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Simultaneous learning of two languages from birth positively impacts intrinsic functional connectivity and cognitive control

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ABSTRACT

This study explores the effect of individual differences in the age of acquisition of a second language using resting-state functional magnetic resonance imaging (rs-fMRI) to examine functional connectivity and its relation with cognitive control within bilinguals. We compared simultaneous bilinguals, who learned two languages from birth, to sequential bilinguals, who learned a second language following mastery of their first language. Results show an effect of language experience on the strength of anticorrelation between the default mode network and the task-positive attention network and on cognitive control, with simultaneous bilinguals demonstrating stronger anticorrelations between the two networks, as well as superior cognitive control compared to sequential bilinguals. These findings demonstrate that the timing of language learning may have an impact on cognitive control, with the simultaneous learning of two languages being associated with more optimal brain connectivity for cognitive control compared to sequential language learning.

1. Introduction

It has now been well documented that language experience has an impact on the brain and that being bilingual may positively affect cognitive control processes (e.g., Bialystok, Craik, & Luk, 2012; Costa & Sebastian-Galles, 2014), but what aspect of the bilingual experience exerts an influence is still a matter of debate. Bilingual language experience has been related to changes in brain structure and function in terms of white matter integrity (e.g., Luk, Bialystok, Craik, & Grady, 2011; Pliatsikas, Moschopoulou, & Saddy, 2015), cortical thickness (e.g., Klein, Mok, Chen, & Watkins, 2014; Mårtensson et al., 2012), gray matter density (e.g., Berken, Gracco, Chen, & Klein, 2015; Mechelli et al., 2004) and functional activity in various brain regions (e.g., Berken, Gracco, Chen, Watkins, et al., 2015; Kovelman, Baker, & Petitto, 2008). Although the majority of studies have compared bilinguals to monolinguals, some have shown differences within bilingual groups themselves, with factors such as age of second language acquisition (AoA) or language proficiency exerting an influence on brain organization.

In bilinguals, AoA has been found to be related to cortical thickness such that earlier AoA has been associated with thinner cortex in the left inferior frontal gyrus (IFG) and thicker cortex in the right IFG, although in this study language proficiency was not held constant (Klein et al., 2014). In another study, simultaneous and sequential bilinguals, who were matched in terms of second language (L2) proficiency and differed only with respect to their accent in L2, were found to have differences in gray matter density (Berken et al., 2015); however, only limited behavioural measures were considered, making it difficult to interpret the exact role of specific brain regions in relation to bilingual language experience. A recent fMRI investigation in sequential bilinguals has also shown that AoA was related to the degree to which brain regions associated with speech-motor control and orthographic to phonological mapping were activated to a greater extent in L2 compared to L1 while reading (Berken, Gracco, Chen, Watkins, et al., 2015). Others have found that AoA is related to patterns of brain activation during lexical retrieval (Perani et al., 2003) and speech processing (Archila-Suerte, Zevin, & Hernandez, 2015) in an L2. AoA of an L2 has also been related to the laterality of language organization, with a meta-analysis showing that early bilinguals (AoA before 6 years old) show bilateral language organization as compared to late bilinguals who showed left hemisphere dominance for language (Hull & Vaid, 2007). Different EEG patterns during language processing tasks have also been related to AoA (Genesee et al., 1978). Taken together, these findings demonstrate the impact of different language experiences, namely AoA, on brain structure and function as well as language organization – a conclusion also reached by Hull and Vaid (2007).

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To date, most studies have focussed primarily on brain structural measurements and task-related brain activity in order to examine the effect of different language experiences on the bilingual brain. More recently, people have looked to resting-state functional magnetic resonance imaging (rs-fMRI) as it can identify task-independent effects of language experience on brain function and connectivity. Resting-state fMRI is a measure of spontaneous low frequency (< 0.1 Hz) fluctuations in the blood oxygen level-dependent (BOLD) signal while the brain is not engaged in an external task (i.e., at rest) (Cordes et al., 2001). Using rs-fMRI, functionally connected brain regions have been found to show correlated spontaneous low frequency fluctuations in the BOLD signal over time (e.g., Biswal, Zerrin Yetkin, Haughton, & Hyde, 1995; Hampson, Peterson, Skudlarski, Gatenby, & Gore, 2002; Smith et al., 2009). In terms of bilingualism, greater functional connectivity and a more distributed pattern of connectivity has been observed in bilingual as compared to monolingual older adults (Grady, Luk, Craik, & Bialystok, 2015; Luk et al., 2011). A correlation between rs-fMRI and AoA has also been shown, with greater functional connectivity between the left and right inferior frontal gyri and the inferior parietal lobule being associated with earlier AoA (Berken, Chai, Chen, Gracco, & Klein, 2016), although again no additional behavioural evidence was provided to interpret these findings in terms of cognitive control directly.

The current investigation importantly, moves away from a comparison of bilinguals to monolinguals, which, as has been previously noted by others, is a potentially problematic confound given that bilinguals have variable language experience (e.g., Kaushanskaya & Prior, 2014; Luk, 2015; Luk & Bialystok, 2013). We focus more specifically on different groups of bilinguals to determine what aspect of the bilingual language experience might have an effect on brain organization and cognitive control. Using both rs-fMRI and behavioural measures of cognitive control we examine whether the timing and manner in which the L2 is learned has implications for language-experience related differences at the level of the brain and behaviour. We do this by comparing equally high proficiency bilingual individuals who differ in whether they learned both of their languages simultaneously or learned their L2 sequentially, following mastery of their native language. Thus, the question is whether the simultaneous exposure and learning of two languages exerts different influences on brain organization and cognitive control than sequential exposure and use of two languages. In other words, does setting up the language system for two languages from birth have different implications in terms of brain organization and cognitive control than learning an additional language later, using the neural architecture of the already established language?

Previous research has used a variety of tasks to investigate language group differences in cognitive control, including primarily the Stroop task (e.g., Bialystok, Craik, & Luk, 2008; Bialystok, Poarch, Luo, & Craik, 2014; Kousaie & Phillips, 2012; Kousaie & Phillips, 2017; Kousaie, Sheppard, Lemieux, Monetta, & Taler, 2014), the flanker task (e.g., Abutalebi et al., 2012; Kousaie & Phillips, 2012; Kousaie & Phillips, 2017), and the Simon task (e.g., Bialystok, 2006; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok et al., 2008; Kousaie & Phillips, 2012; Kousaie & Phillips, 2017; Kousaie et al., 2014). However, findings of language group differences have been variable within and across tasks, and it has been shown that these different tasks show little convergence suggesting that observed effects of language group may be task-specific (see Paap, Johnson, & Sawi, 2015). In the current investigation we chose to use the Simon task because it is a non-verbal cognitive control task that has previously been shown to be sensitive to differences between monolinguals and bilinguals and the inclusion of the three conditions in the Simon task used here allows for a calculation of different measures of cognitive control (described in more detail in the Methods).

In terms of rs-fMRI and cognitive control, research has demonstrated that the resting brain is intrinsically organized in two opposing, or anticorrelated networks, one demonstrating task-related increases in activation (task-positive attention network) and the other showing task-related decreases in activation (task-negative or default mode network; DMN) (Fox et al., 2005). Furthermore, and of particular relevance to the current investigation are studies showing that variations in the degree or strength of anticorrelation between these two networks are related to performance of executive function tasks. Specifically, greater anticorrelations between the DMN and the attention network have been associated with more stable performance on a flanker task (Kelly, Uddin, Biswal, Castellanos, & Milham, 2008), as well as better working memory performance (Hampson, Driesen, Roth, Gore, & Constable, 2010; Keller et al., 2015).

Here we use rs-fMRI to detect language experience-related differences in intrinsic connectivity within the bilingual brain. Specifically, we explore the relationship between the DMN and the task-positive attention network, how this relationship differs as a function of L2 language learning experience, and how this relationship is related to cognitive control. Based on previous research showing that the degree of anticorrelation between the DMN and task-positive network is related to cognitive control (e.g., Kelly et al., 2008) and that AoA impacts brain structure (e.g., Berken et al., 2015; Klein et al., 2014), function (e.g., Archila-Suerte et al., 2015; Berken, Gracco, Chen, Watkins, et al., 2015; Perani et al., 2003), including rs-fMRI (Berken et al., 2016), and organization (Hull & Vaid, 2007), we hypothesized that if AoA has an impact on the development of these brain networks related to cognitive control then: (1) the simultaneous exposure and acquisition of an L2 would be associated with stronger anticorrelation between the two resting state networks as compared to the sequential acquisition of two languages, and (2) this difference in brain connectivity would in turn be associated with differences in cognitive control, with stronger anticorrelations being associated with better cognitive control.

2. Materials and methods

2.1. Participants

The unique language environment of Montreal provides access to distinct samples of bilinguals who are consistently exposed to both French and English in their daily lives and differ only with respect to when they learned their L2, allowing us to take advantage of homogeneous samples of participants. We tested two groups of French/English bilinguals – one who learned their two languages simultaneously from birth (n = 11; mean AoA = 0) and the second who learned their L2 after the age of 6 years old, and were matched with the simultaneous group in terms of their L2 proficiency (n = 10; mean AoA = 7.4). All were highly proficient right-handed English/French bilinguals who use both languages on a daily basis. The groups were matched for chronological age, years of formal education, and general intelligence (Table 1). Participants self-reported good health and did not have knowledge of any languages other than French and English. Exclusion criteria included history of a traumatic brain injury or neurological disorder, any medical conditions or medications known to affect cognitive functioning, or any conditions incompatible with MRI (e.g., metal implants, braces, electronically, magnetically, or mechanically activated devices such as cochlear implants, or claustrophobia). Individuals with musical training were also excluded given the link between musical training and brain organization (Gaser & Schlaug, 2003), as well as the possible interaction between musicianship and bilingualism on cognitive control processes (Schroeder, Marian, Shook, & Bartolotti, 2016).

2.2. Stimuli and materials

All participants underwent a behavioural testing session in which they completed a test of cognitive control, a language proficiency assessment, and a test of general intelligence.