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# The Cognitive Science of Bilingualism

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Abstract

Recent research in cognitive effects of bilingualism has generated both excitement and controversy. The current paper provides an overview of this literature that has taken a componential approach toward cognitive effects of bilingualism, according to which bilingual advantages in executive functions are measured in terms of executive control (inhibiting, switching, updating) and monitoring. Findings to date indicate that the presence or absence of bilingual advantages may be influenced by a variety of learner and environmental factors, including the bilingual individual's age, age of acquisition, language proficiency, frequency of language use, and difficulty of the experimental task. The cognitive effects of bilingualism must be interpreted in light of the bilingual's lifelong linguistic experience, which results in adaptive changes in the mind and the brain. We suggest directions for future research in this domain.

## 1. *Introduction*

Bilingualism[1] research has generated much enthusiasm in the study of the mind and brain lately. What has brought bilingualism to the center stage of cognitive science? There may be several reasons, but one key line of research behind the current enthusiasm is the investigation of the cognitive effects of learning and using two or more languages (see a discussion of other reasons Li, 2014). The bilingual brain is a highly adaptive system, and it responds to multiple language experiences flexibly as reflected in the neurocognitive changes (see a recent review by Li, Legault, & Litcofsky, 2014). Although bilingualism comes with costs such as a smaller vocabulary size in a given language (e.g., Bialystok et al. 2010) and slower picture naming (e.g., Gollan et al. 2005), the benefits of bilingualism significantly outweigh such costs. In the past decade, a great deal of research has been devoted to the study of bilingual advantages in non-linguistic cognitive processing, presumably as a result of lifelong bilingual experience. In this review, we focus on bilingual advantages in cognitive processing, especially with respect to executive functions such as inhibitory control and monitoring.

## 2. *Executive Functions: Bilingual Advantages*

The enhancement of executive functions has been reported in the literature as one of the main cognitive effects of learning and using two languages. Such executive functions include the ability to manage a complex set of task demands, to switch attention to goal-relevant information, and to inhibit irrelevant or competing information (e.g., Bialystok et al. 2004; Bialystok et al. 2006; Costa et al. 2008). Different studies may differ in the specific components or processes they include as part of the executive functions. In this paper, we focus on only those functions that have already been carefully studied in the literature: inhibiting, updating, shifting, and monitoring (see Miyake et al. 2000).

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### 2.1. INHIBITING

To test bilingual advantages in inhibiting irrelevant or interference information, researchers have mainly used three non-verbal conflict tasks: the Flanker task (e.g., Costa et al. 2008; De Abreu et al. 2012; Yang et al. 2011), the Simon task (e.g., Bialystok et al. 2004; Bialystok et al. 2005; Martin-Rhee and Bialystok 2008), and the Stroop task (e.g., Bialystok et al. 2008; Egner and Hirsch 2005; Singh and Mishra 2012; Tse and Altarriba 2012). In a typical Flanker task, participants are presented with a series of arrows on a computer screen and asked to indicate the direction of a target arrow occurring in the middle. Participant's response times (RTs) to the congruent condition (i.e., in the series of '> > > > >' or '< < < < <') are generally shorter than RTs to the neutral condition (e.g., '<> <> > <> <>') and the incongruent condition (e.g., '> > < > >'), and RTs to the neutral condition are generally shorter than those to the incongruent condition, which are referred to as the flanker effect. The incongruent condition requires the participant to resolve the conflict between the target arrow and the flanker arrows, that is, to inhibit the responses associated with the direction of the irrelevant flanker arrows while deciding on the direction of the target arrow. In a typical Simon task, participants are instructed to press a key on the right side of the screen when they see a picture (e.g., a red circle) and another key on the left side of the screen when they see a different picture (e.g., a blue circle). Some of the stimuli are presented on the same side of the screen where the correct key is located (the congruent condition), some on the opposite side (incongruent condition), and some in the center (neutral condition). Finally, in a typical color Stroop task, participants are asked to name the print color of a color word (e.g., red, green), and the color can be either congruent or incongruent with the meaning of the word (i.e., the word 'red' printed in red or in green). It has been shown that, for all three tasks, bilinguals, when compared with monolinguals, show smaller RT differences between the incongruent condition and the neutral or congruent conditions, suggesting that bilinguals experience less of a conflict in the incongruent conditions. This type of reduced Flanker, Simon, or Stroop effects for bilinguals has been interpreted as that bilinguals are better at inhibiting irrelevant or conflicting information, therefore having better conflict resolution ability than monolinguals.

Several recent studies and reviews have been unable to find bilingual advantages in non-verbal inhibition tasks (see Hilchey and Klein 2011; Paap 2014; Paap and Greenberg 2013). Below, we present a list of main factors that may modulate the different cognitive effects observed (including the presence and absence thereof), which could help to explain the inconsistent results in the literature. It is worth noting at the outset that these factors are sometimes correlated with one another, and this requires researchers to test their independent and joint contributions in future experiments.

#### 2.1.1. Age

Robust cognitive advantages have been found with children (e.g., Bialystok et al. 2005; De Abreu et al. 2012) and older adults (Bialystok et al. 2008; Bialystok et al. 2004) but not with young adults (Bialystok et al. 2005; Paap and Greenberg 2013; Salvatierra and Rosselli 2010). Even when these advantages are found with young adults, they tend to be moderate in size (Bialystok and Barac 2013). This shows that age is an important factor in modulating bilingual effects. The absence of effects or reduced effects with young adults is probably due to the fact that this age group is at the peak of their cognitive performance, and bilingual experience offers no further boost (Bialystok et al. 2005). A related possibility is that the tasks used are not challenging enough to young adults so that individual differences cannot be revealed (when most participants performing at ceiling level), which brings us to the next factor.

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### 2.1.2. Task Difficulty

The bilingual advantage in conflict resolution may also depend on how difficult the task is. For example, in an article by Martin-Rhee and Bialystok (2008), bilingual children performed more rapidly than their monolingual counterparts in conditions requiring high inhibitory control in the Simon task, whereas in conditions with a long enough delay, both bilinguals and monolinguals were able to resolve the conflict, and therefore, the bilingual advantage disappeared. Other studies have similarly identified the important role of task difficulty, with both young and older adults (e.g., Bialystok et al. 2006). In Salvatierra and Rosselli (2010), for example, older bilinguals (around 61) show a bilingual advantage at inhibiting only under the simple Simon condition (participants responding to either green or red squares that appeared on either the left or right side of the screen, with location as the distracter), not under the more demanding condition (participants responding to four colors instead of two).

### 2.1.3. Language Proficiency

There seems to be a positive relationship between language proficiency and inhibition capacity (Iluz-Cohen and Armon-Lotem 2013). Zied et al. (2004) found that balanced bilinguals at two age groups (younger adults at an average age of 31 years and older adults at an average age of 71 years) responded more rapidly than unbalanced bilinguals in a Stroop task. More recently, Singh and Mishra (2012) found in an oculomotor Stroop task that high-proficiency bilinguals outperformed low-proficiency young adult bilinguals; the high-proficiency bilinguals showed quicker attention orientation toward the correct color patch and had more effective control of the Stroop interference. Tse and Altarriba (2012) also reported similar results, in that L1 and L2 proficiencies of their adult bilinguals were positively associated with the participants' Stroop performance (higher proficiency, less interference, faster RTs, etc.).

### 2.1.4. Age of L2 Acquisition

Age of L2 acquisition has been shown to be an important factor for bilingual cognitive effects. Luk et al. (2011b) found that early bilinguals produced the smallest flanker effect (RT time cost for incongruent trials), while late bilinguals and monolinguals showed no difference from each other. But since early bilinguals had more years of using both languages actively and were more proficient in their L2, one could not identify the unique role of age of acquisition simply based on these results. Tao et al. (2011) also found that their late bilinguals showed more advantage in conflict resolution, which the authors attributed to the fact the late bilinguals were more balanced in the proficiency and usage of their two languages. It seems therefore that age of acquisition, although an important factor influencing the extent of bilingual advantages, may be confounded with years of being actively bilingual, and therefore, it is important for future studies to fully distinguish the contributions of age of L2 acquisition from the amount of experience and the level of L2 proficiency.

### 2.1.5. Frequency of Use

Salvatierra and Rosselli (2010) discussed the role of frequency of use of the two languages: Even late bilinguals may show strong inhibitory advantages if they use their two languages equally often. Carlson and Meltzoff (2008) examined bilingual children who acquired both languages from birth versus those who studied a second language in kindergarten and reported significant conflict resolution advantage for the first group who, presumably, had more exposure to both languages and more frequent use of the two languages. These and other studies indicate that, with more frequent uses of both languages, the bilingual's two languages can be more easily

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activated in parallel, and the bilingual has more needs to inhibit the non-target language, leading to an enhancement of inhibitory control.

### 2.2. SWITCHING (OR SHIFTING)

The similarity between language switching and task switching suggests that bilinguals who switch often between the two languages in their daily life may be better at non-verbal switching tasks. A typical switching task is the color-shape task as used in Prior and MacWhinney (2010) and Paap and Greenberg (2013), in which the participants decide on either the color (e.g., blue vs. red) or the shape (e.g., square vs. triangle) of the object presented. In pure color or shape blocks, participants are asked to decide on only the color or only the shape of the presented objects (e.g., press 'X' if the object is red), whereas in mixed blocks, they will be prompted with a cue (e.g., a rainbow for color or a circle for shape) to make either a color or a shape decision. A trial is designated as a 'repeat' if the cue in the trial is the same as that in the previous trial and a 'switch' if it is different. The RT difference between repeat trials and switch trials in the mixed block is taken as an indicator of 'switch cost', and the RT difference between repeat trials and pure trials is taken as an indicator of 'mixing cost'. Prior and MacWhinney (2010) found a bilingual advantage in switch cost, but not in mixing cost, suggesting that bilinguals are better at switching. By contrast, Paap and Greenberg (2013) did not find a bilingual advantage for either type of cost. Table 1 presents a summary of these and other studies.

Table 1 illustrates several factors that may contribute to bilingual advantages in switching or mental set shifting, factors that also play important roles in bilingual advantages in inhibiting that was discussed above. Soveri et al. (2011) examined these factors by using a multiple regression analysis of data from the performance of a group of 30- to 75-year-old Finnish–Swedish bilinguals on tasks measuring inhibition, switching, and updating. They found that younger age, earlier L2 acquisition, more frequent language switch experience, and a more balanced use of both languages were all associated with smaller mixing costs.

#### 2.2.1. Age

In addition to Soveri et al. (2011) who identified the importance of age of participants for magnitude of mixing costs, Gold et al. (2013) found that older bilinguals showed reduced switch cost, whereas young adult bilinguals did not, and this pattern is consistent with the age effect shown in studies of bilingual advantages in inhibitory control, as discussed above.

#### 2.2.2. Frequency of Language Switching

Prior and Gollan (2011) found that the Spanish–English bilinguals showed less switch costs when compared to the Chinese–English bilinguals; the latter group switched less frequently between their two languages on a daily basis. The importance of language switching experience was also identified in the article of Yudes et al. (2011), in which simultaneous interpreters who frequently switched between languages outperformed bilinguals and monolinguals on the Wisconsin Card Sorting Test, a task that requires switching between three dimensions: color, shape, and number.

#### 2.2.3. Task Difficulty

The first experiment by Hernandez et al. (2013) involved two cued conditions: implicit cue and explicit cue. The explicit cue indicated explicitly when participants needed to change the rule (i.e., 'COLOR' or 'SHAPE'), whereas the implicit cue, which was more difficult, only prompted the participants with a sign (i.e., the sign '∽' indicating switch to the other rule or

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**Table 1. Summary of major studies of bilingual advantages in switching.**

| Study | Participants' mean age (years) | Frequency of language switching | Task difficulty | Switch cost advantage | Mixing cost advantage |
|---|---|---|---|---|---|
| Garbin et al. (2010) | 21.5 (Spanish–Catalan bilinguals) | Regularly (early bilinguals switching between the two languages) | Color–shape switch with explicit cues | Error rate: yes<br>RT: no | n/a |
| Gold et al. (2013) | 32 (younger group)<br>63 (older group) from mixed language backgrounds | Regularly (balanced bilinguals speaking both languages on daily basis since age 10 years or younger) | Color–shape switch with explicit cues | Younger group: no<br>Older group: yes | n/a |
| Hernandez et al. (2013) Experiment 1 | 20 (Spanish–Catalan bilinguals) | Regularly (switching on average 4.7 on a 7-point scale) | Color–shape switch with either implicit or explicit cue | Restart cost:* yes in implicit cue version<br>Local cost: no | n/a |
| Hernandez et al. (2013) Experiment 3 | 20 (Spanish–Catalan bilinguals) | Regularly (switching on average 4.8 on a 7-point scale) | Color–shape switch with explicit cue | No | No |
| Paap and Greenberg (2013) | College students from mixed backgrounds | Regularly (switching daily, and speaking L2 English about 70% of the time) | Color–shape switch with explicit cue | No | No |
| Prior and Gollan (2011) | 20 (Spanish–English and Chinese–English bilinguals) | Switching on average 3.2 between Spanish and English; 2.4 between Chinese and English on a 5-point scale | Color-shape switch with explicit cue | Spanish–English: yes<br>Chinese–English: no | No |
| Prior and MacWhinney (2010) | 18.5 (college students from mixed language backgrounds) | 73% of time speaking L2 English, with both languages learned before 6 years | Color–shape switch with explicit cue | Yes | No |
| Soveri et al. (2011) | Finnish–Swedish bilinguals of various ages from 30 to 75 years | Various frequency of language, contextual, and unintended switching | Number–letter switch with implicit cue | No | Correlated with age, L2 onset age, and everyday use of both languages |

*Note: see end of this section for a discussion of the 'restart cost' vs. 'local cost'.

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the sign '≀' indicating repeat of the previous rule). A bilingual advantage in shifting was found only in the implicit but not the explicit cue condition, and this pattern is consistent with the effect of task difficulty shown in studies of bilingual advantages in inhibitory control, as discussed earlier.

#### 2.2.4. Language Proficiency

Iluz-Cohen and Armon-Lotem (2013) found that language proficiency modulated for both shifting and inhibition abilities for bilingual preschool children. As for shifting, the more proficient children (e.g., balanced and L2-dominant groups) significantly outperformed the less proficient children (e.g., L1-dominant and low-proficiency groups). The modulating effect of language proficiency, however, in some cases, may be less important than other factors such as frequency of language switching, at least for young adults. Dong and Xie (2014) found that, in the Wisconsin Card Sorting Test, there was no difference between young adult bilinguals of different L2 proficiency, but there were significant differences between groups with different amount of interpreting training.

Finally, Hernandez et al. (2013) attempted to identify the mechanisms underlying the bilingual advantage in task switching. These authors distinguished 'restart cost' (longer RTs for the first trial after a repeat cue than for the second trial after a repeat cue) from 'local cost' (longer RTs to the first trial after a switch cue than to the first trial after a repeat cue). They found a bilingual advantage in restart cost but not local cost in their implicit cue condition of the color–shape switch task, suggesting that bilingualism affects the process of reactivating stimulus-response mappings but not the process of reconfiguring stimulus-response mappings.

### 2.3. UPDATING

As part of executive control, updating – the continuous monitoring and quick addition or deletion of contents within the working memory, sometimes also referred to as working memory updating – has also been assumed to be modulated by bilingual experience. However, not much research has been done regarding this function in the literature, probably because of its less recognized relationship with the learning or using of two languages. One exception was Soveri et al. (2011), who conducted regression analysis with data from a single group of bilinguals and found that older bilinguals (compared with younger ones) made more errors in the N-back task, a task in which participants are required to remember the location of previous stimuli, for example, the location of the stimulus before the current one ('1-back') or the one before the previous one ('2-back'). The result indicates that the efficiency of executive control decreases in older age and thus suggests that it is possible to find a bilingual advantage in updating in the elderly. The N-back task has been typically regarded as a working memory task in the literature, and the absence or presence of a bilingual advantage in working memory updating and the relationship between the N-back task and other working memory tasks await further research.

### 2.4. MONITORING

Apart from executive control as described above, learning or using two languages may also produce an advantage in cognitive monitoring. Monitoring, according to Costa et al. (2009), can be operationally defined as the ability to handle tasks that involve mixed trials of different types. The hypothesis of a bilingual monitoring advantage is that bilinguals, as compared with monolinguals, would be more efficient at going back and forth between mixed trials that require conflict resolution. Due to more efficient monitoring, bilinguals, as compared with monolinguals, will thus have an advantage shown as reduced global RTs (e.g., Costa et al. 2009; Hilchey and Klein 2011).

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Monitoring may be an essential part of executive control since bilinguals need to monitor the two languages constantly in order to control the use of them. But monitoring seems to work for the entire process of executive control, not at the same level as inhibiting, switching, or updating. In this perspective, monitoring may be dissociated from executive control per se. As Hilchey and Klein (2011) pointed out, although evidence for bilingual advantages in inhibiting, switching, or updating is not always reliably found, bilinguals consistently show reduced global RTs (e.g., in both congruent and incongruent trials in the Flanker task), which can be attributed to bilinguals' better ability to monitor the executive process. Kroll and Bialystok (2013), in their holistic analysis of bilingual advantages, also maintained that monitoring, as reviewed by Hilchey and Klein (2011), may be a more reliable aspect of bilingual advantages.

The bilingual advantage in monitoring most probably 'comes from the need for monitoring which language to produce in each communicative conversation' (Costa et al. 2009: 144). Because of the massive experience and practice with this need, bilinguals become efficient with conflicting tasks that require the work of monitoring. This view has at least three implications: (1) the bilingual is faster with both congruent and incongruent trials in mixed conditions (see data from Costa et al. 2008); (2) in experiments that have only or mostly (e.g., 92%) congruent or incongruent trials, bilingual advantages would disappear (see data from Bialystok et al. 2006; Costa et al. 2009); and (3) bilingual advantages on the incongruent trials, compared with the congruent trials, would disappear after prolonged practice. In the third experiment of Bialystok et al. (2004), the bilingual advantage found in the first part of a long experimental session (10 consecutive blocks of 24 trials in the Simon task) disappeared in the last part of the session, and the differences between incongruent and congruent stimuli in the last part became minimal.

### 2.5. SUMMARY

It seems widely recognized that the learning and using of multiple languages leads to stronger executive functions, but such bilingual advantages are not always found in every experiment. Part of the reason for the absence of bilingual advantages in some studies is that modulating factors such as task difficulty, age, and language history (e.g. age of L2 acquisition, language proficiency, and frequency of use, which may be correlated with each other) can play important roles, as discussed above. For example, the failure to find bilingual advantages with young adults in some studies may be due to the participants' age (e.g., college students who may be at the peak of their executive processing). Or the tasks used in some studies may not be challenging enough. In general, as pointed out by Hilchey and Klein (2011) and Kroll and Bialystok (2013), bilingual advantages do exist when a more holistic approach is taken.

Finally, there are two relationships between bilingualism and other cognitive abilities that have not been directly discussed above. First, the relationship between bilingualism and intelligence has been identified in some studies, which is likely to be mediated by an inherent relationship between intelligence and executive functions, as many of the non-verbal IQ tests also involve executive functions (see Wechsler 1997: WAIS-III). For example, Ardila et al. (2000) found that switching correlated with WAIS scores. Salthouse et al. (2003) found that inhibiting, switching, and updating in executive control correlated with fluid intelligence in aging adults. Leikin (2013) also found that early bilingualism influenced children's general and mathematical creativity to some extent, and balanced early bilinguals showed more creativity in problem solving. Second, the relationship between bilingualism and working memory has also been discussed in the literature, although discussion of this relationship has focused more on how working memory correlates with L2 proficiency and processing rather than with bilingual advantages (see reviews in Linck et al. 2013; Miyake and Friedman 1998). Again, this relationship may be due to the inherent relations between working memory (especially updating) and

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executive control, as discussed earlier. For example, Morales et al. (2013) found that the bilingual advantage in working memory was especially evident when a task contains additional executive function demands, such as the task that requires the child to hold rules in mind to press a response key and ignore distractions or irrelevant competing information.

## *3. Bilingual Processing and Representation: Sources of Bilingual Advantages*

The effect of bilingual experience on cognitive processing is unique and important in that it reflects often a lifelong experience that results in a cross-domain effect, as compared with most other short-term, cognitive, experiences that typically result in a single-domain enhancement due to training. Action videogame players, for example, respond faster and more accurately than non-players (Dye et al. 2009), but it has been a matter of debate whether the outcome of the gaming experience involves enhancement of general cognitive abilities. The bilingual experience seems to bring about an overall change to the mind and the brain in both the language domain and the more general domain of cognitive processing (Kroll and Bialystok 2013).

### 3.1. BILINGUAL PROCESSING IN THE MIND

Bilingual advantages in general-domain cognitive processing as described above must be a result of language processing that are unique to bilinguals' learning and using of both languages. One important discovery in the literature has been the finding of language-independent activation (i.e., non-selective activation of items from both languages; see a recent review in De Groot 2013). Selection from two jointly activated languages requires inhibition of the non-target language during the bilingual language production and recognition processes, as suggested by the Inhibitory Control Model (Green 1998) and the Bilingual Interactive Activation (BIA+; Dijkstra and van Heuven 2002) Model. Bilingual experience may thus be able to enhance cognitive control, due to the similarities of monitoring, switching, updating, and inhibiting processes involved in both the linguistic and non-linguistic domains, as discussed earlier. It seems also a quite reasonable hypothesis that only an enhanced domain-general executive control ability can manage a lifetime experience in monitoring, selecting, and controlling multiple languages that may be simultaneously active and competing in the bilingual mind.

With regard to the effects of domain-general, non-linguistic, and executive functions, some researchers have highlighted the overall effects of bilingualism for cognitive processing, while others have asked where in the bilingual process a given processing advantage (e.g., inhibition) occurs. Colzato et al. (2008), for example, have tested a proposal that bilinguals may not be necessarily good inhibitors but may be good at goal maintenance. The hypothesis is that bilingual language selection is made possible mainly through 'reactive inhibition' (local inhibitory connections) instead of 'active inhibition' (general global inhibition of the non-target language). In connectionist network terms, this means that effects of bilingualism occur in specific connection patterns across layers of units, rather than the involvement of all active units in the entire network for supporting the inhibitory mechanism (see Li and Zhao 2013; Zhao and Li 2013).

### 3.2. NEURAL REPRESENTATION IN THE BRAIN

It has been suggested that the bilingual experience may lead to a reconfiguration of not only the mind but also the brain (see a review in Bialystok et al. 2012). Abutalebi (2008) and Abutalebi and Green (2007) reviewed a number of neurocognitive studies and suggested that a network of cortical and subcortical structures in the left hemisphere may be responsible for bilingual language monitoring and control. Specifically, a frontal-posterior circuit involving the prefrontal

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cortex (PFC), the anterior cingulate cortex (ACC), and the inferior parietal cortex (IPL) are implicated in monitoring, selecting, and inhibiting one or the other language during bilingual language comprehension and production. The PFC is related to high-level executive functions, many of which are discussed above, including working memory updating, switching, and response inhibition, while the IPL is involved in lexical acquisition, goal maintenance, and phonological storage. The ACC is highly important for conflict monitoring and attentional control. In addition to the above cortical structures, the subcortical structures (e.g., caudates and putamen) are also critical to switching between and selection of multiple languages. These areas may also map onto the executive control components as discussed, although there are no one-to-one correspondences and there are clearly overlapping functions of different brain areas. In general, these different areas may form an integrated neural circuit for cognitive control.

In a more recent fMRI study comparing bilinguals with monolinguals in overt picture naming and reading aloud, Parker Jones et al. (2012) focused on five brain regions in the left inferior frontal and temporoparietal regions that are important for language production in bilinguals as compared with monolinguals. These are the PTr (*pars triangularis*), POp (*pars opercularis*), PrC (*dorsal precentral gyrus*), STG (*superior temporal gyrus*), and PT (*planum temporale*). Both the PTr (and to some extent the adjacent insula) and POp are engaged in modulating the competition between two languages, but the former is more dedicated to the control of interference from the other language and for ensuring correct word selection, while the latter is more involved in the control of articulatory sequences once a word is selected. The PrC is not associated with control of interference per se but more with actual articulation of words, and the high activation of this area along with activations in the STG and PT suggests that bilinguals, compared with monolinguals, may need to recruit these areas more heavily for articulatory output and post-articulatory monitoring. In short, while PTr and POp activities reflect increased demand on the process of word retrieval, selection, and control for bilinguals, PrC, STG, and PT activities reflect higher demands on articulation and auditory-motor interaction.

Finally, there is also increasingly more evidence that bilinguals, perhaps as a result of learning and using multiple languages, develop more neural substrates at a structural/anatomical level, in addition to the functional brain changes discussed thus far (see a recent review in Li et al. 2014). This may be reflected as increased gray matter density or volume in the brain's critical control regions, including the dorsal anterior cingulate cortex (Abutalebi et al. 2012), the inferior parietal cortex (e.g., Della Rosa et al. 2013; Mechelli et al. 2004), and the temporal pole (Abutalebi et al. 2014). Moreover, Luk et al. (2011a) reported increased white matter integrity (e.g., stronger connectivity from anterior to posterior cortical areas) in older bilinguals (i.e., 70 years old) as compared with their monolingual counterparts. This enhanced connectivity of white matter may be a basis for the bilingual advantage, especially the neural basis of a 'cognitive reserve' for older bilinguals. It is also important to note that while most of the aforementioned studies were correlational in nature, some recent studies have attempted to use longitudinal designs to examine the causal links between L2 learning and brain changes. For example, Della Rosa et al. (2013) tracked multilingual children for 1 year and identified gray-matter density changes in the inferior parietal cortex. Mårtensson et al. (2012) examined neural structure changes in interpreter trainees for 10 months and were able to observe neural changes in the interpreter as compared with non-interpreter students across the same time period (e.g., increased cortical thickness in left inferior and middle frontal gyri, left superior temporal gyrus, along with increased hippocampal volume in the right hemisphere). In short, according to Li et al. (2014), the evidence so far from bilingual neuroimaging studies indicates a picture highly consistent with neuroplasticity observed in other domains: bilingual experience-induced brain changes, including increased gray matter density and white matter integrity, can be found

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in children, young adults, and the elderly; can occur rapidly with short-term training; and are sensitive to age, age of L2 acquisition, L2 proficiency or performance level, language-specific characteristics, and individual differences.

## *4. Conclusion*

The bilingual's experience of learning and using multiple languages may be unique because it is extensive, long-term, and brings an overall change to not only how linguistic tasks are carried out but also how nonlinguistic tasks are performed, resulting in an enhancement of both linguistic and domain-general nonlinguistic functions (e.g., Bak et al. 2014). The bilingual experience leads to positive changes in both the mind and the brain, and in both the function and the structure of the brain. Although specific patterns of bilingual advantage are subject to debate, enough evidence has accumulated to motivate us to carry on research in this domain and to study neuroplasticity as a result of learning and using a new language. In this short review, we have identified the role of a set of learning and input factors such as the bilingual's age, task difficulty, and language history (e.g. frequency of language use, age of acquisition, and L2 proficiency) and pointed out how these factors and their interactions may jointly influence measurements of bilingual versus monolingual performance in executive functions. While our review has focused on specific components of executive functions such as inhibiting, switching, updating, and monitoring, we are mindful that a more holistic approach needs to be taken to examine bilingualism (Kroll and Bialystok 2013). Finally, we suggest that it is important to examine not only the cognitive effects as consequences of bilingualism but also the mechanisms and locus of these effects reflected in the bilingual mind and the bilingual brain. A significant direction for future research is to identify the causal relationship through longitudinal studies of bilingual experience and the corresponding neurocognitive and neuroanatomical changes. As a final note for future research, we should also attempt at an understanding of the cognitive science of bilingualism by studying not only the cognitive effects due to bilingual experience (i.e., bilinguals compared to monolinguals) but also individual differences in cognitive effects due to the same type of experience (i.e., bilinguals compared with bilinguals).

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## *Short Biographies*

Yanping Dong is a professor of Applied Linguistics, a deputy director of the National Center of Linguistics and Applied Linguistics, and a director of the Bilingual Cognition and Education Lab. Her research interests are in the psycholinguistics of bilingualism.

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## Notes

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[1] We use 'bilingualism' or 'bilingual' here to refer to both bilingual (two languages) and multilingual (more than two languages) situations.

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