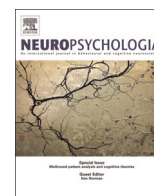




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Bilingualism alters brain functional connectivity between “control” regions and “language” regions: Evidence from bimodal bilinguals

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ABSTRACT

Previous neuroimaging studies have revealed that bilingualism induces both structural and functional neuroplasticity in the dorsal anterior cingulate cortex (dACC) and the left caudate nucleus (LCN), both of which are associated with cognitive control. Since these “control” regions should work together with other language regions during language processing, we hypothesized that bilingualism may also alter the functional interaction between the dACC/LCN and language regions. Here we tested this hypothesis by exploring the functional connectivity (FC) in bimodal bilinguals and monolinguals using functional MRI when they either performed a picture naming task with spoken language or were in resting state. We found that for bimodal bilinguals who use spoken and sign languages, the FC of the dACC with regions involved in spoken language (e.g. the left superior temporal gyrus) was stronger in performing the task, but weaker in the resting state as compared to monolinguals. For the LCN, its intrinsic FC with sign language regions including the left inferior temporo-occipital part and right inferior and superior parietal lobules was increased in the bilinguals. These results demonstrate that bilingual experience may alter the brain functional interaction between “control” regions and “language” regions. For different control regions, the FC alters in different ways. The findings also deepen our understanding of the functional roles of the dACC and LCN in language processing.

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1. Introduction

Language processing in bilinguals is more complex than monolingual language processing. It has been reported that for bilinguals, either for unimodal bilinguals who use two spoken languages (Colomé, 2001; Hatzidaki et al., 2011; Kroll et al., 2006; Wu and Thierry, 2012), or for bimodal bilinguals who use a spoken language and a sign language (Emmorey et al., 2005; Petitto et al., 2001), the language not in use is automatically co-activated and competes with the target language (the one in use) during language production. Given less exposure to and use of each of the two languages, bilinguals also display linguistic disadvantages compared to monolinguals (Bialystok, 2009; Bialystok and Feng, 2011; Gollan et al., 2008; Michael and Gollan, 2005). They are found to be slower in lexical access and reach at a lower level of proficiency even for their

native and dominant language (Bialystok and Feng, 2011; Gollan et al., 2005; Ivanova and Costa, 2008). Accordingly, bilinguals may require more cognitive demand to monitor and manage language processing, to inhibit the non-target language and to facilitate the language in use (Costa and Sebastian-Galles, 2014; Crinin and Price, 2006; Green and Abutalebi, 2013).

From the perspective of neural processing, language production in bilinguals involves participation and cooperation of brain regions for language processing, including the inferior frontal gyrus (Broca's area) and superior temporal cortex (Wernicke's area) (Hickok and Poeppel, 2007; Indefrey, 2011; Price, 2010), and those for language control such as the dorsal lateral prefrontal cortex, dorsal anterior cingulate cortex (dACC¹) and subcortical regions

¹ Abbreviations: L1=first language; L2=second language; CSL=Chinese sign language; FC=functional connectivity; ReHo=regional homogeneity; ROI=region of interest; dACC=dorsal anterior cingulate cortex; LCN=left caudate nucleus; STG=superior temporal gyrus; RolOp=rolandic operculum; PCG=precentral gyrus; MTG=middle temporal gyrus; SMA=supplementary motor area; IPL=inferior parietal lobule; SPL=superior parietal lobule; ITO=inferior temporo-occipital part.

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like the left caudate nucleus (LCN) (Abutalebi and Green, 2007; Crinion and Price, 2006). Previous neuroimaging studies have revealed neuroplasticity at several regions as a result of lifelong bilingual experience (Abutalebi et al., 2012; Grogan et al., 2012; Klein et al., 2014; Li et al., 2014; Mechelli et al., 2004; Stein et al., 2012; Zou, Ding et al., 2012). For example, the study by Abutalebi and colleagues revealed that the dACC of bilinguals functioned more efficiently in a flanker task than monolinguals (Abutalebi et al., 2012), while Zou and colleagues' study found that the gray matter volume in the LCN of bimodal bilinguals was increased as compared to monolinguals (Zou et al., 2012). Notably, these regions are suggested to be responsible for language control (Abutalebi and Green, 2007; Green and Abutalebi, 2013), and they should not function independently, but should function interactively with other brain regions responsible for language processing (Abutalebi et al., 2009; Green and Abutalebi, 2013; Price, 2010). Despite the fact that the role of dACC and LCN in bilingual language processing have been extensively discussed (see the review by Green and Abutalebi (2013)), functional interaction between both regions with language regions is poorly portrayed. Particularly, we hypothesize that lifelong bilingual experience may have substantial effects on the functional interaction among these regions. The present study aimed to address this issue. We examined the group difference of the functional interaction of relevant brain regions between bilinguals and monolinguals for revealing the effects of bilingualism.

As to the role of the dACC in bilingual language processing, it is proposed to initiate language production, and to monitor the conflict arising within and between languages (Abutalebi and Green, 2007; Price, 2010). The dACC is constantly activated to a larger extent when the tasks either create a conflicting situation (Abutalebi et al., 2008), or induce competition from the non-target language (van Heuven et al., 2008). It is also strongly engaged when bilinguals switch between languages compared to non-switching in language production studies (Abutalebi et al., 2012) as well as in more ecological settings such as the perception of language switches during the listening of narratives (Abutalebi et al., 2007). The critical role of LCN is likely to select the target language, particularly when the target language is less proficient (Zou et al., 2012). Several lesion studies found that the patients with damaged LCN could not voluntarily select the target language (Aglioti et al., 1996; Aglioti and Fabbro, 1993), and be easily interfered by the language not in use when speaking (Abutalebi et al., 2000; Abutalebi et al., 2009; Marien et al., 2005). In a recent neuroimaging study with trilingual participants, the LCN was shown to be activated to the largest extent when switching into the least proficient language (Abutalebi et al., 2013), suggesting its crucial role in selecting and learning a new-acquired language (Tan et al., 2011). These evidences indicate that bilinguals rely more on the engagement of the dACC and LCN (as compared to monolinguals) that eventually help bilinguals to handle the tough situation of language conflicts and linguistic disadvantage.

For unimodal bilinguals, both spoken languages activate similar or largely overlapping language regions in inferior frontal gyrus and superior temporal cortex, even though they are from distinct language families (Chee et al., 1999; Chee et al., 2003; Perani and Abutalebi, 2005; Simos, 2005). It may be, hence, more difficult for unimodal bilinguals to separate the neural substrates of languages and likewise to calculate the functional interaction with the dACC and LCN for each language. Bimodal bilinguals provide a unique perspective for this issue of functional interaction (Emmorey and McCullough, 2009; Zou et al., 2012). Bimodal bilinguals acquire their languages and achieve linguistic skills similarly to unimodal bilinguals, as suggested by studies on bilingual children and adults (Emmorey et al., 2005; Petitto et al., 2001). However, the brain regions engaged by a spoken language and a sign language are not

necessarily overlapping because of the different modalities of languages used, with sign language more relying on activation of parietal and tempo-occipital regions (Emmorey et al., 2008; Emmorey and McCullough, 2009; Korzeniewska et al., 2011; MacSweeney et al., 2002; Zou et al., 2012). Although bimodal bilinguals can use their two languages simultaneously, the engagement of language control and facilitation is still demanding because the two languages differ in grammar and are less proficient compared to monolinguals (Emmorey et al., 2005; Zou et al., 2012). More importantly, a previous study with bimodal bilinguals has found neuroplastic changes in the LCN, suggesting that bimodal bilingual experience does, indeed, affect the brain (Zou et al., 2012). Therefore, the use of bimodal bilinguals in the present study may provide us a useful tool to unravel the effect of lifelong bilingualism on the functional interaction of each language and how "control" regions functionally interact with "language" regions.

Functional interaction can be measured with functional connectivity (FC) by calculating how the responses or activities of two brain regions correlate with each other either when carrying out a task or during a resting state (Biswal et al., 1995; Friston et al., 1993). Here we explored the differences of FC in bimodal bilinguals compared to monolinguals with both task-related fMRI and resting-state fMRI. For the task-related fMRI, brain images were collected when the participants named pictures in their first language (L1). This allowed us to study the functional interaction between control regions (e.g. dACC and LCN) and language regions of bilinguals when these neural substrates are potentially engaged to perform a specific language task. Given their disadvantages for each language and more demand of control processes in single-language context, such as goal maintenance and interference control (Bialystok, 2009; Gollan et al., 2008; Green and Abutalebi, 2013), we expected the functional interaction of control regions and language regions to be different for bilinguals as compared to monolinguals. For the resting-state fMRI, brain images were collected when the participants did not perform any specific task. Unlike in the language task, bilinguals have no need to handle conflicting situations (typically observed during language production) during resting state, and hence, allowing us to obtain basic or intrinsic FC (the FC in resting state is often referred to as intrinsic FC) within a certain brain network (Cordes et al., 2000; Dosenbach et al., 2008).

2. Material and methods

This study included two fMRI scanning sessions, a task-related fMRI scanning during picture naming and a resting-state scanning. The present study was approved by the local ethics committee and carried out in compliance with its guidelines.

2.1. Participants

Twenty-seven participants took part in the task-related fMRI scanning, including 14 highly proficient bimodal bilinguals (3 male; mean age 49, from 33 to 65) whose native language was Mandarin and second language (L2) was Chinese Sign Language (CSL), and 13 monolingual peers (3 male; mean age 48, from 31 to 67) with comparable educational and socioeconomic backgrounds. The bimodal bilinguals acquired CSL late in life (mean age 19), and self-rated it as very proficient (mean=4.5 on a scale of 1–5, 1 means not proficient, and 5 means very proficient).

Twenty-nine participants took part in the resting-state scanning, including 14 high proficient bimodal bilinguals (4 males; mean age 49.5, from 36 to 61) and 15 matched monolinguals (5 males; mean age 43.54, from 29 to 56). Among them, 7 bilinguals and 6 monolinguals also took part in the task-related scanning.

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