bilinguals are better than monolinguals at detecting instances of conflict, leading to the recruitment of fewer attentional resources and greater efficiency, as evidenced by the larger P3 amplitude, when evaluating and categorizing a stimulus.

Altogether the findings from neuroimaging studies demonstrate that the bilingual brain is more efficient at suppressing incorrect responses with less recruitment of frontal regions while still achieving similar levels of performance as monolinguals. The electrophysiological studies revealed that bilingualism facilitates the earlier engagement of conflict monitoring and stimulus evaluation processes, which may account for the overall difference in RTs that is often observed between bilinguals and monolinguals (Hilchey & Klein, 2011). Given these neural effects are essentially caused by experience, there is the possibility that neural efficiency will be further impacted with the acquisition of additional languages, as there would be a need to manage attention between three or more languages instead of two.

Third-Language Learners

Third-language learners are in the process of acquiring a non-native language. These individuals have either previously acquired or are in the process of acquiring two other languages, and may therefore require greater cognitive control to manage language interference relative to bilinguals. According to the supply-demand framework described by Schroeder and Marian (2017), cognitive gains emerge when individuals are challenged (but not overwhelmed) by a linguistic task – that is, when the cognitive demands of using a target language and suppressing non-target languages necessitates an increase in the “supply” of cognitive resources. To the extent that learning and managing three languages imposes a greater demand than two languages, trilingualism could be expected to elicit greater changes to the cognitive system than bilingualism. And yet, behavioral measures seem to indicate that the effects of learning a third language are not additive. Rather, it is the knowledge of more than one language that is the modifying variable – both bilinguals and trilinguals outperform monolinguals on cognitive control tasks while performing similarly to each other (e.g., Chung-Fat-Yim, Sorge, & Bialystok, 2020; Poarch, 2018; Poarch & Bialystok, 2015; Poarch & Van Hell, 2012b). The possibility remains, however, that distinct effects of acquiring a third (vs. second) language are detectable at the neural level using more sensitive measures.

In a longitudinal study, Della Rosa et al. (2013) compared multilingual children’s gray matter volume at two time points that were one year apart. The multilingual children were from South Tyrol, a province in northern Italy, and had knowledge of German, Italian, and Ladin, while English was acquired at school. Though the participants could be considered fourth-language learners, it is important to note that proficiency in Ladin was quite low and at a similar level to English. The authors measured each participant’s multilingualism score as well as their performance on the Attention Network Test (ANT). In addition, the interaction of the measures representing the combined effects of cognitive control abilities and language competence were entered into the analysis to predict changes in left inferior parietal lobe (LIPL) gray matter density. The LIPL is thought to be responsible for general attentional processes when focusing on or detecting a target (Singh-Curry & Husain, 2009). The authors found that the increase in gray matter density in the LIPL was associated with better performance on the ANT (smaller conflict effect) and with the degree of multilingualism, such that the more multilingual the child was, the greater the increase in the LIPL.

Even more striking are the findings by Kwon and Lee (2017) who tested Korean-English bilinguals registered in an introductory-level German course and a control group of Korean-English bilinguals on the AX-Continuous Performance Test (AX-CPT) at two time-points while their EEG was recorded. On the AX-CPT, letter strings appear one at a time and participants answer “yes” only when the letter A precedes the letter X (AX-condition). The AX-condition occurs on 70% of trials, building up the expectation that the letter X will most likely appear after the letter A. On another set of trials (AY-condition), the letter A is followed by a random letter, which often primes the participant to incorrectly answer “yes.” In such instances, both proactive (N2 component) and reactive control (P3 component) processes are engaged to suppress the preparatory motor response. In the BX-condition, a random letter is presented followed by the letter X. This condition engages reactive control because participants must inhibit the motor response of answering “yes” every time an X appears. After only 6 weeks of learning German, third-language learners had a larger P3 amplitude on the BX-condition, with no comparable electrophysiological changes in the bilingual control group. Unfortunately, because no analyses were conducted on RT and accuracy, it remains unknown whether the increase in P3 amplitude after training leads to better performance for third-language learners in comparison to bilinguals.

For third-language learners, the effects associated with early-stage language training may first emerge at the neural level, but eventually transfer to behavior once a certain level of fluency has been reached. Similar to Kwon and Lee’s (2017) observations, Sullivan et al. (2014) found that language learning induced electrophysiological changes among English monolinguals taking an introductory Spanish course. EEG measures collected at the start and end of the course revealed that after training, the Spanish-learners had an increase in P3 on a go/no-go task (Figure 1d), while the monolingual control group showed no changes. However, there were no differences in behavior between groups. Therefore, early-stage third-language learning can produce changes in the components underlying cognitive control, but these changes are more likely to be detected at the neural level using more sensitive measures.

Young Adult Multilinguals

Neuroimaging studies on trilinguals typically either attempt to determine whether there is a common neural substrate supporting all learned languages, or they examine the overlap between language selection and executive control. The samples usually consist of a single group of multilinguals or a multilingual group that is split based on a single language factor (e.g., age of acquisition or level of proficiency). To our knowledge, no neuroimaging studies have directly compared the cognitive control processes of bilinguals and trilinguals, but existing research on language representation and language switching can be used to inform predictions about the effect of trilingualism on cognitive control. Table 1 presents a summary of neuroimaging studies on multilingual adults.

Previous studies have shown that multilinguals engage a common set of brain regions when performing various linguistic tasks in their first (L1), second (L2), and third (L3) language (Briellman et al., 2004; Videsott et al., 2010; Vingerhoets et al., 2003). In a neuroimaging study by Vingerhoets et al. (2003), native Dutch speakers, who acquired English and French as foreign languages during adolescence in school, performed a fluency task, a picture naming task, and a reading task in each of their languages. On each linguistic task, the same set of brain regions were activated for all three languages. However, languages learned later (i.e., French and

English) recruited a more widespread set of neural substrates, including left frontal and premotor brain regions. Because lexical access and retrieval of words in the foreign language are less automatic, multilinguals had to recruit additional brain areas, specifically in frontal regions, to avoid interference from the dominant language. In another study, Bloch et al. (2009) demonstrated that the degree of neural overlap when processing different languages varies depending on the age at which the second language was acquired. Multilinguals who acquired their first two languages simultaneously from birth had less variability in activation in Broca's area and Wernicke's area across their three languages, while larger variability was found for both sequential multilinguals, who acquired their second language between the ages of 1 and 5, and late multilinguals, who acquired their languages after the age of 9. The effect of acquisition age appears to be graded, such that among sequential multilinguals, greater variability was found for those who acquired L2 after the age of 9 compared to those who learned the L2 between ages 1 and 5. These findings suggest that language representation in multilingual brains is impacted not only by the timing at which the third language is acquired, but also by the age of second language acquisition.

More widespread activation of brain regions associated with language-control has been observed in bilinguals compared to monolinguals on the flanker task (Luk et al., 2010) and on non-linguistic switching tasks (e.g., Rodríguez-Pujadas et al., 2013; Timmer, Grundy, & Bialystok, 2017). When trilinguals use their foreign languages, there is the possibility that they may also engage a more widespread network of neural substrates and that through repeated use of the third language, they may strengthen the executive control network over time, leading to an increase in cognitive gains for trilinguals compared to bilinguals on cognitive control tasks. In addition to examining how trilinguals process each of their languages, the impact of multilingualism on cognitive control can be informed by examining the neural processes that enable trilinguals to switch between languages.

For multilinguals, language control refers to the cognitive mechanisms required to correctly use the target language while avoiding interference from two or more irrelevant languages. Cognitive control tasks typically have two features that are competing for attention. In many cases, the distractor is more enticing than the target, creating a scenario that requires the need to overcome a strong prepotent response. In both cases, the individual is required to maintain attention on task-relevant information while ignoring irrelevant information. On a language-switching task, Dutch-English-German trilinguals switching into their less proficient languages (English and German) recruited brain areas associated with inhibition, such as the right inferior frontal gyrus and pre-supplementary motor area, as well as cognitive control, such as the anterior cingulate cortex and caudate nucleus (de Bruin et al., 2014). In addition, better inhibitory abilities (i.e., smaller Simon effect) were associated with smaller switch costs into the two less proficient languages. Therefore, proficiency plays a major role in modulating activation in the brain regions associated with cognitive control. Cummins (1976, 1979) hypothesized that in order for a speaker to reap the benefits associated with a second language, they must reach a certain level of proficiency in that language. Although Cummins was referring to the literature on bilingualism, the same can apply to third-language learners. Hervais-Adelman, Egorova, and Golestani (2018) examined the relationship between multilingual experience and subcortical morphology within a group of young adult multilinguals, who were fluent in at least three languages. Multilingual experience was measured by calculating a Language Experience and Proficiency (LEXP) score, which was the weighted sums of the age of acquisition (AoA) and the proficiency across languages. The proficiency, but not the AoA, component of the LEXP was positively correlated with caudate volume. Left caudate activity was similarly found to be moderated by proficiency in a study by Abutalebi et al. (2013b). In this study, switching from a high-proficiency language to a language of equal proficiency (L1 vs. L2) was compared to that of switching into a low-proficiency language (L1 vs. L3). The left caudate was more engaged when switching from L1 into L3. The authors argued that naming pictures in a less proficient language likely elicits significant activation in the caudate nucleus because of the need to inhibit activation from the stronger and more dominant language. Hence, the caudate appears to change as a function of proficiency, such that with increasing proficiency there is a gradual increase in gray matter volume. This is consistent with Grogan et al.'s (2009) finding that bilinguals' gray matter density in the caudate nucleus increased with higher L2 proficiency, as assessed by a phonemic fluency task.

Along with the caudate nucleus, the left putamen is a subcortical structure involved in language processing, specifically in motoric activities like articulation and production (Wise et al., 1999). Abutalebi et al. (2013a) examined whether language control would be associated with greater activation of the left putamen for multilinguals, due to their experience speaking multiple languages and using a wider repertoire of articulatory sounds. Compared to L1 and L2, naming in L3 was associated with greater left putaminal activation. Furthermore, switching into the L3 activated more extended regions of the prefrontal cortex, such as the frontal operculum and anterior cingulate cortex.

In a review paper, Pliatsikas (2020) noted that the sequential acquisition of a third language follows a very similar pattern of structural changes in the brain as those caused by the sequential acquisition of a second language, suggesting that previously-changed regions may need to re-adapt to accommodate new languages. In other words, it is plausible that the number of languages beyond monolingualism may not fundamentally alter neural function, and the critical development may be between knowing one language and knowing more than one language rather than a distinction between two or more than two languages. The alternative, however, remains a possibility. Similar to bilingualism, repeated usage and exposure to the third language may strengthen the brain regions associated with cognitive control (e.g., ACC and DLPFC) leading to more efficient processing on conflict trials for multilinguals than bilinguals. However, this remains an open question because none of the studies to date have explored multilinguals with similar levels of proficiency across all three languages. Future studies should aim to compare multilinguals to bilinguals on language control and cognitive control tasks and include a group of trilinguals who are highly proficient in all three languages. The next section will focus on a unique group of multilinguals, simultaneous interpreters, who have mastered a high level of proficiency in multiple languages and are actively using their languages on a regular basis as part of their profession.

Extreme Language Control: The Case of Simultaneous Interpreters

Interpreters are a unique group of multilinguals who are required to rapidly translate a message from one language to the other in real time. Unlike consecutive interpreters, who wait for a pause in the speech stream before delivering the translated message, simultaneous interpreters translate a message as it is unfolding. Therefore, simultaneous interpreters have the challenging task of synchronously encoding incoming speech from the source language, reformulating the contents of the speech to a lexically, semantically, and syntactically valid form in the target language, and expressing the newly reformulated information into the target language. The cognitive demands elicited by simultaneous interpretation presumably exceeds the demands carried out by everyday language switching, leading to the possibility that such a high degree of language control may yield even larger gains in cognitive control than what is observed between monolinguals and bilinguals. Table 2 presents a summary of neuroimaging studies on simultaneous interpreter trainees and professionals.

As prospective simultaneous interpreters are already expected to have a strong foundation in multiple languages, training generally focuses on improving non-verbal cognitive skills to divide attention between input and output and the efficient use of working memory (Hervais-Adelman, Moser-Mercer, & Golestani, 2015). At the behavioral level, several components of executive function have been examined in simultaneous interpreters and bilinguals. Compared to other bilinguals, simultaneous interpreters often perform better on working memory (e.g., Christoffels, de Groot, & Kroll, 2006; Morales et al., 2015b; Signorelli, Haarmann, & Obler, 2012) and shifting (e.g., Becker et al., 2016; Yudes, Macizo, & Bajo, 2011) tasks. Though some studies have additionally found that simultaneous interpreters have superior inhibitory control (e.g., Dong & Zhong, 2017; Woumans et al., 2015), others have reported no difference compared to other bilinguals (e.g., Babcock & Vallesi, 2017; Morales et al., 2015b). It may be the case that inhibition is less likely to be impacted because, to some degree, interpreters need to keep both languages active. Complete inhibition of one language would make the task of interpreting in real time almost impossible as there would be a constant need to reactivate the language that has been suppressed. Hence, expertise in monitoring speech (i.e., hearing one while speaking another), evaluating consistency between two messages, and mentally shifting between languages may promote not only cognitive advantages in performance, but also neuroplasticity in the brain (see Ferreira, Schwieter, & Festman, 2020; Hervais-Adelman & Babcock, 2020 for reviews).

Neuroimaging studies on simultaneous interpreters can be broken down into two types of studies. The first type of studies examines brain plasticity as a result of intensive simultaneous interpretation training, in which simultaneous interpreter trainees are compared to other multilinguals trained in a non-linguistic field. The second set of studies consists of comparing professional simultaneous interpreters to other multilingual controls.

Hervais-Adelman and colleagues (2015; 2017) investigated brain plasticity that arises from extreme language control by comparing simultaneous interpreters before and after enrolling in an intensive training program to a control group of multilinguals who were not enrolled in the program. Hervais-Adelman, Moser-Mercer, and Golestani (2015) found that when actively interpreting sentences (as opposed to passive listening or shadowing), intensive training led to reduced activation in the right caudate nucleus for the simultaneous interpreters, but not for the controls. The authors concluded that with training, the processes engaged during simultaneous interpreting become more automatic, requiring fewer cognitive resources to effectively carry out the task. Intensive training in simultaneous interpretation also produces increased cortical thickness in brain regions implicated in speech comprehension and production and in a set of brain regions implicated in attentional control, such as the right superior parietal lobe, intraparietal sulcus, and the posterior superior frontal gyrus (Hervais-Adelman et al., 2017). Increased cortical thickness in simultaneous interpreters suggests that a high degree of language control may serve as a protective factor contributing to cognitive reserve. This idea is consistent with literature on multilingualism and cognitive control in older adults demonstrating that multilinguals who practice more than two languages are at a lower risk of cognitive impairment after adjusting for age and education (Perquin et al., 2013).

Studies have also shown that professional simultaneous interpreters and multilingual controls differ in white matter FA tracts (Elmer et al., 2011) and in gray matter volume (Elmer, Hänggi, & Jäncke, 2014). Relative to multilingual controls, simultaneous interpreters had reduced FA in the caudate nucleus, inferior parietal lobe, and the corpus callosum (Elmer et al., 2011), as well as reduced gray matter volume in the left middle-anterior cingulate gyrus, bilateral middle-anterior insula, left supramarginal gyrus, bilateral pars triangularis, and left pars opercularis (Elmer et al., 2014). Note that a reduction in gray matter volume for simultaneous interpreters contrasts with previous research that shows increased gray matter volumes in bilinguals when compared to monolinguals (Della Rosa et al., 2013; Mechelli et al., 2004). Elmer and colleagues (2014) speculated that distinct effects observed for bilinguals (relative to monolinguals) and simultaneous interpreters (relative to multilinguals) may have to do with the developmental stages during which bilinguals' vs. simultaneous interpreters' control mechanisms are "trained." They argue that bilinguals are training their executive functions in childhood, a period when cortical development is increasing, while cognitive demands for simultaneous interpreters tend to emerge in early adulthood when synaptic pruning takes place to promote specialization. Therefore, the intense training in language control may produce synaptic pruning as a means of eliminating inefficient pathways or nerve cells in order to increase efficient processing and specialization. Interestingly, the reduction in gray matter volume was inversely correlated with the number of cumulative hours spent interpreting (Elmer et al., 2014), which is consistent with the findings by Becker and colleagues (2016), who observed greater gray matter volume in the frontal poles for simultaneous interpreters compared to multilingual controls.

Becker et al. (2016) compared simultaneous interpreters to multilingual controls on dual-task and task-switching paradigms. Behaviorally, simultaneous interpreters outperformed the multilingual controls on both tasks. Furthermore, simultaneous interpreters had greater gray matter volume in the left frontal pole, which was more functionally connected to the left inferior frontal gyrus and left middle frontal gyrus, than multilingual controls. Therefore, this greater functional connectivity in the left frontal area is likely what contributes towards better performance on cognitive control tasks among simultaneous interpreters. In another study that examined resting-state EEG signals, Klein et al. (2018) found stronger interhemispheric hyperconnectivity in alpha frequency oscillations between the ventral part of the prefrontal cortex and the dorsolateral prefrontal cortex in simultaneous interpreters compared to multilingual controls. Alpha frequency band oscillations have been shown to be associated with attention, inhibitory control, and working memory processes (Klimesch, 2011; Klimesch, Sauseng, & Hanslmayr, 2007; Wolff et al., 2017). Similarly, Van de Putte and colleagues (2018) found greater connectivity in the frontal-basal ganglia subnetwork for simultaneous interpreter trainees compared to other translators.

In summary, research on simultaneous interpreters suggests that intense language control may be associated with more widespread connectivity between different areas of the brain, as well as with reduced gray matter volume and lower white matter integrity. In addition to the mastery of multiple languages, it is likely that the repeated engagement of attentional control and working memory processes affords simultaneous interpreters with more efficient brains and better cognitive control compared to other bilinguals.

Conclusion

Multilingualism can have pervasive effects on cognition and the brain. Longitudinal studies with third-language learners have revealed effects of language training on cognitive control, as well as on the neural activity and structures that support executive function. In many ways, however, the impact of third language acquisition and processing largely mirror those observed during the acquisition and use of a second language. Relative to using a first language, language processing and control of a second or third language generally result in greater neural activation of frontal regions in areas typically associated with domain-general cognitive control. Structural changes observed during second language acquisition are similarly observed during third language acquisition. The relatively comparable impact of second and third language acquisition on neural activity and structure may be the underlying reason why both bilinguals and trilinguals have been found to outperform monolinguals on cognitive control tasks, and yet do not appear to differ from each other in behavioral performance. Hence, it may be the case that there is a qualitative shift in the attentional system from someone who knows one language to someone who knows more than one language rather than an incremental benefit with each additional language.

This is not to say, however, that no variability is found among individuals who speak at least two languages. Simultaneous interpreters, for instance, often outperform other multilinguals on various cognitive control tasks. Additionally, simultaneous interpreters show reduced gray matter volume and white matter integrity in brain areas that are used for language acquisition and control, including the caudate and anterior cingulate cortex, compared to multilingual controls. It has been hypothesized that the increased demands of frequently switching between languages can lead to more efficient pathways through synaptic pruning and automatization. It is likely the case that neural efficiency and subsequent benefits for behavioral performance are more contingent on how proficiently and intensively known languages are used than on the number of languages acquired.

Research on the neural architecture of trilingualism and cognitive control is still in its infancy. Only a small number of studies have examined cognitive control in speakers who know more than two languages, which means that there are many questions yet to be answered. Based on the very few studies on third-language learners, a recommendation for future studies would be to take a longitudinal approach and trace the development of cognitive control over time in third-language learners, as they are still in the process of mastering their third language. Longitudinal studies provide valuable information not only on the trajectory of language acquisition, but also on the interaction between linguistic abilities and cognitive control abilities, while accounting for intra-individual and inter-individual differences. In addition, assessments of performance and neuroimaging data should be recorded at multiple time intervals to determine whether the effect of learning a third language occurs in a graded fashion with increased proficiency/usage or if a certain level of proficiency needs to be achieved before the effects emerge.

When comparing groups of young adult multilinguals, the focus has been largely on the age of second or third language acquisition or proficiency of each language. Based on the simultaneous interpreter literature (Hervais-Adelman & Babcock, 2020) and the older adult literature on cognitive reserve (Cherkow et al., 2010; Perquin et al., 2013) and cognitive performance (Pot, Keijzer, & de Bot, 2018), one important factor that previous studies on multilinguals often overlooked is the degree of language use and exposure. Professional simultaneous interpreters spend hours of their day switching, monitoring, and selecting among languages. In addition, older adult trilinguals have accrued experience and expertise switching between multiple languages over the years. For example, some older adults were using different languages for work, in the community, and at home and were actively switching between three or more languages on a daily basis. Hence, the key factor may be how often one uses language rather than achieving a certain level of fluency.

Another factor that may moderate the impact of multilingualism is the context in which a third language is acquired and used. In many of the reviewed studies, the third language was acquired at school. However, in some instances, such as the studies in South Tyrol, trilinguals had exposure to multiple languages in the community. If the languages are integrated within the community, there are more opportunities to practice the language, a greater number of interlocutors to speak to, and more instances of language switching. In contrast, languages learned through formal education are typically used in class and require effort to seek out opportunities for use, which leads to potentially fewer incentives and motivation to maintain the language outside of school. A study by Gullifer and colleagues (2018) has shown that greater diversity in social language usage (e.g., work, school, home, etc.) led to greater resting-state functional connectivity between the anterior cingulate cortex and putamen in speakers of two languages. This finding suggests that trilinguals who engage with their languages in multiple contexts, including the community, may be more likely to show greater functional connectivity than trilinguals who use their second or third language in only one facet of their lives (e.g., at work, but not at home). Future studies should examine how the manner of acquisition (formal education, at home, or within the community) and the relative proportion of language use between L1, L2, and L3 affects cognitive outcomes.

For research on the relationship between multilingualism and cognitive control to advance, efforts towards creating an instrument for assessing multilingualism (three or more languages) need to be made. While several instruments have been created over the years, such as the *Language Experience and Proficiency Questionnaire* (Marian et al., 2007), *Language and*

Social Background Questionnaire (Anderson et al., 2018c, 2020), and *Language History Questionnaire* (Li et al., 2014, 2020), reliable and valid measurement tools to quantify multilingualism remain scarce. Other instruments, such as the *Language Exposure Questionnaire* (Cattani et al., 2014) and *Language Exposure Assessment Tool* (DeAnda et al., 2016), were created to measure multilingual language exposure in infants and children, but not in adults. Given the variability in individual language backgrounds, creating an instrument that accurately captures the linguistic profile of those who speak three or more languages in several sociolinguistic contexts around the world is no easy feat. Marian and Hayakawa (2021) note that it is precisely this variability in language background that researchers should capitalize on to gain a more complete understanding of how language experience affects cognition. The reality is that studies vary in the amount of detail provided about the sample under investigation because there is no consensus in the field on how multilingualism should be defined, measured, and reported.

One solution to this problem suggested by the Marian and Hayakawa (2021) is to set a standard practice across laboratories to report on a minimum set of linguistic variables. For example, Byers-Heinlein and colleagues (2019) provided recommendations and descriptions for the participants section in developmental studies with children, which could be similarly implemented in adult studies. With the rise in globalization, not only is a detailed description of the participants necessary, but it may be beneficial for future studies to also provide details about the linguistic landscape in which the data collection took place. The environmental and sociolinguistic contexts of studies examining how bilingualism affects cognitive or neural outcomes matter because the results will need to be interpreted and evaluated within those contexts (e.g., historical, political, and social). The implementation of such practices and guidelines will allow for appropriate comparisons to be made across studies and enhance communication across laboratories.

Another way to promote research on multilingualism across laboratories is to shift towards open science practices by making scientific articles, data, codes, analyses, or processing pipelines freely and publicly accessible to all (Koch & Jones, 2016; Madan, 2017; Stodden, Guo, & Ma, 2013). The Alzheimer's Disease Neuroimaging Initiative (adni.loni.usc.edu), the NIH-based National Database of Autism Research (http://ndar.nih.gov/), and the Federal Interagency Traumatic Brain Injury Research (https://fitbir.nih.gov) are all notable examples of large neuroimaging and genetic databases created to unite researchers who study Alzheimer's disease, autism, and brain injury, respectively. A similar initiative specific to language research may be beneficial to unite researchers who study the neuroscience of bilingualism and multilingualism. The development of an open platform for sharing neuroimaging data from research laboratories around the world will facilitate the rate of discoveries and improve our understanding of how multilingualism in various contexts leads to anatomical and functional changes in the brain.

Recent neuroimaging studies have moved away from the monolingual-bilingual dichotomy by treating bilingualism as a spectrum of individual and contextual attributes. Active bilingualism, as measured by second language usage, proficiency, or exposure, correlates with more efficient functional connectivity when exerting conflict monitoring processes (DeLuca et al., 2020; Gallo et al., 2020) and with neuroanatomical changes in gray matter volume (Sulpizio et al., 2020) and white matter tracts (DeLuca et al., 2019) that support executive functioning. Often, implicit in the statement that "bilingualism is a continuum," however, is the notion that the scale ends with full competence in two languages. Both in theory and in research practice, multilingualism is sometimes ignored or assumed to reflect yet another step along the continuum

(Figure 3). Future research will need to carefully evaluate the assumption that multilingualism is similar to bilingualism, and questions regarding the impact of trilingualism must first be asked and answered before we can truncate the spectrum of linguistic experience to the space between one and more than one language. This can be achieved by continuing to examine the neural correlates of cognitive control in multilinguals who are third-language learners, highly proficient in three or more languages, and those who live in multilingual societies (like Singapore or Switzerland). From there, research in the field can move from whether or not multilingualism affects the mind and brain towards the conditions and diverse language experiences associated with multilingualism that lead to neural adaptations at different stages of development.

Figure 3 around here

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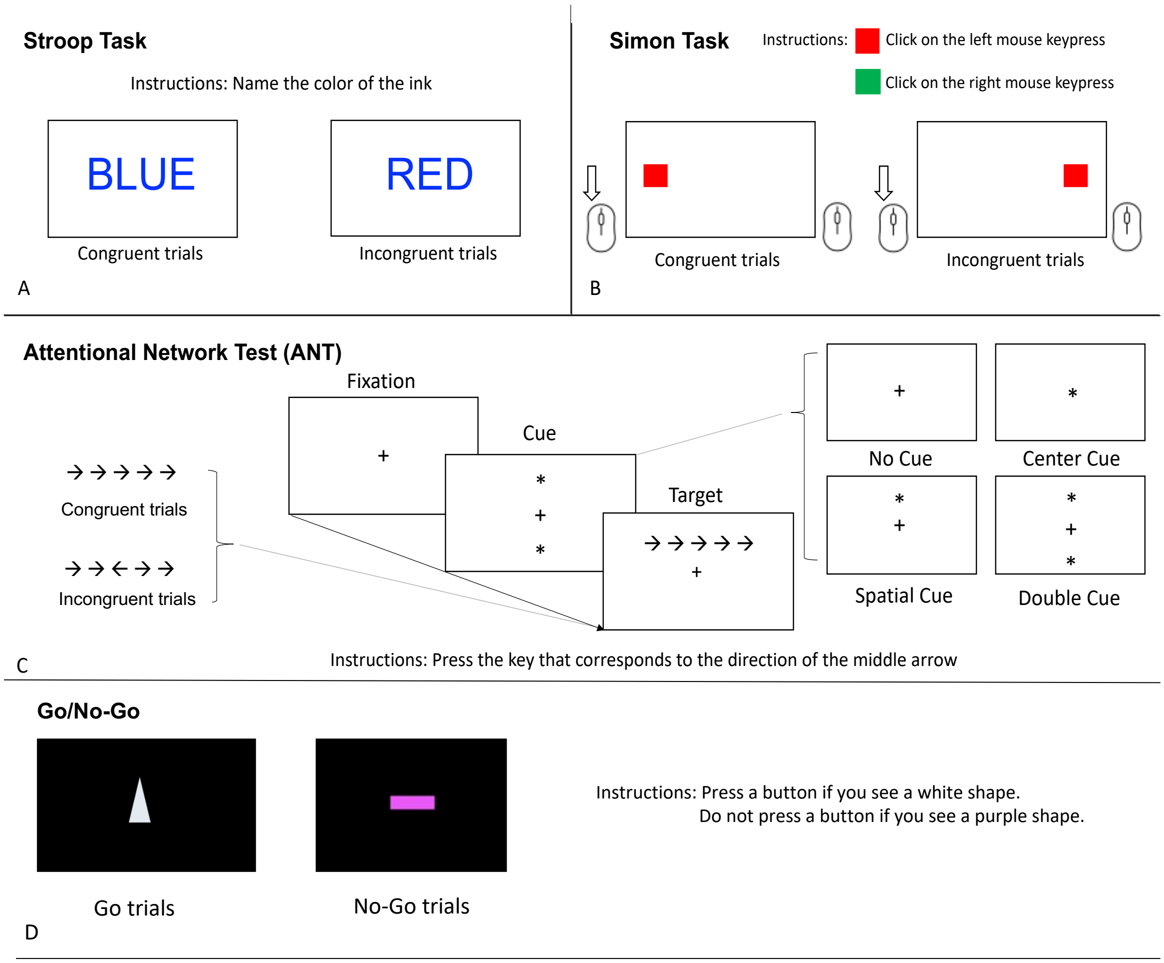

Instructions: Name the color of the ink

Instructions: 🟥 Click on the left mouse keypress
🟩 Click on the right mouse keypress

Instructions: Press the key that corresponds to the direction of the middle arrow

Instructions: Press a button if you see a white shape.
Do not press a button if you see a purple shape.

Figure 1. Schematic of four cognitive control tasks widely used in bilingualism research -- the Stroop Task, Simon Task, Attention Network Test (ANT), and Go/No-Go task. A) In the Stroop task, participants are required to name the color of the ink. On congruent trials, the word and the ink color are the same (i.e., the word “blue” written in blue ink), but on incongruent trials, the word and ink color are different (i.e., the word “red” written in blue ink). B) In the Simon task, participants are instructed to press the left button when a red square appears and the right button when a green square appears. The square can appear either on the same side as the response (congruent trials) or on the opposite side of the response (incongruent trials). C) The ANT includes four different cue conditions (no cue, central cue, double cue, and spatial cue). Participants are required to respond to the direction of the central arrow. The surrounding arrows

either point in the same direction as the central arrow (congruent trials) or in the opposite direction as the central arrow (incongruent trials). D) In the Go/No-Go task, participants are instructed to press a button when a white shape appears (go trial) and to withhold a response when a purple shape appears (no-go trial).

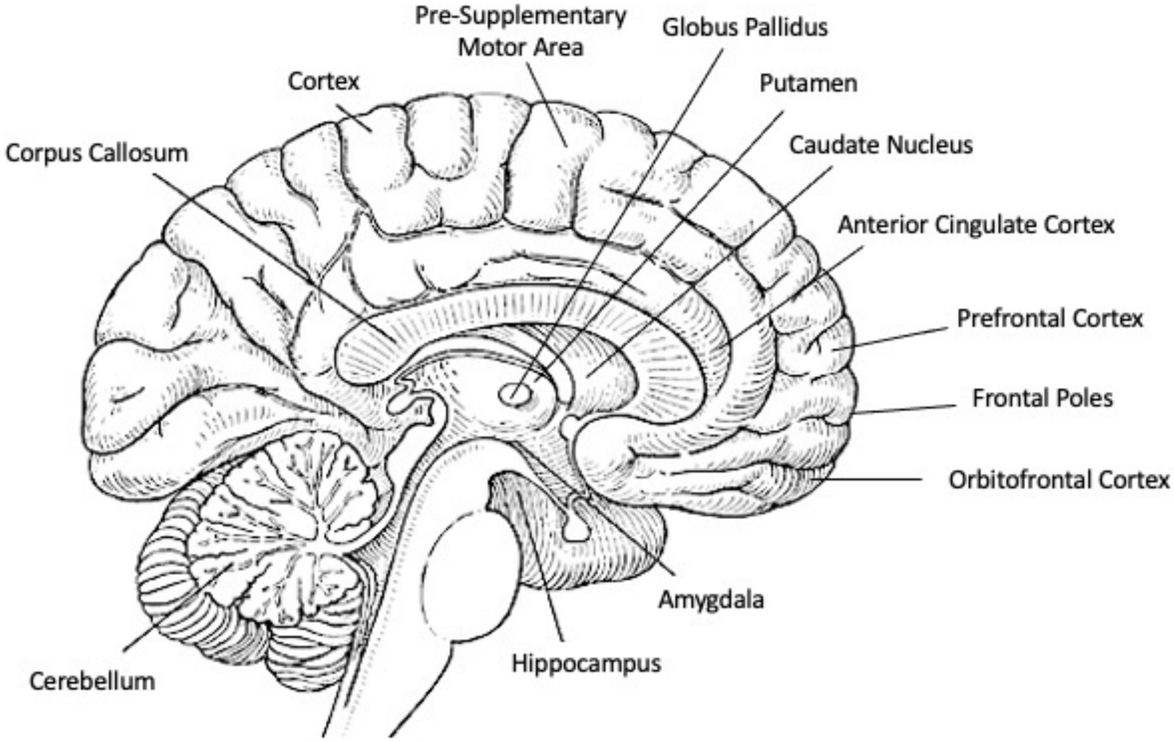

Figure 2. Medial view of the brain regions associated with cognitive control. The cognitive control network includes the prefrontal cortex, orbitofrontal cortex, and anterior cingulate cortex. The basal ganglia are a group of subcortical nuclei that include the globus pallidus, putamen, and caudate nucleus.

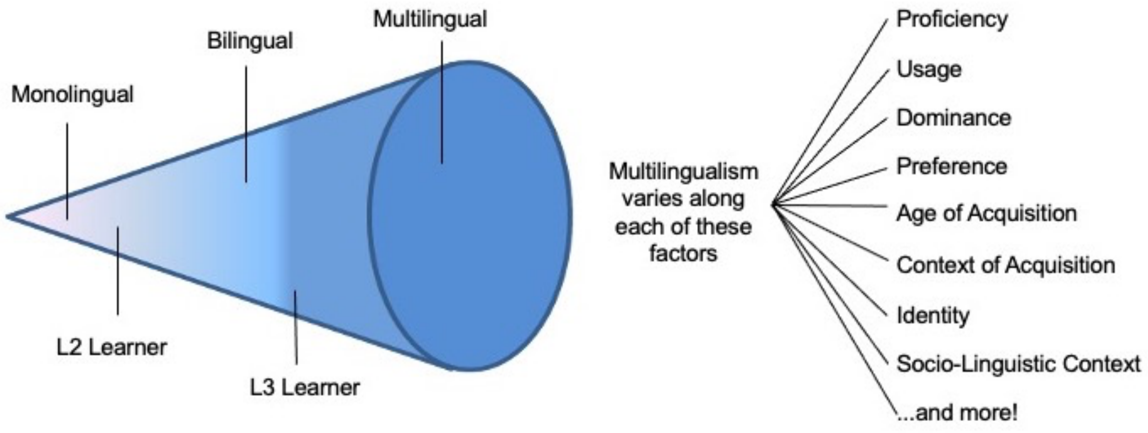

Figure 3. Language experience exists along a multidimensional continuum, with individual variability in proficiency, usage, age of acquisition, and more. As an individual develops fluency in multiple languages, from monolingual to multilingual, there is an increase in complexity along each factor for each additional language acquired.

Table 1.

Summary of Neuroimaging Studies on Multilingual Young Adults

Study	Groups	Age	Mean L2 AoA	Neuroimaging Technique	Functional Task	Measure	Differences
Abutalebi et al. (2013a)	14 German-Italian-English Trilinguals 14 Italian Monolinguals	All participants: 23.4	L2: 6, L3: 8	fMRI	Language Switching	BOLD	-Left caudate: L1 < L2 < L3 -pre-SMA and ACC: M = T
Abutalebi et al. (2013b)	14 German-Italian-English Trilinguals 14 Italian Monolinguals	All participants: 23.5	L2: kindergarten, L3: early	fMRI VBM	Picture Naming	BOLD and GM	-Left putamen: T > M -Left putamen activation: L3 > L1 and L2 -Prefrontal activation: L3 more extended
Bloch et al. (2009)	16 Simultaneous Bilinguals 8 Covert Bilinguals 8 Sequential Bilinguals 12 Late Multilinguals	All participants: 28.0	0 0 1-5 years 9	fMRI	Narration Task	BOLD	-Late multilinguals show more activity for L2 and L3 than L1 -Simultaneous and covert bilinguals exhibit low levels of variability in activation of three languages -Sequential and late show larger variability in degree of activation in three languages
Briellmann et al. (2004)	6 Multilinguals	37.0	Varied	fMRI	Noun-Verb Generation Task	BOLD	-Common neural substrate for all languages -Right frontal regions: Greater activation in lower proficiency languages
de Bruin et al. (2014)	18 Dutch, English, and German Multilinguals	22.2	-	fMRI	Picture Naming task	BOLD	-Right IFG and pre-SMA: Switch into L2/L3 > L1 - ACC, DLPFC, and striatum: L2/L3 > L1
Hervais-Adelman, Egorova, & Golestani (2018)	75 Multilinguals	25.9	-	Vertex-wise	-	GM Volume	-Proficiency component of LEXP more positively correlated with caudate volume than AoA

Kaiser et al. (2015)	24 SiM 20 SuM	27.7 27.8	L2:0; L3:9 L2:2-9; L3: 9	VBM	-	GM Volume	-Bilaterally in the medial frontal gyrus, left IFG, right IFG, right medial temporal gyrus, left inferior temporal gyrus, and right inferior posterior parietal gyrus: SiM < SuM
Videsott et al. (2010)	20 Ladin-Italian-German-English Multilinguals	27.3	L2: 5; L3: 7; L4: 14	fMRI	Word Production	BOLD	-Common neural substrate for all languages -Left IFG and cerebellum: Greater activation in English (foreign language) -Right DLPFC: Ladin > English
Vingerhoets et al. (2003)	20 native Dutch Speakers with English and French as Foreign Languages	27.6	L2: 10.3; L3: 13.5	fMRI	Picture Naming, Reading Comprehension, and Verbal Fluency Tasks	BOLD	-Common neural substrate for all languages -Foreign Languages: Increased activation in left inferior-lateral and medial frontal regions for picture naming and comprehension

Abbreviations. ACC = Anterior Cingulate Cortex; AoA = Age of Acquisition; BOLD = Blood Oxygen Level-Dependent; DLPFC = Dorsolateral Prefrontal Cortex; DTI = Diffusion Tensor Imaging; EEG = Electroencephalogram; FA= Fractional Anisotropy; fMRI = functional Magnetic Resonance Imaging; GM: Gray Matter; IFG = Inferior Frontal Gyrus; L2: Second Language; L3: Third Language; L4: Fourth Language; LEXP = Language Experience and Proficiency; MEG = Magnetoencephalography; SiM = Simultaneous Multilinguals; SMA= Supplementary Motor Area; SMG = Supramarginal Gyrus; SuM = Successive Multilinguals; VBM = Voxel-Based Morphometry.

Table 2.

Summary of Neuroimaging Studies on Simultaneous Interpreters

Study	Groups	Age	Mean L2 AoA	Neuroimaging Technique	Functional Task	Measure	Differences
Becker et al. (2016)	27 SI 23 CI and Translators	42.0 40.9	11.56 12.78	VBM fMRI	Task-Switching and Dual Task	GM Volume	-Left frontal pole: SI > Professional Multilinguals -SI: Greater connectivity from left frontal pole to other nodes (Left IFG and MFG)
Elmer et al. (2011)	12 SI 12 MC	37.8 28.4	All subjects L2: 8-14 L3: 18+	DTI	-	FA Tract	-Caudate nucleus, inferior parietal lobe, and corpus callosum: SI < MC
Elmer, Hänggi, & Jäncke (2014)	12 SI 12 MC	37.8 28.4	All subjects L2: 8-14 L3: 18+	VBM	-	GM Volume	-Left middle-ACC, bilateral pars triangularis, left pars opercularis, bilateral middle part of the insula, and left supramarginal gyrus: SI < MC
Hervais-Adelman, Moser-Mercer, & Golestani (2015)	19 SI Trainees 16 MC	22-32 20-33	-	fMRI	Simultaneous Switching Task: "Listen", "Repeat", and "Switch"	BOLD	-Caudate nucleus: training led to decrease activation in SI, but not controls
Hervais-Adelman et al. (2017)	34 SI Trainees 33 MC	26.0 25.7	-	Cortical Thickness	-	Cortical Thickness	-Right parietal lobule (domain-general EC), right dorsal PMC (working memory), right AG (propositional speech), left posterior STG, anterior SMG, and planum temporale (phonetic processing): SI trainee > MC after training
Klein et al. (2018)	16 SI 16 MC	34.7 34.3	9.4 9.2	Resting-state EEG	-	Functional Connectivity and Source analysis	-Alpha frequency in the left DLPFC, left pars opercularis, and pars triangularis and the corresponding homologues in the right hemisphere: SI > MC
Van de Putte et al. (2018)	18 SI Trainees 18 Translator Trainees	21.4 21.9	9.8 9.5	fMRI DTI	Color-Shape switch, Simon, and verbal fluency tasks	BOLD and FA	-Right AG and left STG: SI Trainee > Translator Trainee in the color-shape switch task and Simon task after training

-Functional connectivity between frontal regions to basal ganglia: SI Trainee > Translator Trainee

Abbreviations. ACC = Anterior Cingulate Cortex; AG = Angular Gyrus; AoA = Age of Acquisition; BOLD = Blood Oxygen Level-Dependent; CI = Consecutive Interpreters; DTI = Diffusion Tensor Imaging; EEG = Electroencephalogram; FA= Fractional Anisotropy; fMRI = functional Magnetic Resonance Imaging; GM: Gray Matter; IFG = Inferior Frontal Gyrus; L2: Second Language; L3: Third Language; MC = Multilingual Controls; PMC = Premotor Cortex; SI = Simultaneous Interpreters; SMG = Supramarginal Gyrus; STG = Superior Temporal Gyrus; VBM = Voxel-Based Morphometry.