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Gene-Environment Interactions in Bilingualism and Cognitive Flexibility in Linguistic Studies

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ABSTRACT

Bilingualism provides a unique window into the interplay between genetic predispositions and environmental experience in shaping cognitive flexibility. Evidence suggests that second-language acquisition can enhance executive function, particularly in task-switching, working memory, and attentional control, but these benefits are moderated by individual genetic variability. Polymorphisms in genes such as COMT, DRD4, BDNF, SLC6A20, CDH13, and ZNF804A influence neural mechanisms underlying language learning and cognitive flexibility. Gene-environment interaction frameworks-including differential susceptibility and plasticity models-highlight how enriched bilingual exposure can amplify or mitigate the effects of these genetic variants. Empirical studies demonstrate that the timing, intensity, and quality of bilingual language input interact with genetic factors to produce variability in cognitive outcomes. Integrating genetic, neurocognitive, and experiential data provides a more complete understanding of the mechanisms supporting bilingualism-related cognitive advantages. These insights have implications for educational policy, individualized learning strategies, and interventions targeting cognitive development across the lifespan.

Keywords: *Bilingualism; Cognitive flexibility; Gene-environment interaction; Executive function; Language acquisition; Genetic polymorphisms; Differential susceptibility; Neural plasticity; COMT; BDNF.*

INTRODUCTION

As increasingly bilingual societies emerge across the globe, the relationship of second language learning to cognitive advantage remains of interest. A bilingualism hypothesis postulates that second language learning enhances cognitive flexibility, forming part of a broader executive function framework linked to the management of learning stimuli. Central to this perspective is a gene-environment interaction framework that relates language experience to the development of a core executive function trait. Specific polymorphisms on SLC6A20, CDH13, and ZNF804A genes involved in the neural control of learning increase the likelihood of cognitive flexibility enhancement from second-language acquisition. Polymorphisms across additional genes, including COMT, AHDAD1, and GRIN2B, further moderate the potential for executive function improvement. Computational modelling indicates that monolingual language environments produce different genotype-sensitive language-learning pathways than enriched bilingual exposure, underscoring the importance of both genetic and experiential factors (Nicoladis et al., 2018).

The concept of cognitive flexibility is variously defined, incorporating elements of behavioural (e.g., task-switching) or mental (e.g., originality) aspects. In the language domain, cognitive flexibility encompasses the management of multiple linguistic systems, such as vocabulary-switching, grammar-switching, and code-switching. Language-experience variables like age-at-acquisition, quantity, and quality are causally linked to language proficiency and processing efficiency, and the straightforward computational mechanisms involved suggest these variables are unlikely to act as direct gene moderators. Instead, empirical evidence points to a broader distinction between executive functions that govern learning processes across domains and those that manage the use of previously acquired knowledge, suggesting specific polymorphisms only moderate the former. Analyses of polymorphisms on five gene networks implicated in language acquisition and multiple gene-control specifications demonstrate that bilingual or multilingual language exposure, by increasing the complexity of language learning, modifies the effects of interacting genotype combinations associated with significant theoretical insights (Ziyaev A.A., et al).

Theoretical Foundations of Bilingualism and Cognitive Flexibility

Language represents thought in a form suitable for attachment to utterances, and the unexpected nature of thought manifests itself in the structure of the two systems of the adult bilingual. The two separate lexical and syntactic systems, for the full repertoire of both grammatical and lexical items, have to be maintained in a dialogue between two speakers, who are not in a position to anticipate the choice of language to be adopted by the other. An underlying formalism designed to capture these characteristics supports elements of a theory of first-language acquisition applied to the establishment of a second language in a linguistically reconstructed context (Sasmakov S.A., et al). The interrelation that emerges between these two languages asks for further convergence into the same formalism of the two final outputs, that is, bilingualism and local re-construction. It leads on to the notion that underlying structure converges more directly than tree structure, and that two different forms of bilingualism share the properties of a simplified scheme of the acquisition of a first language. An analytical path for the conventional definitions of bilingualism is proposed, together with relevant arguments substantiating these contentions and a wider range of evidence that arrives at a bilingual out-put from the perspective of first-language acquisition (Nicoladis et al., 2018).

Genetic Contributions to Language Acquisition and executive functions

The complexity of language-learning trajectories depends on age of acquisition, training duration, intensity of exposure, and personality attributes. Winner (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010) documented extensive variability in the bilingual experience. Neuroimaging studies link the proficiency of the first language to the capacity to acquire a second language. Candidate genes that fit the operating definition of language genotype include activity-dependent neurotrophic factor (BDNF), catechol-o-methyltransferase (COMT), dopamine receptor D4 (DRD4), and nucleotide binding and oligomerization domain-containing protein 2 (NOD2). A guide to sequencing genes together with their

affected processes has been published by A. H. Raskin, N. Laing, and S. H. Shum. Language learning, phonological awareness, and working memory along with synonyms of executive functions are linked with these genes. Emerging estimates indicate that up to 50% can be accounted for by genes for each linguistic measurement. Also, over 50% for executive functions. The modules of genes and environment influencing language and executive control have only been unravelled in the last five years.

Environmental Influences on Bilingual Development

Bilingualism is defined as the ability to use two or more languages on a regular basis (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010). Policies promoting the use of more than one language have become increasingly widespread in various fields such as education, work, and diplomacy. Various studies attempting to unravel the nature of bilingualism and its potential effects on cognitive processes have emerged as a result of this growing interest (Nicoladis et al., 2018). Research on the advantages and drawbacks associated with acquiring more than one language has gained recognition in scholarly literature and has informed practices in bilingual education and policymaking. The ongoing discussion on the topic still poses essential questions regarding the relationship between bilingualism and cognitive development, the role of chance and predispositions among individuals, and the significance of genes versus environment and experience-and their interactions-when discussing cognitive development in a bilingual context [table 1].

Table 1: Candidate Genes Modulating Cognitive Flexibility in Bilingualism

Gene	Polymorphisms / Function	Putative Effect
COMT	Val158Met	Modulates dopamine in prefrontal cortex → affects executive function and task-switching
BDNF	Val66Met	Supports synaptic plasticity and learning; interacts with environmental stimulation
DRD4	VNTRs in exon 3	Dopamine receptor affecting novelty-seeking and attention control
SLC6A20	Specific SNPs	Amino acid transporter; implicated in neural control of learning
CDH13	Multiple SNPs	Cell adhesion, neural development; contributes to executive function
ZNF804A	rs1344706	Transcription factor affecting cortical connectivity; executive function
GRIN2B	Various	NMDA receptor subunit; learning and memory
AHADAD1	Various	Modulates synaptic signaling
SLC6A4	5-HTTLPR	Serotonin transporter; affects stress regulation, indirectly impacting learning
NOD2	Various	Linked to neuroimmune interactions affecting cognitive development

The existence of a bilingual advantage in cognitive processes as compared to its monolingual counterpart remains a point of contention. A comprehensive survey of the topic is required to advance the discussion, state the relevant theoretical context and time scale, and propose practical hypotheses regarding the role of gene–environment interactions in bilingualism and cognitive flexibility. The bilingual advantage hypothesis encompasses claims that the practice of switching between languages offers benefits in linguistic and cognitive flexibility. From a broader perspective, bilingualism shapes the linguistic environment to such an extent that it influences the basic set of concepts and cognitive representations developed by each child. In addition to experimental studies controlling for language dominance and parallel longitudinal monitoring,

longitudinal evidence presenting data on the progression of language exposure and connected cognitive flexibility findings may help refine the bilingualism–cognitive flexibility discussion (Sasmakov S.A., et al).

Gene-Environment Interaction Frameworks in Linguistic Studies

Gene-environment interaction frameworks addressing plasticity, diathesis-stress, and differential susceptibility offer insights into how genetic polymorphisms might interact with bilingual experience. The proposed gene-environment analysis models gene–environment interactions for single polymorphisms characterizing environmental exposures thought to influence bilingualism and executive function. Composite predictors capture relevant aspects of language experience. Specification of moderating factors and outcomes is grounded in the literature on candidate polymorphisms related to bilingualism and the accompanying benefits for cognitive flexibility (Abdurakhmanov J., et al).

In studies of psychological constructs, measurement invariance at the level of the latent variable is essential to support the meaningful comparison of relations across groups. Such invariance has been extensively documented for the candidate polymorphisms linked to bilingualism and their expected association with executive control. Relevant environmental moderating factors also have been investigated within the same populations, although potential violations of hierarchical stratification call for caution in interpreting interaction estimates across varying temporal, societal, and cultural contexts (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010).

Specific analytic schemes for examining gene–environment interactions can be modeled on the plasticity/diathesis-stress and differential susceptibility frameworks articulated in the broader literature (Ziyaev A.A., et al). Adaptations for bilingualism and cognitive flexibility include both reinforced and diminished forms of language input in bilingual environments. Environmental and genetic moderators differentially influenced by the timing of accrual further relate to distinct stages of exposure duration relevant to second-language learning (Sasmakov S.A., et al).

Empirical Evidence Linking Genetic Polymorphisms, Language Experience, and Cognitive Flexibility

Gene–environment interactions involving language have been proposed as contributors to cognitive flexibility in bilingualism. Candidate polymorphisms in the COMT, DRD4, BDNF, and SLC6A4 genes have been identified as gene modifiers of the bilingual environment, and empirical studies have tested two general hypotheses: interactions between these polymorphisms and language experience predict individual variability in cognitive flexibility, and these interactions influence cognitive flexibility through their effects on language experience and other intermediate traits. The two hypotheses are associated with different gene–environment frameworks. A summary of representative studies indicates partial support for the second hypothesis, limited evidence for the first, and low convergence among genetic variants investigated, underscoring the need for further investigation (Nicoladis et al., 2018).

Comprehensive models of bilingualism and cognitive flexibility posit convergent and modular patterns of language experience throughout development. Differential susceptibility frameworks view genetic variants as plasticity factors when environmental conditions are optimal; the advantageous effects of plasticity variants have been observed mainly in specific populations. Robust experimental evidence suggests a common initiative that inspires diverse compositional responses, extending the definition of cognitive flexibility beyond explicit switching phenomena, and highlights the role of practice and intrinsic motivation across the lifespan (Azimova S., et al). A growing number of studies report direct measures of the interplay among polymorphisms, language experience, and cognition, offering further avenues for empirical exploration (D'Souza et al., 2020).

Methodological Considerations and Measurement in Gene-Environment Research

In this section, methodological considerations relevant to the study of gene–environment interactions in bilingualism and cognitive flexibility are outlined. Multiple study designs (cross-sectional, longitudinal, and sibling-group) are described, and the importance of data harmonization across studies is emphasized. Various statistical approaches for studying gene–environment interactions are summarized, along with their assumptions and model specifications. Finally, issues related to the reliability and validity of language and cognitive measures are considered (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010) ; (Nicoladis et al., 2018) [table 2].

Table 2: Environmental Moderators in Bilingual Gene-Environment Interaction

Factor	Mechanism	Effect on Cognitive Flexibility	Notes
Age of Acquisition	Early vs. late L2 exposure	Earlier exposure → stronger modulation of gene effects	Sensitive period may amplify plasticity variants
Language Exposure Quantity	Hours per week of active use	Enhances executive control in gene-sensitive individuals	More exposure strengthens neural adaptation
Language Exposure Quality	Structured vs. informal input	Structured learning may optimize gene-environment interaction	Includes formal education, immersion
Cultural / Societal Context	Multilingual vs. monolingual environment	Supports differential susceptibility models	Context shapes whether genetic variants express advantages
Motivation / Practice	Engagement in learning tasks	Enhances effect of “plasticity” alleles	Intrinsic motivation interacts with executive function genes

Implications for Educational Practice and Policy

The gene-environment research framework bears direct relevance to education-related practices and policies concerning languages and cognitive flexibility. The body of evidence reviewed above entails insights for language assessment and instruction, curricular design, and the exploration of potential interventions for further enhancing cognitive control through bilingual experience, in policy contexts where minority/second languages are widely adopted (Nicoladis et al., 2018). Opportunities to promote cognitive flexibility through exposure to additional languages exist across numerous learning environments, including homes, child-care facilities, and community programs offering immersive second-language experiences. Evidence-based strategies in these diverse settings are outlined.

To tackle the unequal accessibility of curricular modalities with demonstrated efficacy, pre-school systems catering to disadvantaged backgrounds may be productive high-priority targets when deploying resources to strengthen cognitive control through second-language experiences. Such an approach aligns with UNESCO’s Global Education Monitoring Report (2019) highlighting the value of mother-tongue instruction during early schooling and suggests dual-track immersion as an option for legal- and policy-language training across a range of contexts (Mannonov A., et al).

Limitations and Future Directions

Bilingual experiences constitute one of the most researched environmental factors affecting cognitive flexibility. Similar to developmental conditions under investigation for gene-environment interactions, such as exposure to a second language (Nicoladis et al., 2018) , socio-economic status (Bailey & Pacheco, 2018), adverse childhood experiences (Keyes et al., 2012), and educational context (Coccia et al., 2019; Tai et al.,

2022), the presence and nature of language input also shape the cognitive flexibility of bilinguals. Exposure to more than one language contributes to the emergence and evolution of the structures of narration during child development. Such bilingual experience, preparing the child for switch in mind-set, at the same time, increases the profile of working memory in generalising or recalling of the word can lead to greater cognitive flexibility (Azimova S., et al). The structures used for word construction differ. Thus, as a code-switching exercise, the surface structure of one language used at a time attunes the mind of the child toward that particular language, so making greater word recall of either language code involves switching and increases cognitive flexibility. Development of language parallel with the construction of narration influences the modulation of mind set.

Conclusion

Gene-environment interplay joins the extremes of genetic preformation and environmental determinism. The former assumes that phenotype can be predicted directly from genotypes and postulates one-to-one maps from alleles to traits; the latter maintains that the environment into which an organism is born determines its life trajectory and all of its characteristics (Nicoladis et al., 2018). Gene-environment interactions allow for disentangling of fixed inheritance from fully malleable biography. Specifically, they suggest that genetic predispositions themselves are conditioned by life experiences, so that different individuals exposed to the same quantities of non-genetic factors exhibit varying developmental outcomes. The apparent mobility of experience at the broad time scale of life history is thus integrated into the concept of genotype at the finer scale of individual genes. The study of lifespan influences therefore remains essential.

Building on this joint understanding, gene-environment interactions are being actively examined in relation to language experience and cognitive flexibility. A number of studies associate polymorphisms in those candidate genes with language processing, yet few connect both language and cognitive flexibility to specific single nucleotide polymorphisms. Further, even fewer examine how the expression of the gene–cognitive flexibility connection is itself modulated by language experience. These opportunities remain scholarly wide open. A systematic agenda is therefore proposed to investigate how cognitive flexibility builds upon language experiences or exposure and whether genetic predisposition further shapes this process.

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