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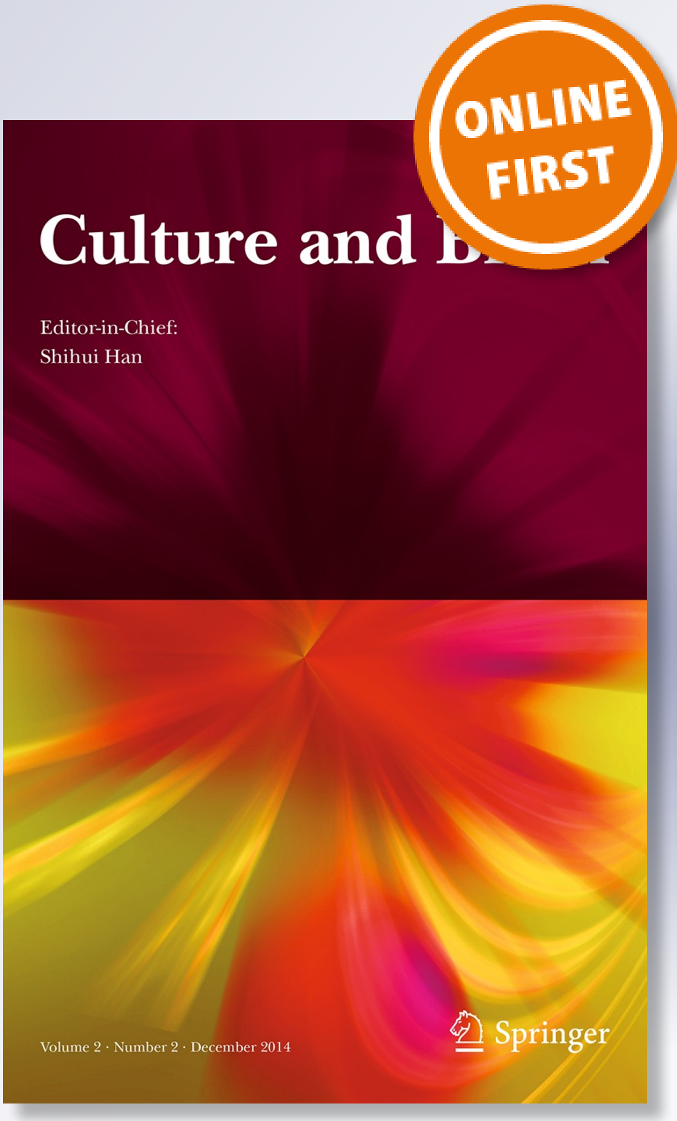

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ORIGINAL RESEARCH

Bilingualism, executive control and neuroplasticity

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Abstract The beneficial effects of bilingualism on executive functions have been shown through studies that demonstrated the outperformance of bilingual individuals than monolingual individuals in cognitive tasks involving attention, working memory and conflict resolution. However, the neural mechanisms of how bilingualism influence these cognitive processes remains unclear. In addition, there is a considerable amount of diversities and inconsistencies in the link between bilingualism and executive control, which altogether require a thorough discussion. In this paper, we will provide a concise and informative mini-review of how one cultural experience—bilingualism influences executive control and explore the underlying brain mechanisms that reveal the relationship among bilingualism, executive control and neuroplasticity. Furthermore, how bilingualism could benefit other important aspects of regulatory processes through interacting executive control are also discussed.

Keywords Bilingualism · Executive control · Neuroplasticity · Emotion regulation

Introduction

As globalization gradually becoming a dominant trend in recent decades, multilingualism is common in the majority of world's population due to cross-cultural communication that often involves using more than one language to interact with other people in daily life. In 2011, about one-fifth of the populations in the

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United States were bilinguals, and this number is still continuously increasing each year (Bialystok et al. 2012). Being bilingual is a cultural phenomenon that not only helps communication, but also has crucial cognitive implications well beyond basic language functioning. For instance, studies have shown bilingual individuals outperformed monolingual individuals in cognitive tasks that involve attention, control, working memory and conflict resolution. In particular, these differences are especially evident at older ages (Marian and Shook 2012). Both functional and structural MRI have revealed differences between the bilingual brain and monolingual brain in neural activity and networks while performing tasks and structural connectivity that persists throughout the life time (Gold et al. 2013). Moreover, bilingualism has been associated with the delay onset of symptoms of dementia and its subtypes independent of socioeconomic factors when compared with monolingualism (Alladi et al. 2013). These results all suggested that bilingualism may induce neuroplasticity that fosters a cognitive reserve, which could potentially combat age-related declines and may have further impact on other related regulatory processes (Gold et al. 2013).

Executive control

One prominent regulatory function of the human brain is executive control. Executive control regulates cognitive processes and supports activities such as high level thought, multi-tasking, and sustained attention (Bialystok et al. 2012). Overall, bilinguals across all ages have notably better executive control than monolinguals when matched in age and other background factors (Marian and Shook 2012). In a set of studies that involved children performing a Simon-type task that manipulated working memory demands or a visuospatial span task that manipulated other executive function components, it was found that bilingual children outperformed monolingual children in both reaction time and accuracy (Morales et al. 2013). Another study has found that adult bilinguals are more efficient in the alerting and executive control networks when performing the Attentional Network Task (ANT), and are also better at resolving conflicting information, as demonstrated by the shorter reaction time (Costa et al. 2008). Moreover, in a separate experiment using perceptual task, bilingual older adults have shown better task-switching performance than their monolingual peers while displaying decreased activation in left lateral frontal cortex and cingulate cortex, a brain activation pattern resembled that of younger adults for the same task (Gold et al. 2013).

However, it should be noted that bilingualism does not influence every aspect of executive control. Additionally, some of the bilinguals' advantages seem to be task dependent and do not exemplify significant differences when contrasted with monolinguals from various age groups. According to the literature, inhibitory control can usually be enhanced by bilingual experiences, since speaking more than one language often requires the ability to suppress other languages except the currently preferred language (Colzato et al. 2008). In a set of experiments, Colzato and colleagues compared the differences in inhibitory control between bilinguals and monolinguals through examining three phenomena including stop signal performance, inhibition of return, and the attentional blink. It was found that monolinguals and bilinguals did not differ in stop signal reaction time, but bilinguals showed no facilitation from spatial cues, had a strong inhibition of return effect and exhibited a more pronounced attentional blink. Based on these results, the authors concluded that bilingualism does not necessarily improve active inhibition, but have fostered a better ability to maintain action goals and to use them to bias goal-related information, which may indirectly lead to more significant reactive inhibition of irrelevant information (Colzato et al. 2008). Another review delineated the validity of bilingual advantages in inhibitory control through assessing the performance of bilinguals and monolinguals in nonlinguistic interference tasks from eight studies (Hilchey and Klein 2011). Notably, the authors suggested that bilinguals typically outperform monolinguals on both compatible and incompatible trials by similar magnitudes, suggesting bilinguals do generally have more cognitive advantages than monolinguals. However, the bilingual advantages in interference effect in young adult populations are often unstable and appear only briefly in the beginning of trials and then subsequently vanish. Yet, these advantages can be surprisingly significant in middle-aged and elderly adults (Hilchey and Klein 2011). Overall, the bilinguals' advantages in inhibitory control can best be characterized as equivocal and may not be apparent in traditional assays of nonlinguistic inhibitory control processes.

Neuroplasticity

Cultural effects across different populations are evident in both behavior and brain. Specifically, these experience-dependent influences are typically examined in the context of neuroplasticity. In the case of bilingualism, studies on brain structure have shown that although white matter integrity decreases with age in adulthood, lifelong bilingualism can result in the maintenance of white matter integrity in the corpus callosum extending to the superior and inferior longitudinal fasciculi measured by fractional anisotropy (FA) compared to monolinguals in older adults (Luk et al. 2011). These results suggested that the mechanism underlying advantages in the better performance of executive functions in bilinguals may be due to their differences in brain functional activation and structural connectivity.

In the case of cultural experiences, previous studies have indicated the distinctive cognitive process between people from Eastern and Western culture (Nisbett and Masuda 2003; Tang et al. 2006), indicating that East Asians tend to examine information in a holistic way, while Westerners incline to process information analytically, possibly due to the collectivist versus individualistic biases (Nisbett and Masuda 2003; Nisbett and Miyamoto 2005). When performing tasks that involve contextual judgment, Westerners often have longer reaction time than East Asians, since Western population tend to focus more on object-related information than contextual ones. Further investigation has shown that Westerners have greater neural activities in frontal, parietal and occipital areas than East Asians. At the same time, Westerners also showed greater suppression of the default network under these high demanding cognitive challenges, suggesting a possible coping mechanism

(Goh et al. 2013). Another study focusing on structural contribution to cognitive processing has revealed the underlying differences between East Asians and Westerners in cortical thickness and found that young Western adults have thicker cortex in several regions of frontal, parietal and medial-temporal polymodal association cortices in both hemispheres (Chee et al. 2011). In addition, western high-performing elderly in cognitive tests have greater thickness in frontal and right inferior temporal areas than Eastern elderly, suggesting possible neural underpinnings for analytic cognitive processing, especially when the engagement of frontal regions are often associated with analytical thinking and reasoning. Thus, sustained cultural experience can potentially shape cognitive processing through altering brain structure in the same way as how bilingualism induces functional and structural connectivity changes in the brain to influence cognitive functioning.

Diversity

The majority of research studies on bilingualism have primarily focused on English versus other languages, and only a few literatures have compared less ubiquitous languages and their influences on cognition and neuroplasticity. Some of the findings that are discussed in this review range from Latin root languages such as English and Spanish to Eastern languages such as Hindi and Arabic (Alladi et al. 2013; Costa et al. 2008; Gold et al. 2013; Morales et al. 2013). It would be nice to see more comprehensive studies involving diverse languages and comparing the various contributions to cognition and neuroplasticity. Furthermore, the cultural differences and unique background underlie each language may also contribute to the diversity in cognitive performance that has been shown in most findings on bilingualism. It should be noted that different language structure could potentially play a role in aspects of cognition. For instance, study has demonstrated a differential cortical representation of numbers between native Chinese and English speakers. Specifically, native English speakers largely employs a language process that relies on the left perisylvian cortices for mental calculation such as a simple addition task, whereas native Chinese speakers engage a visuo-premotor association network for the same task. This is likely due to the fact that different biological encoding of numbers may be shaped by visual reading experience during language acquisition and other cultural factors such as mathematics learning strategies and education systems, which cannot be explained completely by the differences in languages per se (Tang et al. 2006). Therefore, future research should take such cultural factors into account to fully explain the observed bilingual advantages in different experimental tasks and designs. Another important issue that needs to be considered is the possible influence of multilingualism on cognitive functions and brain plasticity. Most studies limited the comparison to only two languages and sometime treat multilingualism as same as bilingualism. Given the previous example of research that indicates the large variance between two languages when performing simple arithmetic task, it is very likely that other languages could also show similar differences and may further complicate the research on bilingualism and cognitive function when more than two languages are spoken by the same individual.

Therefore, the diversity of languages and their cultural background could result in considerable variation among bilingual or multilingual populations and may affect aspects of cognition such as numerical processing or other cognitive functions reside in the human brain. The field of bilingual research would benefit from more studies that include a large sample size with individuals from different cultural and language background, and thoroughly examine the differences that exist among different combination of languages.

Emotion regulation

While most of the research studies have focused on the effects of bilingualism on executive control in younger and aging population, little is known about its potential influence on other areas that rely on cognitive control, such as emotion regulation.

Emotion regulation is often thought to be related to the capacity of control, which involves the initiation of new or the alteration of ongoing and emotional responses through the action of regulatory processes (Ochsner and Gross 2005). Studies have examined emotion regulation from the scope of automatic bottom-up processes (triggered by emotionally aroused stimuli) and top-down control processes (activation in prefrontal cortical area) (Gyurak et al. 2011). Specifically, attentional control is often involved in the top-down control processes that include diverting and selecting attention from emotional stimuli and thereby regulating emotional response and monitoring internal emotional state (Viviani 2013). This form of voluntary cognitive control closely associates with aspects of executive control that involve attention and attention disengagement, and consistently activate frontal brain regions such as the anterior (middle) cingulate cortex, superior temporal gyrus, and angular gyrus, and also cortical and subcortical emotion-generative systems in emotion regulation tasks (Kohn et al. 2013). Similar brain areas have also been found during bilingual switching between languages and related executive control processes (Bialystok and Craik 2010). Functional MRI results have shown that language switching is accompanied by activation in the dorsolateral prefrontal cortex (DLPFC), an area known to be part of the general executive control system (Hernandez et al. 2001). Later studies have revealed distributed activation pattern involving bilateral frontal regions, precentral areas, caudate and temporal regions in bilinguals during language switching. In particular, the anterior cingulate cortex (ACC) was shown to be critical for both language switching and nonverbal switching, and was also a pivotal region previously identified as a main component in executive control (Bialystok et al. 2012). Therefore, it is not difficult to observe this convergence of brain activation in the frontal regions related to bilingual language switching, executive control and emotion regulation.

Overall, the frequent participation of frontal brain regions in executive control, emotional regulation and bilingualism hints the possibility of a shared brain mechanism of these three processes. In particular, given that bilingualism requires task switching to accomplish the alternation between languages, a process that involves aspect of attention disengagement, and that attention disengagement is also a key component in the top-down control process of emotion regulation, it is possible that bilinguals may be more efficient in emotion regulation than monolinguals and could induce better cognitive control through convergent functional and structural connectivity in the brain. Future research warrants the further investigation.

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