Exploring the genetic basis of second language learning: A systematic review

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Abstract

The study of second language (L2) learning provides insight into how our brains organize more than one language. Studies of the cognitive changes associated with bilingualism, of the genetic basis of learning, and of the genetic basis of first language acquisition are well documented; however, studies of the genetic basis of L2 acquisition are not as prevalent. Understanding its impact could help inform teaching practices and help raise understanding of the difficulties students may face learning L2s. The evidence in this review describes the unique genetic and environmental factors that contribute to L2 learning. It also discusses the potential role of dopamine. Finally, it discusses the relationship between white matter structure and L2 learning. Some potential avenues for future research include the effects of language modality, the effect of teaching style, or utilizing genome-wide association studies (GWAS) to identify other genes with a strong impact on L2 achievement among learners.

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Bilingualism is defined as "the regular use of two or more languages" (Grosjean, 1982). One's first language is referred to as L1 and their second language is referred to as L2. It is suggested that the cognitive systems that control L1 and L2 are largely overlapping; however, a difference in proficiency is observed between "early bilinguals" with similar proficiency in L1 and L2 and "late bilinguals" (Friederici & Wartenburger, 2010). Discrete regions of the brain are dedicated to language processing; the study of bilingualism allows insight into how our brains both organize language and represent two languages (Friederici & Wartenburger, 2010).

L2 students worldwide have the opportunity to learn a lingua franca like English, where 74% of speakers speak it as an L2 (Eberhard et al., 2022), but also can fight the extinction of many at-risk languages (Moseley, 2010). Providing global opportunities to students would allow new voices to enter the conversation, which is especially valuable for those coming from endangered L1s. Language is intrinsic to the culture that developed it; using genetic evidence to promote varied teaching styles that help all students learn an L2 with the most longevity could be used by language revival efforts to avoid extinction.

Understanding the underlying biological mechanisms of second language acquisition and communicating them effectively to educators could potentially inform educational practices (Ansari & Coch, 2006; Goswami, 2006; Posner & Rothbart, 2005). Therefore, understanding high-level cognitive mechanisms of second-language learning, informed by genetics, could potentially lead to changes in second-language educational practices.

The gap that this review aims to cover is to aggregate the research related to the heritability of and gene by environment interactions of L2 acquisition. The gap filled in by this review sits at the intersection of (a) cognitive changes associated with bilingualism, or "the bilingual advantage" (Hernandez et al., 2015; Tao et al., 2021), (b) the genetic basis of learning (P. C. M. Wong et al., 2012), and (c) the genetic basis of first language acquisition (Graham et al., 2015; Grigorenko, 2009). First, this review will explain how the resources were collected, then discuss the relevent evidence, and lastly suggest considerations and future directions.

Methods

This systematic review was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). The PsycINFO database was used to search for peer-reviewed journal articles using a keyword advanced search and search filters. The database advanced search created from the key terms selected was as follows:

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(("second language acquisition") OR ("second language learning") OR
(bilingual*)) AND (("gene") OR (genetic*) OR (genom*) OR (allele))
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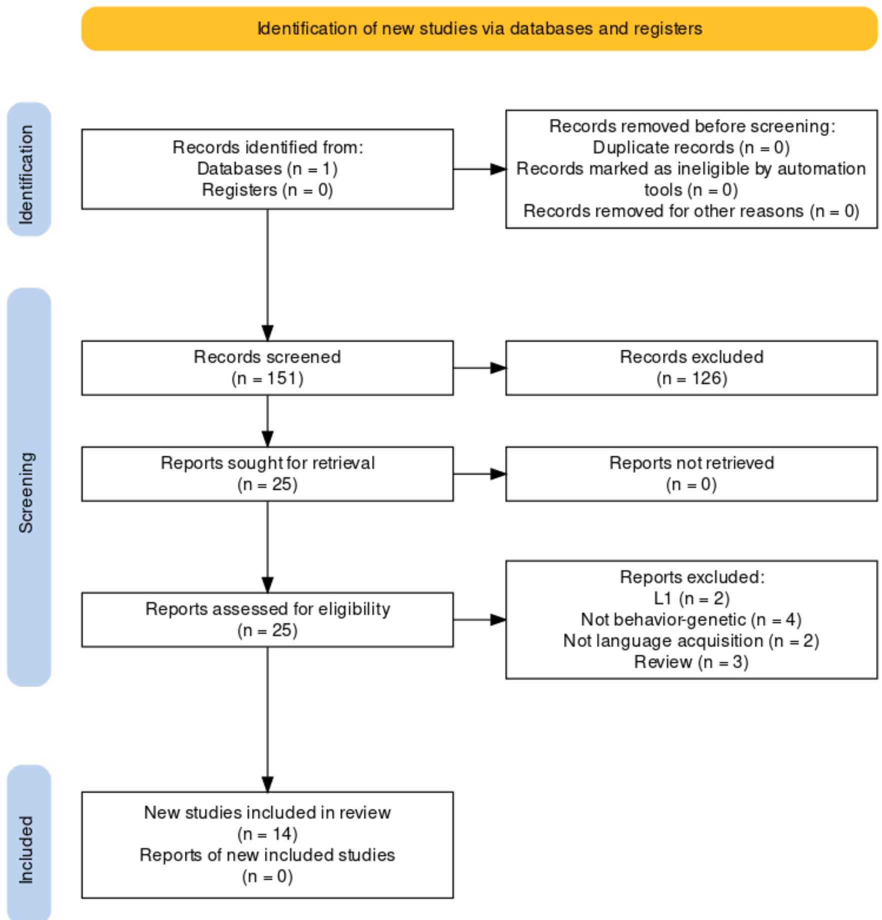
All resulting titles that mentioned language acquisition along with a genetic or biological mechanism moved on to a second round of screening. Those titles that were explicitly focused only on L1 acquisition, were related to cognitive changes associated with bilingualism, were reviews, or were a different topic entirely were dismissed. The abstracts of the first group were evaluated and those that did not specifically focus on genetic or biological factors or did not focus on L2 were dismissed. A total of 14 studies met the criteria for inclusion in this review. Figure 1 shows the number of articles removed at each step of the screening process.

Figure 1: PRISMA flowchart describing screening and exclusion process (Haddaway et al., 2022)**.**



Results

Three major topics were derived from the literature gathered from PsycINFO. First, many studies provided initial evidence of a heritable basis of second language learning: Parsing environmental influences and genetic influences by studying twins. Next, several studies investigated candidate genes as potential predictors of one's performance in an L2. Lastly, the changes in neural substrates with genetic foundations associated with learning a second language were investigated by some evidence. Table 1 provides a breakdown of the studies, including the participants' L1 and L2, the size of the sample, and the structure of the study (twin, candidate gene, etc.).

Table 1: Results from Database Search

	Type	Sample Size	L1/L2	Findings	Other Factors of Note
Vaughn & Hernandez, 2018	Candidate genes (*COMT* & *DRD2*)	n = 117	Spanish/English	*COMT* Val158Met heterozygosity and Taq1a A1+ show highest bilingual proficiency	Strong impact of age of acquisition (AoA)
Hernandez et al., 2015	Candidate gene *DRD2*	n = 122 n = 58	Spanish-English English	A1 allele carrier proportion higher in bilinguals	
Mamiya et al., 2016	Candidate gene *COMT*	n = 44 n = 35	Chinese-English Chinese-English	Carriers of Val allele show stronger changes in white matter after language immersion than non-carriers	Measured with fractional anisotropy and radial diffusivity
Xie et al., 2022	Twin study	n = 349 twins	Chinese-English	Genetic overlap in bilingual achievement of twins	
Zuo & Mok, 2015	Twin study	n = 8 twins	Shanghainese & Mandarin	Twins speak similar in dominant language, but speaking choices play a role	Two L1s, phonetic focus
Wong et al., 2014	Twin study	n = 279 twins	Chinese-English	Genetic factor in L1 and L2 proficiency. Language skills explained by genetic and environmental factors	Cholesky decompositio n analysis
Vaughn et al., 2016	Candidate gene *DRD2*	n = 49	Spanish-English	ROI activity predicted by genotype	Language production tasks used
Antón-Méndez et al., 2015	Twin study	n = 562 twins	Varied	Identifies environmental factors on proficiency like	

				anxiety and attitude	
Dale et al., 2012	Twin study	n = 1632 twins	Varied	Genetic influence on L1 largely separate from influence on L2	
Yamamoto & Sakai, 2016	Imaging study	n = 26 n = 24	Japanese-English Japanese-English	Left arcuate thickness associated with shared factors, fractional anisotropy is not	
Coventry et al., 2012	Twin study	n = 251 twins	Varied	Genetic effect on L2 instruction stronger than environmental effect	
van der Slik et al., 2015	Database study	n = 27,119	Varied-Dutch	Females outperform males learning Dutch in speaking & writing	
Dale et al., 2010	Twin study	n = 604 twins	Varied	Genetic influence on L1 and L2 has high overlap	
Vaquero et al., 2020	Imaging study	n = 62	English-French French-English Other-French/English	Plasticity of brain affected by AoA	

Heritability

Second language learning is influenced by a variety of both genetic and environmental factors (Dale et al., 2010; Xie et al., 2022). The first twin study aiming to study second language acquisition suggested that there was a robust genetic factor, but it contributed to both L1 and L2 acquisition, whereas environmental effects differed more between the L1 and L2 acquisition (Dale et al., 2010). Later, the evidence suggests that the genetic effect on language is largely distinct between L1 and L2; further, the degree of genetic and environmental contributions to L2 performance is the same for individuals exhibiting average performance or extreme performance below and above average (Dale et al., 2012).

Evidence has shown that genetic effects potentially play a strong role in L2 variability, but the measures initially used were categorical and based on teacher, family, and subject surveys (Coventry et al., 2012; Dale et al., 2012). In response to these two early studies, studies investigating cognitive skills rather than categorical response variables were developed and similarly found genetic influence but with a stronger cognitive foundation (S. W. L. Wong et al., 2014; Xie et al., 2022).

Environmental factors that may interact with genetic variation in L2 acquisition were identified by several studies. Attitude towards language learning, anxiety in the classroom (Antón-Méndez et al., 2015), socioeconomic status, and exposure to the language at home (Xie et al., 2022) all are associated with variability in L2 acquisition. In one study, the age of acquisition did not have any significant impact on proficiency (Antón-Méndez et al., 2015); however, proficiency in L1 as children and L1 reading as adolescents were reliable predictors of L2 acquisition (Dale et al., 2012). Gender or sex potentially plays a role too; females consistently outperformed males when learning Dutch as a second language, even when environmental differences were taken into account (van der Slik et al., 2015). As language is a complex cognitive phenomenon, there is also the impact of one's decision to deliberately alter how they speak. Although twins raised separately pronounced an L2 phoneme as similar as twins raised together, it was found that some twins actively chose to speak in a way that was similar to their twin (Zuo & Mok, 2015).

Candidate genes

DRD2 and *COMT* are genes that have been associated with bilingual achievement (Hernandez et al., 2015; Vaughn et al., 2016; Vaughn & Hernandez, 2018). Between a group of bilinguals and monolinguals, bilinguals had a higher proportion of carriers for the Taq1A allele of the ANKK1 domain of *DRD2* (A1+), associated with higher levels of subcortical dopamine (Hernandez et al., 2015). When a second language was learned earlier in life, the A1+ individuals with higher subcortical dopamine had higher levels of bilingual proficiency (Vaughn & Hernandez, 2018). Being a carrier for A1 is a viable predictor of L2 performance; carriers had different activation of language areas of the brain during language and cognitive tasks such as object naming, a color-shape switching task, and the Simon task (Vaughn et al., 2016).

The *COMT* gene contains a polymorphism, Val158Met, where the replacement of valine with methionine reduces the efficiency of COMT, which is necessary for breaking down dopamine in the prefrontal cortex (Witte & Flöel, 2012). When a language is learned later in life, carriers of one Met allele of COMT (Val/Met) showed the highest bilingual achievement (Vaughn & Hernandez, 2018).

COMT gene polymorphisms and ANKK1 polymorphisms in the *DRD2* gene have unique associations with bilingual proficiency related to the region of dopamine affected, either cortical or subcortical; additionally, age of acquisition is an environmental factor that can influence bilingual proficiency (Vaughn & Hernandez, 2018). The relevance of age of acquisition posited by Vaughn & Hernandez (2018) is inconsistent with previous claims such as that of Antón-Méndez (2015). The claim that age of acquisition is a relevant environmental factor is based on the distinction between (a) the importance that DRD2 and subcortical dopamine play in earlier bilingual achievement and (b) the importance of COMT and cortical dopamine play in later-in-life bilingual achievement.

Different properties in white matter connectivity in the right arcuate between second language speaker performance in an immersion program were associated with the genotype of the individual COMT gene (Mamiya et al., 2016). In an instance of a vantage sensitive gene and environment interaction, it was found that individuals with at least one Val allele had stronger and more interconnected white matter (measured by fractional anisotropy [FA] and radial diffusivity [RD]) at the end of the program than individuals with the same genotype at the beginning of the program. Those with Met/Met genotypes showed no association between days in the class and white matter integrity. Later, they found that the white matter integrity and COMT genotype predicted the individual's performance in the immersion program.

Neural pathways of L2 acquisition and the roles of genetics

The connectivity of the left inferior frontal gyrus (IFG), including the arcuate fasciculus (Arcuate) in the brain, are integral to language processing, as is the role of genetics in the development of these regions (Mamiya et al., 2016; Vaquero et al., 2020; Yamamoto & Sakai, 2016). Bilingualism is associated with structural changes in the brain, specifically the left Arcuate of the dorsal pathway of language processing (Vaquero et al., 2020). There was a stronger difference in structure between the left and right Arcuates in individuals with an earlier age of onset of L2 compared to those with later age of onset.

A twin study supported that the dorsal pathway for language processing, the Arcuate, is more reflective of performance in a second language than the ventral pathway, the fronto-occipital fasciculus (Yamamoto & Sakai, 2016). Although higher fractional anisotropy of the left Arcuate was associated with syntactic performance in a second language, its thickness was not. When investigating twins, shared genetic and environmental factors were associated with the thickness of the left Arcuate. In a candidate gene association study, carriers of the Val *COMT* allele had a stronger association between time in an immersion program and white matter fractional anisotropy in the dorsal pathway; both had strong predictive power of performance in the program (Mamiya et al., 2016).

Discussion

Age of acquisition, proficiency in L2, and circumstances of acquisition all are intrinsic to bilingualism; although Grosjean’s definition is a useful baseline, some have suggested that these factors contribute to more than thirty types of bilinguals (Bailey et al., 2020). This may help clarify the balance between genetic effects and environmental effects on L2 acquisition covered in this review.

One aspect of language learning that should be addressed in future research is the impact of the modality of the language on genetic and environmental influences. Some authors touched on this by considering bilingualism between logographic and alphabetic scripts (S. W. L. Wong et al., 2014; Xie et al., 2022), but it could be an important factor based on the cognitive differences observed when reading different modalities. It was observed that when English is written ideographically (“1”) or alphabetically (“one”), language-impaired subjects demonstrated stronger processing of the ideographic representation of numbers which suggests different pathways in the brain (Besner & Coltheart, 1979). Languages where the writing does not consistently correspond to the sounds in spoken language were compared, and the larger the discrepancy between writing and speaking in the language, such as English (discrepant) compared to Japanese hiragana (very consistent), the more errors accumulated (Ellis et al., 2004). None of the studies investigated signed languages, which have been shown in bilingual-bimodal individuals to have a unique neural pathway engaging the visual pathway and auditory pathway together in the language processing areas of the brain (Söderfeldt et al., 1997).

Many of the twin studies were based in L2 classrooms. The effect of the standard classroom would be interesting to challenge by investigating the effect of different teaching styles to see if the conclusions still hold up. Other considerations that might be variables are beliefs about language learning and anxiety in the classroom. We have seen anxiety and choice be brought up as environmental influences in Antón-Méndez (2015) and Zuo & Mok (2015), respectively. Evidence that beliefs and anxiety are associated with L2 performance have been found and suggest that different classroom approaches to lower anxiety should be employed (Palinkašević & Brkić, 2020).

Lastly, genome-wide association studies (GWAS) have revealed polymorphisms associated with language proficiency in the subjects' word recognition skills in Chinese as an L1 (Zhu et al., 2015). A similar experimental paradigm could be applied to L2 proficiency by investigating cognitive measures such as phonological awareness, morphological awareness, vocabulary (Xie et al., 2022), visual word recognition, receptive vocabulary, phonological memory, or speech discrimination (S. W. L. Wong et al., 2014) in conjunction with genome-wide data.

Overall, there are many potential routes for this field to explore. There are few studies that investigate L2 teaching methods and its interaction with genetic profile. It was observed that teaching modality had no difference in impact between monozygotic and dizygotic twins, but the genetic effect on their learning was clear and each teaching modality had its own strengths relating to the students' personal learning aptitudes (Ando, 1992). However, bridging the gap between neuroscience and education is possible as long as the application of neuroscientific principles in education is supported by evidence of efficacy (Ansari & Coch, 2006; Goswami, 2006; Posner & Rothbart, 2005). There is potential that the cognitive mechanisms of second language learning based in genetics could help improve how second languages are taught or explain why some individuals may face challenges in achieving bilingualism that others do not. Improved understanding can help curb the anxiety that often plays a role as an environmental factor.

However, before applying any findings, the field needs to fortify research relating to the use of other language modalities, the effects of different teaching styles, and measuring language proficiency cognitively, as lacking a clear definition of bilingualism or second language proficiency can be seeds of conflicting conclusions. Biologically informed teaching strategies could aid those who struggle to learn second languages and contribute to students' global opportunities or language revitalization efforts (O'Grady, 2018).

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