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Becoming a balanced, proficient bilingual: Predictions from age of acquisition & genetic background

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ABSTRACT

Genetic variants related to dopamine functioning (e.g., the ANKK1/TaqIa polymorphism within the *DRD2* gene and the Val158Met polymorphism within the *COMT* gene) have previously been shown to predict cognitive flexibility and learning (e.g., Colzato et al., 2010; Stelzel et al., 2010). Additionally, researchers have found that these genetic variants may also predict second language learning (Mamiya et al., 2016), although this relationship may change across the lifespan (Sugiura et al., 2011). The current study examined the role of the ANKK1/TaqIa and Val158Met polymorphisms along with age of second language acquisition (AoA) in order to predict levels of bilingual proficiency in Spanish-English bilinguals. Results indicated a three-way interaction such that the relationship between the genetic variants and bilingual proficiency depended on AoA. At earlier AoAs, having the genetic variant associated with higher levels of subcortical dopamine (A1 +) predicted the highest levels of bilingual proficiency. At later AoAs, individuals with the genetic variant associated with cortical dopamine levels that are balanced between stability and flexibility (Val/Met) predicted the highest levels of bilingual proficiency. These results fit with theories about the development of language as a subcortical process early in life and as a cortical process later in life (Hernandez & Li, 2007), as well as the importance of both stability and flexibility in bilingual language development (Green & Abutalebi, 2013). Finally, this study raises questions about the direction of causality between bilingualism and cognitive control, which is central to the debate over the "bilingual advantage."

1. Introduction

Acquiring skills or knowledge is based on the appropriate environmental stimuli and on neural systems, such as the dopamine system, which allow the brain to adapt to these environmental stimuli. Wong, Morgan-Short, Ettlinger, and Zheng (2012) were the first to suggest that acquiring a second language is no different, and that individual differences in the functioning of the dopamine system, as indicated by genetic variants in dopamine-related genes such as the D2 dopamine receptor gene (*DRD2*) and Catechol-*O*-methyltransferase gene (*COMT*), may predict second language learning. The current study tested this hypothesis using genotypes of single nucleotide polymorphisms (SNPs) located within the *DRD2* and *COMT* genes, as well as age of second language learning, to predict proficiency and balance in the first and second languages of adult bilinguals.

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1.1. Neurobiological theories of language learning

One of the current neurobiological theories of language learning is the Declarative/Procedural model (Ullman, 2016), which suggests that language is built using the same memory systems as other types of knowledge. Specifically, knowledge of words and idiosyncratic information about language is stored as declarative memory, which is associated with the medial temporal lobes. Procedural memory, on the other hand, is related to learning the phonological and syntactic rules of language, and involves connections between the basal ganglia and frontal cortex. This model makes predictions about the neural bases of different language functions (e.g., phonology, semantics, syntax), but does not consider the role of neural development, which likely influences language learning when it occurs at different ages, as is often the case with second language learning.

A theory of language learning that does consider age of acquisition was proposed by Hernandez and Li (2007) in their Sensorimotor Hypothesis. This theory takes into account the neural development at the onset of language learning to account for the neural and cognitive systems involved in learning that language. For example, when a second language is introduced in childhood, subcortical regions of the brain are still developing, and children tend to approach new information in a sensorimotor fashion (e.g., exploring objects through touch and physical interaction). Later in life, the cortex maintains some plasticity, and learning occurs most often through reading or listening, which are cognitive, rather than sensorimotor, strategies. This theory suggests that learning a second language early in life may lead to adaptations in subcortical structures such as the basal ganglia, whereas learning a second language later in life may lead to adaptations in cortical structures.

What the Procedural/Declarative model and the Sensorimotor hypothesis have in common is an important role of the basal ganglia and frontal cortex in language learning. Theories about language impairments have also begun to suggest that these regions may underlie developmental language disorders such as specific language impairment and dyslexia (Krishnan, Watkins, & Bishop, 2016). This focus on basal ganglia and frontal regions opens up questions about the role of dopamine, which is involved in connections between these two regions, in learning a second language.

In addition to these more general theories regarding the neurobiology of language, Stocco, Yamasaki, Natalenko, and Prat (2014) propose a theory about “bilingual brain training” that specifically connects bilingual language experiences to basal ganglia and frontal cortex functioning based on the conditional routing model. According to this theory, the basal ganglia acts to override automatic cortico-cortical responses in situations where a non-automatic response is preferred, such as in situations of language or task switching. In other words, connections between the basal ganglia and frontal regions are responsible for flexibility in adapting to new tasks. The researchers who developed this theory relate it to bilingualism in situations where one needs to flexibly switch between languages. The language currently in use may produce cortico-cortical responses that are automatic, but the basal ganglia can override these responses in favor of the language not currently in use in order for the speaker to switch languages.

In sum, these three theories about the neurobiology of languages (the Declarative/Procedural Model, the Sensorimotor Hypothesis, and the Bilingual Brain Training Framework) suggest that connections between the basal ganglia and frontal cortex are important for rule-based or procedural knowledge of language, for learning a language at different ages, and for flexibly using the two languages based on context (i.e., switching between the two languages when appropriate). Dopamine may play a role in this relationship through a variety of cognitive functions such as learning (Bäckman & Nyberg, 2013; Knecht et al., 2004), cognitive flexibility (Dang, Donde, Madison, O'Neil, & Jagust, 2012; Steenbergen, Sellaro, Hommel, & Colzato, 2015), and motivation (Frank, Doll, Oas-Terpstra, & Moreno, 2009; Kasanova et al., 2017). The current study will examine the role of dopamine in the basal ganglia and frontal cortex in order to understand bilingual proficiency as a function of subcortical and cortical dopamine levels at different ages based on these theories.

1.2. Genetic variants in the DRD2 and COMT genes

Variation in both the *DRD2* gene and the *COMT* gene has been suggested to be associated with individual differences in language learning because of the role of both genes in the dopamine system turnover, which allows the brain to flexibly adapt to environmental cues. This cognitive flexibility is associated with single nucleotide polymorphisms (SNPs) located within each of these genes. The first of these, ANKK1/Taq1A (rs1800497) is located within the *DRD2* gene. The *DRD2* gene codes for D2 dopamine receptors that are found subcortically, specifically in the striatum. Typically, two genotypes are identified for this polymorphism: A1+ (i.e. carrying at least one A1 allele) and A1- (carrying no A1 alleles). Individuals with the A1+ genotype show a reduction in D2 receptors, which leads to increased subcortical dopamine (Laakso et al., 2005). Research by Stelzel et al. (2010) indicates that individuals with the A1+ genotype, also called “A1 carriers,” showed greater flexibility during cognitive tasks. A1 carriers in their study responded more quickly and made fewer errors on a cognitive flexibility task compared with non-carriers. Of note, other studies have found advantages for non-carriers in other tasks, including long-term memory (Persson, Rieckmann, Kalpouzos, Fischer, & Bäckman, 2015), associative memory (Papenberg et al., 2017), and the trail-making test (Fagundo et al., 2014).

Vaughn et al. (2016) extended this work by examining the relationship between neural activity and *DRD2* genotype in bilingual participants who performed a cognitive flexibility task, a language production task, and an inhibition task. fMRI data from the bilingual sample was analyzed using multiple regression where *DRD2* genotype, language proficiency, and age of second language acquisition were entered as predictors of neural activity during each of the tasks. *DRD2* genotype predicted neural activity during both the cognitive flexibility task and the language production task, but not the inhibition task. These findings suggest that subcortical dopamine may be involved not only in cognitive flexibility, but also in some aspects of language use for bilinguals.

Additional support for the association between bilingualism and this *DRD2* polymorphism comes from Hernandez, Greene, Vaughn, Francis, and Grigorenko (2015). This study found that bilingual and monolingual college students differed in the prevalence