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Bilingualism trains specific brain circuits involved in flexible rule selection and application

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ABSTRACT

Bilingual individuals have been shown to outperform monolinguals on a variety of tasks that measure non-linguistic executive functioning, suggesting that some facets of the bilingual experience give rise to generalized improvements in cognitive performance. The current study investigated the hypothesis that such advantage in executive functioning arises from the need to flexibly select and apply rules when speaking multiple languages. Such flexible behavior may strengthen the functioning of the fronto-striatal loops that direct signals to the prefrontal cortex. To test this hypothesis, we compared behavioral and brain data from proficient bilinguals and monolinguals who performed a Rapid Instructed Task Learning paradigm, which requires behaving according to ever-changing rules. Consistent with our hypothesis, bilinguals were faster than monolinguals when executing novel rules, and this improvement was associated with greater modulation of activity in the basal ganglia. The implications of these findings for language and executive function research are discussed herein.

1. Introduction

One of the most puzzling findings in recent cognitive neuroscience research is that individuals who develop bilingually outperform monolinguals on tests that measure non-linguistic executive functions. After decades of research failing to find generalized "training" effects (Melby-Lervåg & Hulme, 2012; Shipstead, Redick, & Engle, 2012), the fact that children born into bilingual families exhibit superior performance on non-linguistic tasks suggests that some aspect of the experience of managing multiple languages must "train the brain" in a way that gives rise to generalized improvements in cognitive functioning (Stocco, Yamasaki, Natalenko, & Prat, 2014). It is particularly interesting that these improvements are found in executive functions, which in many ways represent the apex of human cognitive abilities. Although this finding has been demonstrated throughout the lifespan (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Carlson & Meltzoff, 2008), using paradigms that test different facets of executive functioning (e.g., susceptibility to interference using the Simon or Stroop tasks; flexibility using task switching or card sorting paradigms), the biological nature of the bilingual advantage still remains largely unexplained.

In this paper, we test a proposed neurocognitive mechanism underlying the bilingual advantage in executive functioning, namely, that the advantage stems from the strengthening of a general circuit for routing signals to the prefrontal cortex (PFC) through the basal ganglia (Stocco et al., 2014). Specifically, because this circuit is known to be involved in rule-based behaviors (Muhammad, Wallis, & Miller, 2006; Pasupathy & Miller, 2005), we test the hypothesis that the need for flexible linguistic rule application in bilingual language use gives rise to greater flexibility in adapting behaviors according to novel or changing rules. Using a neuroimaging instantiation of a Rapid Instructed Task Learning (RITL) paradigm (Cole, Laurent, & Stocco, 2013), we compared the behavioral and neural responses of monolinguals and proficient bilinguals while executing novel and practiced arithmetic operations. Below we summarize the research on the bilingual advantage in executive functioning that provided the rationale for this paradigm choice, and a more complete description of the theory that motivated the research herein.

1.1. The bilingual advantage in executive functioning

The term "executive functions" refers to the set of higher-level cognitive processes that oversee and coordinate the control of

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lower-level behavior (Elliott, 2003; Miyake et al., 2000). In other words, executive functions are the mechanisms that enable human cognition to move away from automatic responses, towards more complex, goal-driven behaviors.

Experimental psychologists have largely tried to characterize executive functions by adopting a "divide and conquer" approach. For instance, in an influential study, Miyake et al. (2000) used latent variable analysis to identify distinct mechanisms that underlie performance on a number of executive function paradigms, such as Stroop, *N*-back, and task switching paradigms. The authors were able to break down the monolithic notion of "executive functions" into three loosely independent faculties, namely: inhibition, updating, and set shifting.

Research on the nature of the bilingual advantage in executive functions has largely mimicked this "divide and conquer" approach, attempting to identify the specific components of executive functioning that are strengthened through bilingual language use. Unfortunately, results from these experiments have not converged on a straightforward answer. For instance, a number of experiments carried out with the Simon task (a task that requires inhibition of interference) seem to suggest that bilinguals have better inhibitory processes than do monolinguals (Bialystok, 1999; Bialystok et al., 2004). However, Colzato et al. (2008) found little evidence for a bilingual advantage in tasks that target different facets of inhibitory control, such as the Stop-Signal or the Inhibition of Return tasks. Similarly, there is evidence that bilinguals have better capacity to shift between mental sets than do monolinguals, as indicated by their reduced switch cost in task-switching paradigms (Garbin et al., 2010; Prior & MacWhinney, 2009). However, these results do not generalize to other set-shifting paradigms, such as the Dimensional Change Card Sort Task (Bialystok, 1999; Bialystok & Martin, 2004). Finally, some authors have failed to replicate the bilingual advantage altogether (Paap & Greenberg, 2013).

There may be two reasons behind the heterogeneity of these findings. One possibility is that the bilingual groups recruited in these studies were not comparable with one another. This is because bilingualism is not a dichotomous, or nominal category, but a multi-dimensional variable in which any of a number of factors may drive the bilingual advantage in executive functioning. For instance, bilingual individuals differ from one another in terms of relative language proficiencies, age and method of L2 acquisition, and patterns of language use (e.g., speaking two languages every day vs. speaking one language most of the time). All of the above factors have been shown to modulate the effects of bilingualism. For instance, Luk, De Sa, and Bialystok (2011) found that the age of acquisition modulates the performance of bilinguals in the Flanker task, with early bilinguals showing the least interference to incongruent stimuli. Studies conducted in different locations typically have access to populations that vary significantly along these dimensions, thus making some findings harder to reproduce.

Another possibility is that the "divide and conquer" method may not be the approach best suited for understanding the mechanism behind the bilingual advantage in executive functions. First, bilinguals do not consistently outperform monolinguals across different tasks that rely on the same sub-component process (e.g., inhibition) of executive functioning. Additionally, although inhibitory processes have received a considerable amount of attention in the literature, the bilingual advantage has been demonstrated in tasks that measure updating (Carlson & Meltzoff, 2008) and set shifting (Prior & MacWhinney, 2009) as well. Furthermore, in nature, many of the component processes of executive functioning happen in tandem. For instance, when you switch to a new task, the previously appropriate stimulus–response rules must be inhibited before the new ones can be executed (Mayr & Keele, 2000). Finally, using a divide-and-conquer method does not easily allow one to bridge the link between the bilingual advantage as measured in the laboratory and its implications for real-world processing advantages in bilingual individuals.

Thus, we argue that our understanding of the bilingual advantage can be advanced by carefully considering how bilingual participants are defined and selected, and by choosing an experimental paradigm that captures the robustness of flexible information processing in bilingual individuals. In the current study, the critical feature considered for defining bilingualism was *L2 proficiency*, with only participants who were highly proficient in reading, speaking, and understanding both of their languages being considered as part of the bilingual group. We chose to focus on proficiency as a defining characteristic of bilingualism because several neuroimaging investigations have shown that proficiency is a more powerful determinant of patterns of neural activation observed in bilinguals than is age of L2 acquisition (e.g., Briellmann et al., 2004; Chee, Hon, Lee, & Soon, 2001; Perani et al., 1998). Additionally, in the population of bilingual participants tested at the University of Washington, great variability can be observed in the frequency and proficiency with which *early* bilinguals use their non-English language. Thus, in the current study, we chose to use degree of proficiency as a defining characteristic for inclusion in the bilingual group.

Furthermore, rather than adopting a divide-and-conquer approach, we employed a complex task that involves many components of executive functioning, and more closely emulates real-world scenarios. Specifically, one of the goals of executive functions is to flexibly adapt behavior to accomplish a task that is non-automatic. In fact, some researchers have recently argued that the capacity to change and modify behavior according to internal plans and rules might be the core property of executive functioning, which can be studied using RITL paradigms designed to measure rearrangements of behavior in response to rules (Cole et al., 2013). In this experiment, we used a RITL paradigm to test the hypothesis that bilingualism trains the general capacity to behave adaptively, with language serving as an ever-present condition that provides a dynamic "context" for selecting appropriate behaviors (e.g., Buchweitz & Prat, 2013; Green & Abutalebi, 2013; Stocco et al., 2014).

1.2. Rapid Instructed Task Learning (RITL)

RITL paradigms differ significantly from "traditional" experiments because of the nature of the question they were designed to investigate. In traditional research paradigms, participants are typically initially instructed on how to perform an experimental task, and subsequently given a series of homogeneous experimental stimuli to perform the task upon. In RITL paradigms, on the other hand, participants are given new instructions at the beginning of each trial; thus each trial in a RITL paradigm represents a "novel task".

Different novel tasks are typically generated by combining a set of basic operations in unique ways, so that each resulting task is comparable in terms of complexity and structure to all the others. For instance, in the experiment by Hartstra, Kühn, Verguts, and Brass (2011), each task consisted of responding with finger presses to specific classes of visual stimuli, and different tasks were generated by varying the stimuli and the fingers used to respond. Thus, one task could be "respond with your index finger to cars and with your middle finger to animals", and a different task could be "respond with your middle finger to plants and with your index finger to houses". Similarly, Stocco, Lebiere, O'Reilly, and Anderson (2012) generated different tasks by combining basic arithmetic operations (such as add, subtract, and multiply) into sets of three. For instance, one task could be "add one to *x*, divide *y* by two, and sum the results" and a subsequent task could be