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Language experience differentiates prefrontal and subcortical activation of the cognitive control network in novel word learning

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ABSTRACT

The purpose of this study was to examine the cognitive control mechanisms in adult English speaking monolinguals compared to early sequential Spanish–English bilinguals during the initial stages of novel word learning. Functional magnetic resonance imaging during a lexico-semantic task after only 2 h of exposure to novel German vocabulary flashcards showed that monolinguals activated a broader set of cortical control regions associated with higher-level cognitive processes, including the supplementary motor area (SMA), anterior cingulate (ACC), and dorsolateral prefrontal cortex (DLPFC), as well as the caudate, implicated in cognitive control of language. However, bilinguals recruited a more localized subcortical network that included the putamen, associated more with motor control of language. These results suggest that experience managing multiple languages may differentiate the learning strategy and subsequent neural mechanisms of cognitive control used by bilinguals compared to monolinguals in the early stages of novel word learning.

Introduction

The current study seeks to uncover how bilinguals and monolinguals differ in their ability to learn new vocabulary. Many researchers have sought to uncover the neural mechanisms required to learn both our first language as infants (Bates, 1999; Kuhl and Rivera-Gaxiola, 2008), and a second language later in life (Bosch et al., 2000; Hernandez et al., 2005; Kroll, 1994; Meschyan and Hernandez, 2006; Perani and Abutalebi, 2005). Very few studies, however, have specifically examined the cognitive control mechanisms needed during the earliest stages of second language vocabulary acquisition and how experience managing multiple languages may affect the brain regions employed. Current research suggests that bilinguals have an advantage in cognitive control related tasks (Bialystok, 2001; Bialystok and DePape, 2009; Bialystok and Shapero, 2005; Carlson and Meltzoff, 2008; Kaushanskaya and Marian, 2009; Waldie et al., 2009; Ye and Zhou, 2009). Bialystok and DePape (2009) propose that bilinguals train general and language specific control abilities on a daily basis through managing multiple languages, resulting in enhanced cognitive control across many cognitive domains. Recent neuroimaging studies support a bilingual cognitive advantage and have shown that this lifelong experience managing multiple languages increases both frontal white matter integrity and connectivity (Luk et al., 2011). Additionally, Abutalebi et al. (2012) recently found that specific brain areas implicated in both domain general and language specific cognitive control in bilinguals are activated more efficiently than in monolinguals. Specifically, the authors found that the anterior cingulate cortex (ACC), a domain-general and language specific control region, is activated less strongly in bilinguals compared to monolinguals, suggesting more efficient use of this brain area in monitoring conflict in verbal and nonverbal tasks. Hence, this developing line of research suggests that when learning novel vocabulary, bilinguals may utilize the cognitive control network differently or more efficiently than monolinguals, who do not have the same extensive experience managing multiple languages. To test differences in the use of control mechanisms between Spanish–English bilinguals and English monolinguals during early word learning, the current study scanned subjects using functional magnetic resonance imaging (fMRI) during a difficult lexico-semantic task after 2 h of exposure to novel vocabulary flashcards. A set of targeted regions implicated by the literature in cognitive control of language was evaluated: dorsolateral prefrontal cortex (DLPFC), anterior cingulate (ACC), striatum (caudate and putamen), inferior parietal lobe, and supplementary motor area (SMA). The novel word stimuli were divided into cognates and noncognates to additionally examine if orthographic and phonological overlap modulates neural activity during this early period of learning and affects the activation of cognitive control regions. In the following sections, an overview of the neural mechanisms engaged in the early stages of novel word learning and how cognitive control significantly impacts a bilingual's ability to manage multiple languages will be provided. The latter literature clearly shows that bilinguals may possess an advantage in cognitive control processes and suggests that the added experience managing multiple languages might allow them to learn a subsequent language differently than a monolingual.

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Neural activation in the first stages of word learning

Whereas previous research has focused on novel word learning in infants (Kuhl and Rivera-Gaxiola, 2008) and word learning after extensive training (McCandliss et al., 1997), few studies have focused specifically on the first few hours of novel word learning (McLaughlin et al., 2004; Shtyrov et al., 2010) or the neural mechanisms that drive early second language vocabulary acquisition in adults (Raboyeau et al., 2010) who classically have greater difficulty learning a second language. McLaughlin et al. (2004) revealed that during the early stages of word learning in adults, subtle changes not yet evidenced in behavioral measures might be detectable in neural measures; event-related potential (ERP) differences suggested that individuals could distinguish words from pseudowords after 14 h of total instruction, despite behavioral measures failing to show changes at greater than chance levels. Examining the neural changes that occurred within 14 min of passive perceptual exposure to novel spoken pseudowords, Shtyrov et al. (2010) discovered a neural response to learning, suggesting that neuronal circuits may be formed or altered for linguistic events very quickly.

McLaughlin et al. (2004) and Shtyrov et al. (2010) demonstrated the utility of ERP evidence in examining the immediate neural changes that occur in language learning. Other researchers have utilized alternative imaging techniques to identify the specific neural structures that underlie these rapid changes, which Catani et al. (2005) and Shtyrov et al. (2010) suggest may involve areas that extend beyond traditional language processing regions such as Broca and Wernicke's areas. Shtyrov et al. (2010) suggest that this human capability of developing large lexicons is facilitated by a network of brain regions that connect the left temporal and frontal perisylvian areas. In their examination of fiber tracts that connect classic language related regions, Catani et al. (2005) found that the arcuate fasciculus fiber distribution extends beyond what is traditionally thought of as Broca's area to include middle frontal and inferior precentral gyri, which are known to be involved in cognitive control of language functions (Abutalebi and Green, 2007). Raboyeau et al. (2010) used event-related fMRI to examine the neural mechanisms involved in the early stages of word learning related to different word types in a group of French–English bilinguals. After exposure to picture-word pairs over five 20-minute training sessions, neural activation was seen in the left inferior frontal regions associated with lexical retrieval and phonological processing, ACC, and the DLPFC in response to monitoring and control, suggesting that even after less than 2 h of total instruction time, distinct neural patterns in response to learning can be identified. These regions extend beyond traditional temporal and frontal language related areas, and Abutalebi and Green (2007) theorize that these inferior frontal, middle frontal, and anterior cingulate regions are involved in cognitive control. Given this evidence, it is important to evaluate the selective activation of these cognitive control regions and others during the acquisition of novel vocabulary, as the networks that are involved in early word learning may be different between monolinguals and bilinguals, drawing upon areas associated with cognitive control. The current study expands on these and other studies that used longer periods of vocabulary instruction (Lee et al., 2003; McCandliss et al., 1997) by exploring how experience managing multiple languages affects the cognitive control network during early novel word learning.

Cognitive control and the bilingual executive advantage

Much of what is known about cognitive control in language comes from studies of bilinguals. Many studies have examined the neural mechanisms used by bilinguals to manage the control of multiple languages (Abutalebi and Costa, 2008; Abutalebi and Green, 2007, 2008; Hernandez, 2009; Wang et al., 2007). Bilingual research indicates that multiple languages share a common neural system rather than relying on separate neural representations for each language. The use of different languages is then managed by an intricate control system made up of cortical and subcortical regions. According to Abutalebi and Green (2007), the integration of the anterior cingulate cortex, basal ganglia, inferior parietal lobe, and prefrontal cortex is responsible for bilingual language control, which is "not concerned with the representation of language but the selection and temporal sequencing of such representations" (Abutalebi and Green, 2007, p. 249).

Abutalebi and Green (2007, 2008) and Abutalebi and Costa (2008) introduced the exploration of cognitive control mechanisms in bilinguals; however, less research has focused on the development of these mechanisms in adult monolinguals learning a new language and if these pathways may differ from those individuals already fluent in two or more languages. In order to explore the bilingual executive advantage, the majority of current research focuses on comparisons of bilinguals and monolinguals during language and non-language related cognitive control tasks. Some studies suggest that this advantage is language specific, particularly in word learning (Kaushanskaya and Marian, 2009), but the advantage may extend to other more general executive domains (i.e., an executive advantage) as well (Abutalebi and Costa, 2008; Abutalebi et al., 2012; Bialystok, 2001; Kaushanskaya and Marian, 2009). Bilinguals across the lifespan show this advantage in language and non-language related control tasks that require conflict resolution, switching, and flexibility (Bialystok and Shapero, 2005; Bialystok et al., 2004). Abutalebi et al. (2012) recently addressed differences between monolinguals and bilinguals and found that the ACC, a region involved in both domain-general and language specific cognitive control, is used more efficiently by bilinguals in both verbal and nonverbal tasks of conflict resolution. Garbin et al. (2010) also examined the brain basis of the bilingual advantage in cognitive control by comparing the neural activity of monolinguals and bilinguals during a non-language switching task. Results indicated that monolinguals expressed activity in the right inferior frontal cortex and anterior cingulate, whereas bilinguals utilized the left inferior frontal cortex and striatum during task switching. All of these regions were implicated in linguistic cognitive control in bilinguals by Abutalebi and Green (2007), suggesting that monolinguals and bilinguals may utilize the components of this control network differently due to their experiences managing multiple languages.

Bialystok and DePape (2009) proposed that the advantage bilinguals have over monolinguals in cognitive control is the result of daily training of general executive abilities. That is, if these mechanisms are generalized, then training in a different domain may similarly contribute to greater development of cognitive control as well. Bialystok and DePape (2009) examined whether other intensive activities, such as musical training, could also bolster cognitive control. They hypothesized that intensive musical experience may contribute to enhanced general cognitive control mechanisms in musicians in much the same way that management of two language systems has strengthened cognitive control mechanisms in bilinguals. Bialystok and DePape (2009) concluded that much like bilingualism, musicians also showed heightened control on cognitive tasks requiring inhibition and restraint. These results suggest that regular experience with tasks that require inhibition, switching, and conflict monitoring is capable of altering, and possibly enhancing the development of certain general cognitive control abilities and support an association between bilingualism and better inhibitory and switching skills.

Although little is known about the earliest stages of learning a new language as an adult, Raboyeau et al. (2010) suggest that changes in brain activation are noted within the first few hours of exposure to novel words. Research in the area of cognitive control suggests that adult bilinguals may have an advantage over, and activate different areas than monolinguals when performing tasks requiring higher-order cognitive processes such as switching between languages and inhibiting the dominant language for a new language being learned. As such, we hypothesized that bilingual adults would utilize the components of the cognitive control network differently, possibly more