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Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function

Andrea Stocco, Brianna Yamasaki, Rodion Natalenko and Chantel S. Prat
University of Washington, USA

Abstract

Individuals who develop bilingually typically outperform monolinguals on tests of executive functions. This advantage likely reflects enhanced prefrontal function, but the mechanisms that underlie this improvement are still poorly understood. This article describes a theory on the nature of the neural underpinnings of improved executive function in bilinguals. Specifically, we propose that growing up in a bilingual environment trains a gating system in the striatum that flexibly routes information to the prefrontal cortex. This article is divided into three sections. Firstly, literature establishing a three-way connection between bilingualism, executive function, and fronto-striatal loops is summarized. Secondly, a computational model of information processing in the basal ganglia is described, illustrating how the striatal nuclei function to transfer information between cortical regions under prerequisite conditions. Finally, this model is extended to describe how bilingualism may "train the brain," enabling improved performance under conditions of competitive information selection during information transfer. Theoretical implications and predictions of this theory are discussed.

Keywords

Bilingualism, executive functions, learning, prefrontal cortex, basal ganglia, striatum, inhibition, shifting

It is well known that bilingual individuals outperform monolinguals in a number of tasks involving executive function (e.g., Bialystok, 1998, 1999, 2004, 2009). The cognitive nature of this advantage, however, is still debated, and its neural mechanism unspecified. In this paper, we propose a brain-based computational model of information routing from the striatum to the frontal cortex that simultaneously explains how bilingualism "trains" the brain and clarifies the

Corresponding author:
Chantel S. Prat, Institute for Learning & Brain Sciences (I-LABS), Box 357988, University of Washington, Seattle, WA 98195-7988, USA.
Email: csprat@uw.edu

nature of improved computations in bilinguals. Our explanation links recent developments from two apparently distinct areas of neuroscience (the neuroscience of bilingualism and the neuroscience of cognitive flexibility) to support the hypothesis that extensive bilingual experience reinforces the basal ganglia's capacity to modulate the flow of signals across cortical regions. This hypothesis helps unify existing results, explaining a number of apparently contradictory findings in bilingual research, and is supported by recent findings on the neural substrates of executive function. In addition, the use of a neurocomputational model of the basal ganglia allows us to make predictions about the precise nature of improved information processing in bilingual individuals.

This article is divided into three sections. Firstly, literature establishing a three-way connection between bilingualism, executive function, and the basal ganglia is summarized. Secondly, a computational model of information processing in the basal ganglia is described. This model is extended to describe how bilingualism may "train the brain" to perform better under conditions of competitive selection during information transfer, thus enabling earlier and improved executive function in bilingual individuals. Finally, the theoretical implications and predictions of this theory are discussed.

Improved executive function in bilinguals

The bilingual advantage on tasks that measure executive function has been well documented throughout the lifespan (e.g., Bialystok, 2001, 2009; Bialystok, Martin, & Viswanathan, 2005). For example, children developing bilingually show improved and earlier development of non-linguistic executive function (Carlson & Meltzoff, 2008), and the effects of aging on declining executive function are ameliorated in bilingual individual (Bialystok et al., 2005). Studies of both children and adults show superior performance in a number of tasks that tap into executive function, such as the Simon task (Bialystok, Craik, Klein, & Viswanathan, 2004), task-switching paradigms (Prior & MacWhinney, 2010), and tasks that require managing internal response conflicts (Carlson & Metzoff, 2008). Most of these tasks do not directly assess linguistic competence, and some of them (like the Simon task) are non-verbal in nature. In addition, research shows that the amount of bilingual experience an individual has (Carlson & Meltzhoff, 2008) and their ability to control use of their two languages (e.g., Festman, 2012) are also related to the extent to which improved executive function is observed. The research suggests, therefore, that a particular linguistic experience, bilingualism, translates into a domain-general advantage in cognitive function.

"Executive function" is a general name for a number of activities that, to a certain extent, can be dissociated from one another. Experts in executive function have described at least three distinct components of performance on executive tasks: inhibition, shifting, and updating (e.g., Miyake et al., 2000). These various aspects of executive function have been discussed and debated in the bilingual research, but no consensus has been reached about which facet (or facets) is specifically improved in bilinguals. Because increased demands for language selection and switching in bilinguals overlaps most directly with the inhibition and shifting components of executive function, investigations of the executive advantage in bilinguals have primarily focused on these aspects. Relatively little work has addressed a bilingual advantage in updating, but one study did report a bilingual advantage on a visually cued recall task involving an updating component (Carlson & Meltzoff, 2008). In this section, we will provide a brief overview of the remaining research that links bilinguals' improved performance on executive tasks to better inhibitory control and switching processes.

Inhibitory control

One proposed explanation of bilinguals' advantage in executive function is that it reflects a superior capacity for inhibitory control, or the capacity of controlling and halting dominant and automatic responses that are strongly associated to environmental stimuli but are not appropriate for the current task (Miyake et al., 2000). Bilinguals may benefit from additional inhibitory control because they need to deal with interfering responses from the unwanted language—responses that are typically activated in parallel with those of the target language (e.g., Bialystok, 2001; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008; Festman, Rodriguez-Fornells, & Münte, 2010). In an investigation comparing the performance of bilinguals and monolinguals across three experiments using the Simon task, a non-verbal response competition paradigm (Simon, Acosta, Mewaldt, & Speidel, 1976), Bialystok and colleagues (2004) presented particularly compelling evidence that bilingual individuals exhibit advanced inhibitory control. The Simon task requires participants to respond to a simple visual stimulus with the left or right hand; the response is based on the stimulus' color. When the stimulus is presented on a screen position that is opposite to the response's hand (i.e., one has to answer with the left hand but the stimulus is presented on the right), response times increase, implying an additional effort to control the natural tendency to respond with the hand that is on the same side as the stimulus. Bialystok et al. (2004) found that, across different experiments and conditions, bilinguals' response times were less affected by the spatial interference during incongruent trials, suggesting improved inhibitory control. These results, however, did not replicate in subsequent experiments (Bialystok, 2006; Bialystok, Martin, & Viswanathan, 2005).

Colzato et al. (2008) advanced the debate by outlining two possible models for inhibitory process in bilinguals: (a) an *active* model in which inhibition spreads "vertically" from task goals to the irrelevant responses; and (b) a *reactive* model where task goals activate both relevant and irrelevant response, but inhibition spreads "horizontally" from the relevant to the irrelevant ones. Colzato et al. (2008) compared the performance of bilinguals and monolinguals across three tasks that engage different inhibitory models: the stop-response task (Logan & Cowan, 1984), the inhibition-of-return task (Posner & Cohen, 1984), and the attentional blink task (Raymond, Shapiro, & Arnell, 1992). Bilinguals did not exhibit any advantage over monolinguals in the first two tasks, but they did show a clear *disadvantage* in the attentional blink task. In this task, participants observe a rapid serial visual presentations of simple visual stimuli (e.g., numbers) in which two targets (e.g., letters) are embedded. While participants can easily detect both targets when they are either in immediate succession or separated by three or more stimuli, they are typically unable to report the second target when it is separated from the first by one or two intermediate distractors. This effect is akin to a temporary "blink" of visual attention. Colzato et al. (2008) found that blink effects were larger in bilinguals than in monolinguals. The authors interpreted this finding as the result of inhibition originating from the attention devoted to the first stimulus, therefore favoring the "reactive" model of inhibition (Colzato et al., 2008). Our model offers a different interpretation of the results discussed in this section. Specifically, it proposes that the larger blink effect in bilinguals is due to the top-down processing of the first stimulus that is mediated by the basal ganglia, a set of brain nuclei that are particularly important for bilingual language production and override the automatic visual processing of the second stimulus.

In summary, while improved inhibitory control has been one of the most popular explanations of improved executive function in bilinguals, a number of recent experimental findings suggest that this may not be the best characterization of bilinguals' cognitive advantage (e.g., Bialystok, 2006; Colzato et al., 2008; Festman et al., 2010).

Set shifting

Another possible explanation for improved executive function in bilinguals is that they are better at the shifting component of complex tasks, or the capacity of flexibly switching back and forth between multiple tasks, mental operations, or response sets (Miyake et al., 2000). The assumption behind this hypothesis is that bilingual experience is a linguistic instantiation of task set shifting, and thus bilinguals' advantage in executive function reflects improved shifting abilities in general. In other words, to be a fluent bilingual, individuals need to switch effectively between the appropriate grammatical rules and phonological outputs for each of the languages they speak. Thus, it is conceivable that bilinguals obtain a general benefit from this continuous practice with shifting. Evidence in this sense can be seen in a study by Festman et al. (2010) that compared the performance of a group of bilinguals across different tasks. In this study, participants were initially required to name pictures alternating between two languages. The number of errors made (i.e., failures to switch language) was taken as a measure of their language control ability. The authors then proceeded to divided the group into "switchers" (less errors, better control) and "non-switchers" (more errors, worse control), and compared these two subgroups on a number of executive function tasks. It was found that "switchers" also performed better on all the executive function tasks, suggesting that having better executive functions is related to the capacity to switch between languages.

A few studies have specifically compared the set-shifting abilities of bilinguals and monolinguals. This line of research has primarily employed task-switching paradigms to investigate shifting abilities. In task-switching experiments, participants shift between two tasks that can be performed on an identical set of stimuli (e.g., Monsell, 2003). For instance, the experimental stimuli might be one-digit numbers, and participants might be required to switch between categorizing each digit as even or odd (Task 1) or as smaller or larger than five (Task 2). The first trial after participants switch tasks takes longer than any trial where they are continuing to perform the same task. The increase in reaction time constitutes the *switch cost*, which is interpreted as the additional control needed to prepare for a new set of mental operations. At least two studies (Garbin et al., 2010; Prior & MacWhinney, 2010) compared bilinguals and monolinguals in a task-switching paradigm, and found that bilinguals exhibit significantly lower switch costs than monolinguals, suggesting a more efficient shifting processes.

One of the most intriguing findings in the task-switching literature is the task-switching asymmetry observed when individuals switch from a more difficult, less automatic task to an easier, or more automatic, task (e.g., Monsell, 2003). In this condition, a larger switching cost is observed than when switching from an easier, more automatic task to a more difficult one (e.g., Allport, Styles, & Hsieh, 1994; Yeung & Monsell, 2003). Interestingly, this asymmetry has a direct counterpart in the bilingual literature: when switching between languages, "unbalanced" bilinguals (i.e., bilingual individuals who are more proficient in L1 than L2) find it harder to switch from the less proficient to the most dominant language, and not vice versa (e.g., Costa & Santesteban 2004). This finding provides empirical support that switching between languages for bilinguals involves some of the same general information-processing principles that operate in non-linguistic task-switching paradigms. This lends plausibility to the theory that bilinguals' cognitive advantage arises because bilingual practice trains the switching sub-component of executive function.

One problem with both the inhibition and switching explanations is that they rely on hypothetical cognitive constructs that are not well specified at the neural or computational level. For instance, vastly different computational models can account for the switching costs (Altmann & Gray, 2002; Gilbert & Shallice, 2002; Schneider & Logan, 2005; Sohn & Anderson, 2001); these models rely on different underlying biological mechanisms to explain the nature of changing tasks. The next two sections will review the most relevant findings about the neural bases of bilingualism and their connections with the neural bases of executive function.

The neural basis of bilingualism

Differences in cognitive function ultimately result from differences in brain processes. Thus, whatever the nature of the bilingual advantage in executive function is, it must be reflected in some feature or features that characterize the bilingual brain. Investigations of the bilingual brain have centered around two problems: how multiple languages are *represented* in the brain, and how they are *controlled* in the brain (see Abutalebi & Green, 2007, for a review).

Recent neuroimaging research suggests a great deal of overlap in the *representation* of multiple languages (see Abutalebi & Green, 2007, p. 256, Table 1). An abundance of studies (Abutalebi, 2008; Buchweitz, Mason, Hasegawa, & Just, 2009; Chee, Tan, & Thiel, 1999; Dehaene et al., 1997; Gandour, et al., 2007; Hernandez & Meschyan, 2006; Vingerhoets et al., 2003) showed that second languages (L2) have a more distributed representation and engage larger cortical areas than do first languages (L1). Most of these differences, however, can be accounted for by differences in proficiency levels in the two languages (Abutalebi, 2008; Perani et al., 2003; Yokoyama et al., 2006). Thus, the general view is that a highly overlapping network of regions is recruited by both languages, and that eventual differences depend on the recruitment of additional regions (often prefrontal regions) to compensate for the less automatic control of the second language (Abutalebi & Green, 2007). An example of the degree of overlap between L1 and L2 comes from a study by Buchweitz, Shinkareva, Mason, Mitchell, and Just (2012). The authors used machine learning techniques to investigate the neural substrates of semantic representations of L1 and L2 in proficient English-Portuguese bilinguals. In particular, the authors trained a multi-voxel pattern classifier to correctly associate distinct patterns of activation elicited by words in L1 (e.g., the pattern of activation elicited by the Brazilian word “Avião”), and found that the same classifier could reliably recognize the homologous words when presented in L2 (e.g., the English word “Airplane”). This finding suggests that words in L1 and L2 not only recruit the same brain network to be processed, but are similarly represented at the neural level.

The fact that L1 and L2 languages share a common neural substrate implies that languages must compete for access to shared neural resources. Thus, a *control* mechanism must be operating in the bilingual brain to monitor and select which language to use. In our opinion, the neural substrates of this control mechanism are tied to the neural mechanisms of the shifting component in executive function.

Investigations of bilingual language control typically involve translation paradigms, language-switching paradigms, or language selection paradigms (see Abutalebi & Green, 2008, for a review). Research has yielded regions of activation that highly overlap with those observed in non-linguistic cognitive control tasks, such as the prefrontal cortex and the anterior cingulate (e.g., Hernandez, Martinez, & Kohnert, 2000; Rodriguez-Fornells et al., 2005). Of particular interest to our hypothesis, a series of investigations have reported subcortical involvement, specifically the basal ganglia, during switching or translating paradigms (e.g., Lehtonen et al., 2005; Price, Green, & von Studnitz, 1999). This research is discussed in more detail in the subsequent section.

The role of the basal ganglia in language

The basal ganglia are a set of interconnected gray matter nuclei located in the middle of the brain. Together, these nuclei form a complex circuit that, by maintaining a careful balance of inhibitory

Table 1. Comparison of basal ganglia activation foci in neuroimaging studies of bilingualism.

Study	Atlas	Region	Coordinates (x, y, z)	Analysis
Wartenburger, Abutalebi, Cappa, Villringer, & Perani (2003)	MNI	L putamen/thalamus	–20 8 6	Grammatical judgment comparison
		L caudate nucleus	–20 0 17	
		R putamen/thalamus	20 4 0	
Abutalebi, Simona, et al. (2007)	Talairach	L head of caudate	–2 10 14	Language switching vs. non-switching in the middle of a sentence
		L putamen	–28 –12 10	
		R putamen	28 –6 8	
		R globus pallidum	14 –6 –2	
Abutalebi, Annoni, et al. (2007)	Talairach	L caudate nucleus	–16 6 6	Bilingual vs. monolingual in naming
		R caudate nucleus	16 8 12	
		L caudate nucleus	–18 0 22	Bilingual > monolingual in naming
		L caudate nucleus	–10 4 4	Naming in L1 > L2
		R caudate nucleus	14 4 6	
		R putamen	30 14 10	
Garbin et al. (2010).	MNI	L striatum	–16 10 2	Bilinguals > monolinguals in task switching
Waldie, Badzakova-Trajkov, Miliivojevic, & Kirk (2009)	Talairach	L caudate tail	–15 –31 20	Bilinguals > monolinguals in Stroop incongruent trials
Ghosh, Basu, Khushu, & Kumaran (2009)	Talairach	R sublobar extra nuclear, caudate body	14 –2 16	Lexical decision > syllable discrimination
Majerus et al. (2008)	MNI	L caudate tail	–12 –30 –18	Low proficiency > high proficiency
		R caudate tail	22 –38 14	
		L pallidum	–12 0 –4	High proficiency > Low proficiency
		R pallidum	14 2 –14	
Klein, Milner, Zatorre, Meyer, & Evans (1995)	Talairach	L putamen	–15 10 –6	Translation (L1 to L2) vs. repetition (L1 to L1).

Table 1. (Continued)

Study	Atlas	Region	Coordinates (x, y, z)	Analysis
Grogan, Green, Ali, Crinion, & Price (2009)	MNI	R head of caudate	14 0 16	Correlation between phonemic task and gray matter volume
		L head of caudate	–14 10 14	
		R head of caudate (L2)	16 10 14	Phonemic task > semantic task
		L head of caudate (L2)	–14 14 10	
		R head of caudate (L1)	12 –2 16	
		L head of caudate (L1)	–8 4 20	
Klein, Watkins, Zatorre, & Milner (2006)	Talairach	L head of caudate	–15 13 6	Word repetition minus silent baseline in L2
		L putamen	–28 13 -8	
Meschyan & Hernandez (2006)	Talairach	R putamen	24 10 14	L2 > L1 in single word reading
		R putamen	26 10 12	L2 > rest in single word reading
Rueschemeyer, Fiebach, Kempe, & Friederici (2005)	Talairach	L caudate	–5 18 3	Correct sentences: Native speakers vs. non-native speakers L2 > L1
		R caudate	11 15 6	
		L caudate	–7 6 3	Syntactically anomalous sentences: Native speakers vs. non-native speakers
		R caudate	8 12 9	
		L caudate	–5 6 3	Semantically anomalous sentences: Native speakers vs. non-native speakers L2 > L1
		R caudate	8 12 9	
Price, Green, & von Studnitz (1999)	Talairach	L putamen/head of caudate	–16 18 0	Translation relative to reading—increases in activation
			–18 22 16	
		R putamen/head of caudate	16 26 2	
			18 14 4	
			18 8 14	
Lehtonen et al. (2005)	MNI	L globus pallidus	–16 4 –4	Sentences translation > control
Crinion et al. (2006)	MNI	L caudate	–6 6 8	Language-specific priming (English-German)
		L caudate	–4 14 2	Language-specific priming (English-Japanese)
Klein, Milner, Zatorre, Meyer, & Evans (1995)	Talairach	L putamen	–15 10 –6	L1 to L2 translation

MNI: Montreal Neurological Institute template.
Talairach: Talairach-Tournoux template.

and excitatory signals conveyed through parallel pathways, controls the thalamic inputs to the frontal lobe (Albin, Young, & Penney, 1989; DeLong, 1990). The most important structure within the basal ganglia is the striatum, which is the largest of the basal ganglia nuclei and constitutes the input station of the circuit. The striatum receives organized projections from the entire cortex (Alexander, DeLong, & Strick, 1986), and projects to and modulates the activity of lower-level nuclei of the basal ganglia, which ultimately control the output of thalamic neurons to the prefrontal cortex. Thus, the striatum is in an ideal position to gather information from all the cortical areas in the brain, and use this information to modulate the subcortical inputs to the prefrontal cortex. In turn, the prefrontal cortex is the part of the brain that is responsible for higher-level behavior (Miller, 2000), including working memory (Cohen et al., 1997), planning (Shallice & Burgess, 1991), rule-based behavior (Strange, Henson, Friston, & Dolan, 2001) and, of course, language (e.g., Just, Carpenter, Keller, Eddy, & Thulborn, 1996).

Until recently, the role of the basal ganglia has been largely disregarded in neuroimaging investigations of language processes—an example of a more general “cortico-centric myopia” that has characterized the cognitive neurosciences (Parvizi, 2009). However, neuropsychological studies have shown that language impairments such as aphasia, normally associated with cortical lesions, can also originate from basal ganglia damage (e.g., Brunner, Kornhuber, Seemüller, Suger, & Wallesch, 1982; D’Esposito & Alexander,1995) or from basal ganglia abnormalities of genetic origin (e.g., Vargha-Khadem et al., 1998; Watkins et al., 2002). In addition, an increasing number of contemporary neuroimaging studies have discussed the relevance of the basal ganglia to language processing, suggesting that this region is substantial for the control of language (e.g., Friederici, 2006; Prat & Just, 2011). To illustrate, we conducted a review of existing neuroimaging research and found that 16 investigations of the neural basis of bilingualism reported activation foci within the basal ganglia nuclei under different conditions (see Table 1). The centroids of these activations in Montreal Neurological Institute (MNI) coordinates are depicted in Figure 1. Taken together, Figure 1 and Table 1 suggest that basal ganglia activation is often found (although not always discussed and addressed) in studies of bilingualism. Furthermore, the distribution of the activation foci in Figure 1 follows a consistent pattern, with the majority of reported foci concentrated on the head of the caudate nucleus, which crucially receives inputs from (and projects to) the prefrontal cortex and has been associated with individual differences in executive function (e.g., Prat & Just, 2011).

One explanation for the different contributions of cortical and subcortical structures to language processes is that language is underpinned by two processes with distinct neural instantiations: a semantic representation system (which involves the cortex) and a grammatical (or rule composition) system (which involves subcortical structures: e.g., Paradis, 2004; Ullman 2001a, 2001b; Ullman et al., 1997). This framework largely overlaps with the ideas of language representation and control previously discussed; however, the constructs are defined within a memory framework. Within this framework, lexical information is represented as part of the declarative memory system, while syntactic knowledge is stored as part of the procedural memory system. In the human brain, declarative memory is thought to be underpinned by cortical structures, and in particular with the temporal lobe (for the encoding of information: Squire, 1992, 2004) and the left inferior frontal gyrus (for the retrieval of information: Sohn, Goode, Stenger, Carter, & Anderson, 2003; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). Procedural memory, on the other hand, is typically associated with the basal ganglia circuit (Cohen & Squire, 1980; Packard & Knowlton, 2002); thus, this framework establishes a link between linguistic rule representation and the basal ganglia. Computationally, the distinction

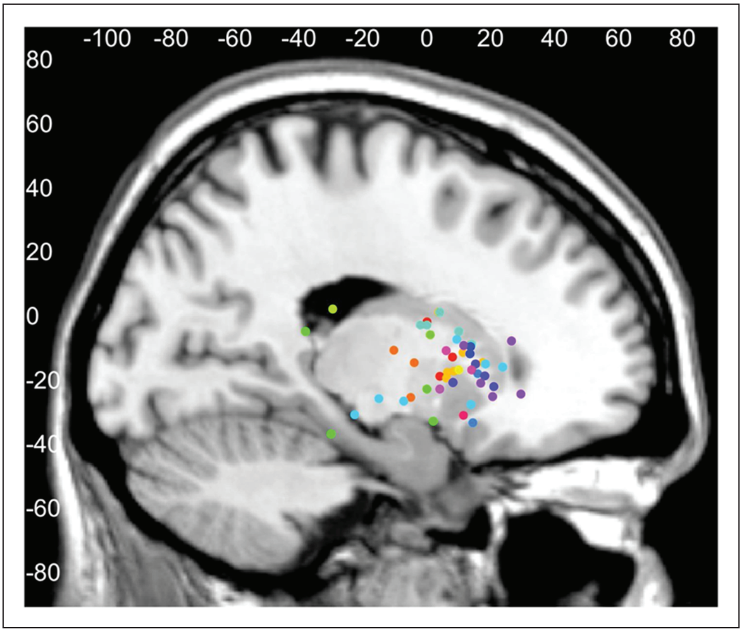

Figure 1. Locations of basal ganglia foci of activations in 16 neuroimaging studies of bilingualism (see Table 1 for references). The foci of activations are overlaid on the Montreal Neurological Institute (MNI) Colin 27 template (Sagittal view, *x* = –20). Different colors (color online only) represent results from different studies; dots of the same color represent distinct foci of activation reported in the same paper (e.g., in two different contrasts). Stereotactic coordinates that were originally given in the Talairach-Tourneaux system were converted to the MNI system using the non-linear transformation algorithm provided in the GingerALE software (Eickhoff et al., 2009).

between dictionary-like semantic knowledge and rule-like procedural knowledge provides an intuitive and powerful basis for explaining the complex phenomenon of natural language use. In fact, this dual mechanism has been applied in computational models of language acquisition (Taatgen & Anderson, 2002), understanding (Lewis & Vasishth, 2005), and language impairments (Stocco & Crescentini, 2005), and is a staple of general-purpose cognitive architectures such as Adaptive Control of Thought—Rational (ACT-R: Anderson et al., 2004) and Executive Processes / Interactive Control (EPIC: Meyer & Kieras, 1997).

The idea that syntactic rules can be encoded in the basal ganglia is supported by this circuit's involvement in acquiring procedural knowledge (Knowlton, Mangels, & Squire, 1996). Experiments with animals have shown, for instance, that basal ganglia impairments prevent the acquisition of stimulus–response associations (e.g., Packard & McGaugh, 1992). In humans, diseases affecting the basal ganglia (e.g., Parkinson's or Huntington's disease) impair the acquisition of new perceptual-motor skills, such as mirror reading (Cohen & Squire, 1980) and the acquisition of complex stimulus–response associations (Knowlton et al., 1996). Thus, experimental and neuropsychological evidence suggest that the basal ganglia circuit is responsible for learning and applying complex stimulus–response transformations—a function that is consistent with the application of grammatical rules.

The basal ganglia and the bilingual brain

This declarative/procedural framework can be usefully applied to explain the proficiency-related differences between L1 and L2 in late bilinguals. While learning a second language, grammatical rules are more likely to be encoded explicitly, and thus retrieved and held in working memory during language tasks. This additional activity would be reflected in larger activation of prefrontal regions for L2 compared to L1. With increasing practice, however, grammatical rules for L2 would be eventually stored in the basal ganglia in the form of procedural rules, thus reducing the difference between L1 and L2 (Paradis, 2004; Ullman, 2001b). This view is confirmed by the fact that, in bilingual individuals with degenerative disorders of the basal ganglia such as Parkinson's disease, greater impairment is found in the language spoken with higher proficiency, whereas less impairment is observed in the language spoken with less proficiency (Zanini, Tavano, & Fabbro, 2010; Zanini et al., 2004; see Fabbro, 2001, for a review).

However, experimental and neuropsychological evidence suggest that, in the bilingual brain, the basal ganglia play the additional role of controlling which language to use. For instance, bilingual patients with injuries spanning the basal ganglia circuit show a pathological tendency to switch back and forth between languages (Fabbro, 2001). This neuropsychological evidence is also corroborated by experimental investigations; for instance, direct stimulation of the left striatum (the largest nucleus of the basal ganglia) during open-skull surgery causes spontaneous language switching (Robles, Gatignol, Capelle, Mitchell, & Duffau, 2005).

One important neuroimaging study conducted by Crinion et al. (2006; see also Friederici, 2006, for a discussion of this study's implications) examined the nature of automatic language switching by using a priming paradigm. In the experiment, bilinguals responded to words that were preceded by either semantically related or unrelated primes. More importantly, the prime word was presented in either the same language as the target word, or in a different language. Noticeably, the authors did not compare L1 against L2, but instead used priming to investigate the nature of language processing when a language switch (L1 or L2) is processed. Semantic priming crosses the language boundary, so that seeing the prime word "Salmon" in English still results in a decreased response time for the target word "Trout" in German ("Forelle"). The priming effect was significant in a distributed cortical network involving most of the brain regions that were recruited by the task. The only exception to this rule was a region in the left striatum. Semantically related words reduced activation in this region only when they were in the same language. In other words, the priming effect in the striatum was selectively modulated by the specific language input.

Crinion et al.'s (2006) finding suggests that the striatum is involved in monitoring which language is in use. It is conceivable that damage to this structure impairs a specific brain circuit that controls which language is used, thus explaining the neuropsychological symptoms described above. Friederici (2006) recognized the connection between this putative function of language selection and the established role of the basal ganglia circuit in selecting motor programs (e.g., Albin et al., 1989).

Summary

In summary, investigations of the nature of language processing in bilinguals have shown that different languages are represented in highly overlapping cortical networks, especially when one accounts for different levels of proficiency and exposure. The basal ganglia seem to play a role both in controlling language selection and in subsequent application of rules. Importantly, in the bilingual brain, this subcortical circuit is involved in a specific function (i.e., switching or translating between languages) that is analogous to the facet of executive function, where bilinguals seem to excel (i.e., switching between tasks or response sets). The next section will describe the functions of this circuit in more detail and their relevance for executive function and shifting.

The basal ganglia and executive function

How might practice with language switching in bilinguals provide an advantage in executive function? We propose that the critical link between bilingual experience and improved executive function arises with training of the fronto-striatal loops, which are involved in both language control and executive function.

The basal ganglia are primarily known for their role in learning and skill acquisition (Knowlton et al., 1996; see Packard & Knowlton, 2002, for a review). However, this circuit has been implicated in a larger number of higher-level cognitive functions, including working memory (McNab & Klingberg, 2008), decision making (Montague, King-Casas, & Cohen, 2006; Tom, Fox, Trepel, & Poldrack, 2007), language (Frederici, 2006; Prat & Just, 2011; Ullman, 2001a, 2001b), planning (Monchi, Petrides, Strafella, Worsley, & Doyon, 2006), and reasoning (Frank, Seeberger, & O'Reilly, 2004; Stocco & Anderson, 2008).

Of particular interest to the theory presented herein, the basal ganglia have also been proposed to play a role in the shifting component of executive function. Some evidence of this comes from deficits observed in patients with diseases such as Parkinson's and Huntington's disease, which selectively damage the basal ganglia. Patients with Parkinson's disease, for instance, have problems switching to new rules in the Wisconsin Card Sorting Task (Gotham, Brown, & Marsden, 1988; Owen, Roberts, Hodges, & Robbins, 1993). In this task, participants go through a deck of cards with colored symbols and are required to put them in piles according to a specific rule. The rule itself is not revealed explicitly; instead, participants need to rely on the yes/no feedback from the experimenter to know whether putting a card in a particular pile (e.g., the pile with all red symbols) is a correct move. Unpredictably, the experimenter sometimes changes the sorting rule (switching from color to shape), so that participants have to learn a different criterion for piling up the cards.

Both Parkinson's (e.g., Rogers et al., 1998) and Huntington's (e.g., Aron et al., 2003) patients exhibit impairments when shifting to new task rules in standard task-switching paradigms, again suggesting a specific involvement of the basal ganglia in the control of alternating behavioral rules. Additional evidence can be found in a number of neuroimaging studies, which report basal ganglia activation in healthy populations during task-switching experiments (Cools, Clark, & Robbins, 2004; Crone, Wendelken, Donohue, & Bunge 2006; Gu et al., 2008; Sohn, Ursu, Anderson, Stenger, & Carter, 2000). Finally, a critical link between set shifting, the basal ganglia, and bilingualism is reported in one neuroimaging investigation of task switching (Garbin et al., 2010). The authors compared the brain activation of bilinguals and monolinguals while performing a task-switching paradigm. The paradigm was designed to be non-linguistic, with the two tasks involving classifying colored shapes according to either their shape (e.g., circle or square) or their color (e.g., orange or blue). Consistent with previous findings (e.g., Prior & MacWhinney, 2010), bilinguals showed a reduced switching cost (e.g., reduced increase in latency) when switching between tasks. Most importantly, however, the size of the switch costs was negatively associated with the activity of the left caudate nucleus in bilinguals, suggesting that successful recruitment of this nucleus results in faster switches. The same correlation was not observed in monolinguals, suggesting that one crucial difference between the bilingual and the monolingual brain is that the bilingual brain relies on the left caudate to switch between tasks, while the monolingual brain does not (Garbin et al., 2010).

In summary, the literature suggests a three-way connection between executive function, the basal ganglia, and bilingualism. Bilinguals exhibit behavioral advantages in executive function, which reflect, in part, superior cognitive control in switching between different rule-based behaviors. This superior control ability relies on the basal ganglia, a set of nuclei that are crucially involved in both switching between different task sets and in switching between languages. Two questions arise at this point. (a) What is the mechanism by which the basal ganglia contribute to linguistic and behavioral switching? (b) Can we use this information to better understand how growing up in a bilingual environment trains the brain in a way that generalizes to non-linguistic executive function? The next two sections will attempt to provide answers to both questions.

Identifying basal ganglia computations in task and language switching

To understand the mechanism behind improved executive function in bilinguals, one must first specify the neural computations that take place in the basal ganglia. Specifically, we must determine whether the same neural computations are involved both in the control and switching between languages and in the control and switching between other, non-linguistic, tasks. In addition, we must determine how this circuit is shaped by practice and, in particular, how domain-specific training (i.e., speaking two languages) generates a domain-general benefit (i.e., improved executive function).

One way to better understand the computations of a specific neural circuit is by generating a computational model of the circuit. Biologically based models are particularly useful, because they provide a direct connection between anatomical structure and function (e.g., O’Reilly & Munakata, 2000). Because of their elaborate patterns of connectivity with the cortex, and their wide involvement in cognitive functions, several models of the basal ganglia have been generated (see Cohen & Frank, 2009; Gillies & Arbuthnott, 2000, for reviews), and some consensus has emerged about the basic nature of their computations. According to several of these models, the basal ganglia provide a complex and flexible mechanism to control information flow to the prefrontal cortex. In many recent models (e.g., Amos, 2000; Frank, Loughry, & O’Reilly, 2001; Gurney, Prescott, & Redgrave, 2001; O’Reilly & Frank, 2006; Stocco, Lebiere, & Anderson, 2010) this “gating” of signals to the prefrontal cortex is performed by monitoring all possible incoming signals from the cortex, and then using the internal inhibitory connections within the basal ganglia to suppress those signals that are not of interest. The signals of interest are then selected and routed to the prefrontal cortex.

This paper adopts one such model, the Conditional Routing Model proposed by Stocco, Lebiere, and Anderson (2010), as a framework for understanding the role of basal ganglia function in the bilingual brain. This model offers a number of advantages over other models. Firstly, it provides a detailed account of both how signals are gated to the prefrontal cortex and of how rule-based behaviors can be encoded in the basal ganglia. Secondly, this model provides a means to explain the activity of the striatum in terms of the execution of abstract “IF–THEN” rules. Finally, the model is biologically plausible and incorporates all of the known inhibitory and excitatory connections between the basal ganglia, the thalamus, and the cortex. These features are important because they can potentially explain both how the appropriate language outputs and grammar processes are selected and switched in the bilingual brain.

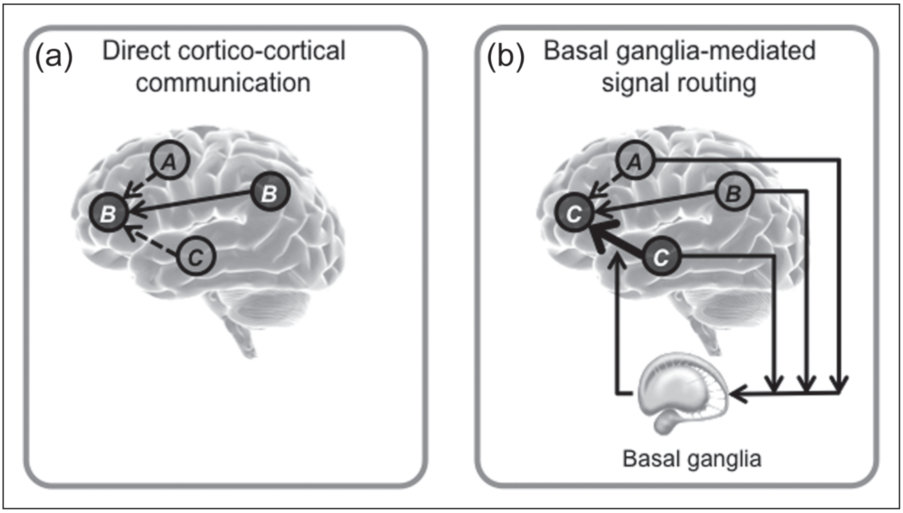

Figure 2. A visual illustration of the role of the basal ganglia in controlling how information is routed in the cortex. (a) Because of the large number of incoming projections, the prefrontal cortex receives many concurrent signals from different cortical areas; under normal conditions, the region with the strongest cortico-cortical connections (region *B*, continuous line) is more likely to successfully affect the prefrontal region than other regions with weaker connection (regions *A* and *C*, dotted lines). (b) The basal ganglia can modify the flow of signals through the cortex by selecting a different pathway (from region *B*, thicker continuous line) and enhancing its strength through the fronto-striatal loops.

The conditional routing model

According to the conditional routing model, the basal ganglia operate as a system that imposes order over the highly overlapping exchange of signals between networks of cortical regions. In the absence of basal ganglia interventions, the flow of signals across the network is determined by the relative strength of cortico-cortical projections. Such relative strength is in turn shaped by previous practice and reward contingencies, and under normal conditions is sufficient to produce effective behavior. However, during learning (where preexisting cortical networks cannot accomplish the task at hand) or in situations where predetermined or automatized cognitive routines cannot accomplish a task goal (such as in a task-switching paradigm), the basal ganglia shape behavior by prioritizing different signals and overriding preexisting cortico-cortical connections.

This idea is visually summarized in Figure 2. Figure 2(a) illustrates a situation where a single prefrontal area (the "target") receives competing signals from three different regions (the "sources") at the same time. As an example, these regions are placed in the frontal (*A*), parietal (*B*), and temporal (*C*) lobes. These three regions contain different types of information, and the "target" prefrontal area must select a signal from only one of them. Since the prefrontal cortex lies at the apex of a hierarchy of converging pathways (e.g., Miller, 2000), such a conflict situation (where multiple signals compete to affect a single region) must not be uncommon. In the absence of basal ganglia routing, the relative strength of these projections, shaped by previous experience and reward contingencies, is sufficient to prioritize signals and produce efficient behavior. In Figure 2(a), the relative strength of cortico-cortical projections is represented by the different lines, with dashed lines indicating weaker connections and solid lines depicting stronger ones. In this hypothetical situation, Region B in the parietal lobes is sending the signal that will have the largest influence on the prefrontal target region.

Under certain situations, however, behavior must be flexibly modified and adapted to perform novel tasks, and the same cortical input region must shift its priority to inputs from another region or regions (e.g., when switching tasks requires attending to a new set of features of the stimuli, or when switching languages requires applying a new set of rules for parsing sentences). According to the conditional routing model, this change in behavior is mediated by the basal ganglia. In particular, the model suggests that the basal ganglia circuit can enhance signals coming from a selected source region, thus increasing the probability of this source's signal to influence the behavior of the target region despite otherwise weaker cortico-cortical connections. The name "Conditional Routing" refers precisely to these circumstances, which can be seen as imposing new routes of information transfer between cortical regions when specific circumstances (or "conditions") arise. An instance of conditional routing is depicted in Figure 2(b), which illustrates a hypothetical situation in which the basal ganglia are routing information from Region C in the temporal lobe to the target area, thus amplifying the signal and reprioritizing the cortico-cortical connections such that Region C is now influencing the target area rather than Region B. In Figure 2(b), the effect of the basal ganglia is illustrated by the thicker line from the temporal region to the target, which replaces the previously weaker (dotted) line.

This process is made possible by the internal organization of the basal ganglia, and in particular of the striatum. According to Stocco, Lebiere, and Anderson (2010), the striatum is internally organized in a way that mirrors the cortico-cortical network, so that "routing" a signal corresponds to activating one particular set of neurons that would eventually activate the corresponding cortico-cortical projection. Importantly, the authors have shown that the routing activity of the basal ganglia can be understood as the execution of conditional rules (i.e., rules of the form "IF … THEN …"). The conditional routing mechanism of this framework has essential implications for the two cognitive functions that are discussed in this paper, namely executive functions and language. The next sections will provide a brief overview of these implications.

Conditional routing, executive functions, and language

As outlined above, there is experimental evidence that connects the basal ganglia to the shifting component of executive function (Yehene, Meiran, & Soroker, 2008). Within the conditional routing framework, such shifting results naturally from the capacity of the basal ganglia to modify the course of information flow within the cortex (e.g., Amos, 2000; Stocco, Lebiere & Anderson, 2010).

According to the conditional routing framework, the importance of basal ganglia function to language arises in part because of the complexity of linguistic rules. Complex rules pose a natural challenge to established cortico-cortical pathways, because they may require flexible activation of particular pathways under specific circumstances. In addition, grammatical rules often depend on complex dependencies between their terms. Take, for instance, the relatively simple English rule for pluralization, which can be stated as: "IF *X* is the singular form and you want to use the plural form, THEN add *-s* to *X*." Applying this rule requires knowing the specific conditions under which it can be applied (for instance, it does not apply to the word "sheep"), mapping the proper word to the variable *X*, and applying an invariant constant term ("*-s*"). The conditional routing model predicts that, with learning, grammatical rules become permanently stored in the basal ganglia in the form of patterns of synaptic strengths that determine signal routing (Stocco, Lebiere & Anderson, 2010).

Thus, the conditional routing model can explain why the impact of basal ganglia lesions on language depends on proficiency (Fabbro, 2001; Zanini et al., 2004). With practice, rules become encoded in the basal ganglia in abstract form, and can be applied whether or not an explicit, conscious representation of the rule exists in the cortex. The model also explains why damage to the basal ganglia would impair precisely these types of automated rule-based behaviors, while sparing to a greater extent behaviors where the rules are explicitly encoded and represented in the cortex (for example, how to pluralize nouns in a less-proficient second language).

The conditional routing model also makes specific predictions about the nature of linguistic errors and mistakes that occur in basal ganglia patients. In particular, the model predicts that complex transformations, requiring simultaneous integration of many sources of information, will require the computations of the striatum, whereas the more direct stimulus–response mappings can be handled by cortico-cortical connections. Because of this dual representation, the model predicts that basal ganglia lesions should impair the production of sentences that require complex grammatical transformations (because they rely on learned patterns in the striatum), but spare those structures that are highly familiar and automatic, such as idiomatic expressions (because their fixed structure remains stored within cortico-cortical connections). Consistent with this prediction, patients with language impairments due to basal ganglia lesions exhibit impoverished grammar in their native language and produce a large amount of language automatisms (Brunner et al., 1982; Code, 1994). While the idea that the basal ganglia encode syntactic rules is common to other accounts (e.g., Paradis, 2004; Ullman, 2001a), the prediction that familiarity predicts the extent to which the basal ganglia will be involved is specific to the conditional routing model.

The connection between language and executive function can be fully appreciated when one notices that, within the conditional routing model, language and executive function share a common set of computations that rely on the basal ganglia circuitry. In particular, the capacity of shifting between tasks and mental sets and the capacity of applying complex rules both depend on the ability of the basal ganglia to properly and timely route the appropriate signals within the network of regions involved in a task. Thus, even if distinct cognitive functions (e.g., language and executive functions) are underpinned by different brain networks, they still rely on the basal ganglia when the communication between different regions needs to be organized according to some complex and non-habitual template. This common ground is central to our theory about how practice within one cognitive function (i.e., managing two languages in the case of bilingualism) can have positive effects on the other (i.e., executive functions).

Conditional routing and bilingualism

To understand how being raised bilingually "trains the brain" in a way that gives rise to improved executive function, one must first explain how bilingualism shapes the basal ganglia circuit. From the point of view of the conditional routing framework, bilingual language experience imposes two concurrent challenges on the basal ganglia circuit. The first is that representation of the two languages needs to be kept distinct, despite the overlapping contexts and information they share. Think, for instance, of an Italian-English bilingual; both languages have morphological rules to mark the plural, but the two rules are different. Deciding which rule to apply depends only on the specific intended language output. According to the conditional routing model, the striatum is necessary to select the appropriate rule based on a specific linguistic context (IF the desired output is English, THEN add "s" to the target noun to pluralize). Recent research has also provided evidence that the basal ganglia are important for maintaining distinct representations of words between languages (Crinion et al., 2006). In Crinion's experiment, the striatum was the only region that showed *language-specific* priming effects (i.e., it was the only region where reduced activation was *only* observed for semantically related words presented in the *same* language). As the authors acknowledged, this effect implies that the activity of the striatal neurons is modulated by language, consistent with its role in discriminating between linguistic contexts. Additional support for this can be found in research showing that direct electrical stimulation of the striatum causes spontaneous and uncontrolled switches between L1 and L2 (Robles et al., 2005).

Thus, for bilinguals, the basal ganglia (and in particular the striatum) face increasing demands to select appropriate rules and representations, and to switch between rules and representations depending on the intended language. Much like switching tasks, switching between languages requires the capacity to override the signals from a network of brain regions that are still active. In many ways, it is even more difficult than the standard task-switching paradigm as it requires switching between two "tasks" (L1 and L2) that are largely automatic and whose neural underpinnings are significantly overlapping. Due to this pressure, we propose that efficient practice in two or more languages has the side effect of increasing the ability of the basal ganglia to exert control over established cortico-cortical connections, resulting in the ability to flexibly reroute signals to the frontal cortex. Note that we chose the word "override," instead of "inhibit," to characterize this process. This choice reflects the fact that, at the *neural* level, "inhibition" refers to the active reduction of a particular signal's strength. The basal ganglia-based mechanism outlined here does not perform "inhibition" in this sense, and relies instead on the timely strengthening of otherwise weaker signals to modify the way information is transferred between different regions of the brain.

In summary, the conditional routing framework predicts that bilingual practice capitalizes on two key functions of the basal ganglia—the capacity of selecting the appropriate rules in response to very specific conditions and the capacity of overriding habitual responses encoded within cortico-cortical connections. These functions are also important in tasks that demand executive functions, such as those that rely on maintaining a top-down goal in the face of distracting information (e.g., the Stroop Task) and those that rely on "shifting" from one determined set of responses to another.

Empirical support

In the previous sections, we have outlined a framework for understanding the mechanisms by which bilingual language practice provides an advantage in executive function. The framework assumes that this advantage is mediated by the basal ganglia and, in particular, that it results from the strengthening of the ability of the basal ganglia to prioritize information flow to the prefrontal cortex, and override cortico-cortical connections. This framework allows for the generation of several predictions, some of which are supported in existing data from other researchers, and others that we are currently investigating.

Perhaps the most interesting prediction concerns situations where the model predicts a *disadvantage* for bilinguals. By predicting that the bilinguals' advantage occurs in terms of a strengthening of the influx of basal ganglia at the disadvantage of cortico-cortical projections, our framework implicitly lays out conditions where bilingual performance should be *inferior* to monolinguals. One can conceive of the difference between striato-cortical and cortico-cortical connections as a difference between endogenous and exogenous control (Monsell, 2003) or, alternatively, as a difference between top-down and bottom-up attentional processes. The research described in the first section of the paper provides extensive evidence that bilinguals are better at exerting top-down control, but are they really worse at capitalizing on bottom-up processes? There is some evidence that this is, indeed, the case. For instance, as seen above, Colzato et al. (2008) reported that bilinguals exhibit inferior performance in the attentional blink task. Successful performance in this task depends on capturing perceptual information flowing in at a fast pace, and missing the second target (during the "blink") might be caused by interference from top-down processes that are still processing the first stimulus. That is, noticing the second target requires suspending, or blocking, the top-down processing that has been initiated on the first target (see Taatgen et al., 2007, for a model of this task that is consistent with this interpretation).

This top-down processing bias is also apparent in the second experiment by Colzato et al. (2008), where the authors compared monolinguals and bilinguals in an inhibition-of-return paradigm. In this paradigm, participants have to attend a stimulus appearing at a particular location. A cue appearing at the same location before the stimulus has the effect of increasing the response reaction time at short Stimulus Onset Asynchronies (SOAs); this fact is usually explained in terms of an automatic inhibition of the previously attended location. The authors reasoned that, if bilinguals' advantage were due to improved inhibitory control, the effect of inhibition of return should be larger in bilinguals, but the prediction was not confirmed. According to our framework, bilinguals' top-down bias should have the effect of speeding up the response times overall (because of the facilitation in setting up the appropriate response set) and actually reducing the effect of the cue (because of the better capacity of ignoring bottom-up information). Colzato's data (see Figure 4, p. 307) suggests that this is, indeed, the case.

Another example of increased top-down control in bilinguals comes from Experiments 2 and 3 in Bialystok et al.'s (2004) paper. In this paper, the authors compared bilinguals and monolinguals in variants of the Simon task. Remember that in the Simon task participants have to respond to the color of the stimulus (e.g., red or green) with the appropriate hand, and ignore its location (left or right). Across different conditions bilinguals showed smaller Simon effects (i.e., smaller costs for responding with the hand to the opposite side of the stimulus), which can be explained as evidence for either better inhibition or for better capacity for ignoring irrelevant perceptual information. In Experiments 2 and 3, however, the authors modified the Simon task by doubling the number of colors of the stimuli. In this condition, the stimuli could have four possible colors (e.g., red, green, yellow, and blue); participants had to respond with the left hand for two out of four possible colors (e.g., red and yellow), and with the right hand for the other two (e.g., green and blue). Thus, instead of selecting between two alternative rules ("if green then press left" and "if red then press right"), participants have to manage four possible rules, some of which entail the same response (e.g., "if red then press right" and "if yellow then press right"). In this modified paradigm, bilinguals showed virtually no increased cost for the additional number of rules, while monolinguals were significantly slower than in the traditional, two-rule version. Our framework can easily account for these findings as a result of the bilinguals' better capacity for rapidly selecting the relevant task rules. An alternative explanation is that bilingual participants had better working memory capacity. The bilingual and monolingual groups, however, were equated for working memory span across two working memory tasks (the alpha span and the sequencing span tasks), thus making our account preferable.

In summary, our framework is consistent not only with the data that show a superiority of bilinguals in switching tasks and managing interference, but also with a number of previously puzzling findings from experiments that used tasks that were designed to examine different components of executive function, such as attentional blink and inhibition of return.

Discussion

This paper provides a comprehensive explanation of the nature of the cognitive advantage that bilinguals exhibit in tasks that require executive function. The proposed theory is that the advantage resides in an increased ability of the signals originating in the striatum to influence the activity of the prefrontal cortex, thus reducing the more automated contributions of other cortical areas. This theory is based on two types of evidence: (a) Evidence that the basal ganglia circuit, and in particular the striatum, is responsible for language selection in bilinguals; and (b) evidence that the same region plays a crucial role in the very same type of tasks where bilinguals outperform monolinguals. In support of this theory, we have described a computational model of how the basal ganglia control and route signals to prefrontal cortex, and propose that extensive language-switching practice in bilinguals strengthens the ability of this system to reroute, or override, cortico-cortical connections, resulting in the empirically observed cognitive advantages in bilinguals.

Understanding the costs of bilingualism

Our proposed framework can be tested and extended in a number of ways.

For instance, it can be used to predict not only those cases in which bilinguals exhibit *superior* performance over monolinguals, but also the situations in which bilinguals are at a *disadvantage* over monolinguals. This has been demonstrated in a number of linguistic tasks, such as those measuring lexical retrieval and verbal fluency (see Bialystok & Feng, 2009, for an example). Our framework can explain these findings in terms of practice effects; because they speak two languages, bilinguals cannot reach the level of performance within one language that can be reached by monolinguals. In addition, at the retrieval level, bilinguals have more interference than monolinguals, with multiple lexical representations sharing an underlying semantic structure.

Crucially, however, our framework predicts conditions where monolinguals should outperform bilinguals in non-linguistic tasks. In particular, we expect that their bias in favor of top-down processing over bottom-up processing would make bilingual individuals less reactive to sudden contextual or perceptual changes that require immediate changes of behavior. Imagine, for instance, an everyday multitasking condition, such as driving and talking to a cell phone. Our framework predicts that bilinguals would be better at performing both tasks concurrently (as indexed, for instance, by measures of lane deviation in the driving task and memory for conversation in the cell phone task), but less reactive to sudden changes in the outside world (for instance, slower at responding to a pedestrian suddenly stepping into the street ahead of them). We see this as an interesting avenue for future research.

Implications for neuroimaging research

The conditional routing framework can also be used to generate testable predictions at the neural level. In particular, it highlights the importance of the striatum as the source of differential abilities to bilinguals. The framework predicts, therefore, that activity of the basal ganglia should exert increased control over the prefrontal cortex in bilinguals. Such differences can be tested using Dynamic Causal Modeling (Friston, Harrison, & Penny, 2003), a methodology that permits comparing the strength of the causal effect exerted by one region on another. It is also conceivable that bilingual practice would result in a measurable increase in the functional connectivity between the striatal nuclei and other language centers (such as Broca's area) or non-linguistic cognitive areas, such as the dorsal prefrontal cortex. A preliminary analysis of this hypothesis has been attempted by Luk, Bialystok, Craik, and Grady (2011) and has yielded positive results, which were also confirmed by more direct measures of structural connectivity, including Diffusor Tensor Imaging.

The case of multilingualism

This paper has primarily discussed how managing *two* languages produces long-lasting changes in behavior and brain circuitry when compared to managing one language. But what can the model say of multilingual individuals (i.e., individuals who speak more than two languages)? Our framework makes two qualitative predictions on this topic. The first prediction is that the behavioral and neural effects of bilingualism should be increased in multilingualism. This prediction arises because the specific operations that “train” the bilingual brain (i.e., switching between languages and overriding intrusive signals from the unwanted language) occur more frequently (and thus are more practiced) in multilinguals than in bilinguals. In other words, an individual that manages three languages in his/her ordinary life needs to switch language more often than an individual who uses only two languages. Furthermore, each linguistic operation of a multilingual needs to override not one, but two or more unwanted languages. Thus, in multilinguals, the amount of interference at any given point is greater than in bilinguals. Within the conditional routing model, this implies that the strength of the fronto-striatal connections needs to be even more enhanced to manage the increasing bottom-up interference. Thus, successful control of many languages should result in an even stronger top-down processing bias (behaviorally) and stronger effect of the basal ganglia on prefrontal activation (neurally).

At the same time, one should not expect these effects to grow linearly with the number of languages spoken by an individual. While a bilingual individual needs to cope with processing difficulties and neural-level conflicts that a monolingual never faces, a multilingual individual can largely use the same brain circuitry that is enhanced in bilingual practice. The specific brain circuit that resolves language conflict in bilinguals is already in place for multilinguals, and while it might need to be “tuned up” to deal with additional interference, it does not require the same amount of reorganization that is necessary to move from speaking one language to speaking two languages. In summary, our model predicts that the behavioral and neural consequences of bilingualism (both positive and negative) should be magnified in multilingualism, but that these effects should follow a law of diminishing returns, with the mastering of each additional language yielding increasingly reduced benefits. This is a testable prediction, which we are currently investigating.

Bilingualism as brain training

Finally, our framework allows for the application of what we have learned from bilinguals to other domains. Specifically, we can adapt bilingual practice as a means to improve cognitive performance or rehabilitate cognitive decline. It is possible that extensive training in task switching produces general cognitive benefits. A great deal has been written about brain training; typically, the results are very domain specific with limited generalization to other domains. As an extreme example, with 230 hours of practice Ericsson, Chase, and Faloon (1980) were able to increase one’s subject digit span from 7 to 79 items; in other memory tests, however, the same participant’s performance improved only modestly. Bilingualism is one of the very few practices that results in general cognitive benefits that have been assessed and replicated. Interestingly, one of the few “brain training” experiments that elicited general cognitive improvements (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008) involved a training regimen that required participants to perform two N-back tasks at the same time, with visually presented and aurally presented stimuli. This training task presents the same characteristics of bilingual practice, including internal control of switching between similar tasks, top-down resistance to interference, and dual tasking. Ultimately, an improved understanding of the mechanisms underlying bilingual brain training could lead to widespread applications for improvement in general cognitive functions.

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Author biographies

Andrea Stocco is a Research Assistant Professor in the Department of Psychology and at the Institute for Learning and Brain Sciences at the University of Washington. His research uses the combination of functional neuroimaging and computational models to investigate the nature of higher-level cognitive processes. He is particularly interested in the role of the basal ganglia in cognitive flexibility.

Briana Yamasaki is a first-year graduate student in the Department of Psychology at the University of Washington. In collaboration with Drs Prat and Stocco, her research investigates the nature of improved executive functions in individuals who develop bilingually.

Rodion Natalenko is an honors student in the Department of Psychology at the University of Washington, working at the Cognition and Cortical Dynamics Laboratory in collaboration with Drs Prat and Stocco. His research interests include individual differences in cognitive styles and their implications for information processing.

Chantel S. Prat is an Assistant Professor in the Department of Psychology and at the Institute for Learning and Brain Sciences at the University of Washington. Her research uses multiple methodologies to explore the biological basis of individual differences in cognitive abilities, with an emphasis on language comprehension. Recently, in collaboration with Dr Stocco, she has begun a series of investigations of the biological basis of improved executive functioning in bilinguals.