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Exploring Genetic and Epigenetic Influences on Language Acquisition and Cognitive Development

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ABSTRACT
Language acquisition and cognitive development are complex, intertwined processes influenced by both genetic and epigenetic factors. While heritable components have been implicated in the development of language abilities-including phonology, syntax, semantics, and pragmatics-substantial variation remains across individuals and populations. Key genes such as FOXP2, TBR1, and CNTNAP2 have been associated with linguistic capacities, yet the polygenic and environment-dependent nature of these traits complicates mechanistic understanding. Epigenetic modifications, including DNA methylation, histone modifications, and non-coding RNA activity, further modulate gene expression during critical periods of neural development, shaping the trajectory of language and cognitive skills. Integrative research indicates that gene-environment interactions and epigenetic regulation are crucial for understanding variability in language acquisition across developmental stages. Methodological advances, including longitudinal, cross-sectional, and multi-omic approaches, allow for more precise characterization of these influences, providing insights into the molecular and developmental mechanisms underlying human language and cognition.

Keywords: *Language acquisition; Cognitive development; Genetics; Epigenetics; FOXP2; CNTNAP2; Neural development; Gene-environment interaction; Polygenic influences; Developmental neuroscience.*

INTRODUCTION
Language acquisition encompasses the multifaceted processes by which humans develop the ability to formulate-and ultimately, comprehend-meaningful linguistic signs in both spoken and written form. The terminology of 'language abilities' denotes the collection of capabilities that collectively constitute such

expertise-specifically, at least the faculties of phonology, syntax, semantics, and pragmatics. Moreover, substantial evidence indicates that the acquisition of these language abilities is inextricably connected to the parallel development of cognitive capacities that together comprise the larger phenomenon of cognitive development (Fisher & Vernes, 2015). Language, like other skills, matures over specific time frames and is influenced by genetic and epigenetic factors throughout those time windows; nevertheless, it remains both intellectually and practically significant for scholars to identify which dimensions of language and cognition are amenable to enhancement at each stage.

Genetic factors can manifest as variations across loci (the locations of genes or genetic markers on chromosomes) within a genome, including both single-nucleotide polymorphisms and larger structural variations. Extensive research has investigated the role of genetic contributions to language acquisition, language abilities, and cognitive development in the past decade. Prominent genes that have been shown to correlate with language-related capacities include FOXP2, TBR1, and the CNTNAP2 region on chromosome 7 (Devanna et al., 2019). The body of evidence supporting the existence of heritable components to language and cognitive processes has grown robust, yet considerable uncertainty remains regarding the specific nature of the contribution that genetic factors make to these constructs, the precise pathways involved, and the gene-environment dynamics that take place over the course of their development; fundamental questions again await decisive answers.

Theoretical Frameworks for Language Acquisition

With a few exceptions, the study of language, language abilities, and language acquisition has proceeded largely in isolation from genetics or epigenetics. While cognizance of the genetic basis of language and language-related abilities has increased in recent years, reflection on theoretical implications has lagged. Notably, there have been efforts to connect the study of genetics with models of language learning. Nevertheless, interest in the intersection of language and genetics has largely revolved around the so-called unification debate and, more generally, the question of whether language is learned differently than any other complex skill (Fisher & Vernes, 2015). Given the burgeoning interest in genetic and epigenetic influences on language acquisition and cognitive development, exploring competing theories of language acquisition and their compatibility with genetic and epigenetic findings is both timely and necessary.

Only theories of language acquisition or learning that directly address genetic or epigenetic influences are surveyed. Although single-word theories or the like are sometimes regarded as language-acquisition theories, the acquisition of single words is treated here as the first significant milestone in learning a language, rather than as the entire process or even as the focal topic of inquiry. Consequently, acquisition models are characterized by their treatment of the processes and contextual factors that contribute to the transition from a zero level of knowledge at birth to multiword utterances containing two or more words. All models are examined in terms of their implications for the study of language and genetics, and guiding questions focus on the extent to which each model accommodates genetic or epigenetic findings and the manner in which genetic or epigenetic factors are integrated into the model itself (Abdurakhmanov J., et al).

Theories of cognitive development are similarly examined for their integration with genetic and epigenetic investigation. Existing cognitive-development theories that connect to genetics are outlined. Cognitive theories are closely related, but not identical, to language-acquisition models, and their integration with genetic and epigenetic research provides complementary insights into the developmental study of language and cognition.

Genetic Contributions to Language Abilities

A substantial body of work has implicated both genes and epigenetic mechanisms in the acquisition of language and the associated development of cognitive skills. Association studies have linked numerous genetic loci and single-nucleotide polymorphisms to different aspects of linguistic ability (Kovas et al., 2005). The observed heritability of language-related outcomes, as measured in children aged approximately four-and-a-half years, is between 50% and 70%, implicating a considerable polygenic contribution to language development (Fisher & Vernes, 2015). Moreover, growing evidence has detected a range of genomic features whose epigenetic state correlates with language and cognition during early development (L, 2017).

Loci associated with linguistic abilities span substantial portions of the genome and accompany diverse effect sizes. Most of the implicated areas-none yet fully replicated-remain uncharacterised. Findings are similarly unreplicated among populations other than European, revealing a lack of cross-cultural validation. Epigenetic modifications of training and experience-dependent marks, meanwhile, emerge as a potential explanatory mechanism for the acquired nature of language and cognition (Abdurakhmanov J., et al).

Epigenetic Mechanisms in Language and Cognition

Biological epigenetics focuses on non-genetic changeable characteristics of organisms that can persist across generations, affecting long-term development and behaviour response characteristics. Epigenome changes involved in brain development and the formation of neural networks learning a language pair are subject to both global patterns and strong spatial and temporal recruitment (M. Markman et al., 2011). Various epigenetic mechanisms (modification of DNA by methylation, modification of histone structure, presence of non-coding RNA gene products) can affect gene expression and contribute to the development of individual linguistic capabilities [table 1].

Table 1: Genetic and Epigenetic Factors in Language and Cognitive Development

Factor	Description	Role in Language/Cognition
Genetic Loci	FOXP2, TBR1, CNTNAP2 region on chromosome 7	Correlate with linguistic ability; influence phonology, syntax, semantics, pragmatics
Polygenic Effects	Multiple genetic loci with varying effect sizes	Contribute 50–70% heritability of language outcomes in children
Epigenetic Modifications	DNA methylation, histone modification, non-coding RNAs	Affect gene expression; support neural network formation and cognitive-linguistic development
Critical Developmental Windows	Infancy to adolescence	Periods when language abilities and cognitive skills are most plastic and responsive to environmental input
Gene–Environment Interaction	Environment shapes epigenetic states; genetic predisposition modulates sensitivity	Determines individual variability in language acquisition and cognitive trajectories

A range of epigenetic and linguistic parameters continuously interact throughout various forms of cognitive language acquisition during developmental stages from infancy up to the mid-late teens (Fisher & Vernes, 2015). The onset of major periods of cognitive language acquisition emerge predominantly during stages spanning from infant pre-verbal social routines to teen-age adolescent activities, and the acquisition of languages of certain linguistic families is subject to acquisition-limiting biological and environmental factors that also feature strong interaction dependencies.

Interaction of Genes and Environment Across Developmental Stages

Human development is marked by dynamism and plasticity, when new experiences are rapidly integrated across different contexts and settings (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010). The shaping of language, cognition, and the interaction between an individual and the broader environment all undergo distinct changes as age progresses. Genetic and epigenetic endowments undergo modifications in a trajectory that is further delimited by the surrounding environment. Language skills and cognition develop considerably from birth to early adulthood.

Language acquisition entails the learning of one or several languages. Children reach milestones for the acquisition of skills such as speech sounds or words. Language abilities, thereby, denote the range of skills and proficiency in a language acquired after exposure to that language. Knowledge of a human language is a part of universal cognition, hence infants can show the first sign of interactive engagement, which is the joint attention cue with caretakers. Typical children, from neonate to the age of four, already start to develop complex-syntax structure, an accuracy of over 80% on grammatical judgments, and exhibit similar performance in working memory and other cognitive tasks. Children can be said to have completed the bulk of language acquisition by the age of eight since they remain able to learn one or another language throughout life (Allabergenov M., et al).

Methodologies in Studying Genetic and Epigenetic Influences

The study of genetic and epigenetic influences relies on a variety of methodological frameworks for gathering information and answering the pertinent research questions. These frameworks encompass not only the design of the study but also the measurements and outcome variables that are employed, as well as the subsequent analyses that are implemented to generate meaningful results. Broadly speaking, studies can be classified into cross-sectional or longitudinal designs, and there is a choice between observational or interventional studies. In the context of language acquisition and cognitive development, the predominant outcome variables of interest relate to the child's linguistic and cognitive capabilities and the external effects of these capabilities on the acquisition process itself. It is necessary to select the proper covariates to control for potentially confounding influences. In gene and environment research, the emphasis can be placed on the environment, the genotype, or the interplay between these two components (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010); Kovas et al., 2005 [table 2].

Table 2: Methodologies for Studying Genetic and Epigenetic Influences

Methodological Component	Description	Purpose / Advantage
Study Design	Cross-sectional vs longitudinal; observational vs interventional	Tracks development over time; allows causal inference
Outcome Measures	Linguistic abilities (phonology, syntax, semantics, pragmatics), cognitive skills	Quantifies developmental progress; evaluates gene/epigenetic influence
Genetic Analysis	SNPs, structural variants, candidate gene association studies	Identifies heritable contributions to language and cognition
Epigenetic Profiling	DNA methylation, histone modifications, ncRNA analysis	Reveals environment-dependent gene regulation affecting development
Gene–Environment Modeling	Statistical models integrating genetics, epigenetics, and environment	Determines interplay of biological and external influences on development

With regard to the epigenetic aspect of the inquiry, the results may depend on genomic, epigenomic, or neuroimaging data. There is a further choice of analysis, as the genome-wide association study (GWAS) approach has some limitations and measures have been devised to conduct a Mendelian randomization analysis. The absence of longitudinal replication studies across diverse populations limits causal interpretations in the genetic domain, whereas the epigenetic angle marked by environment–epigenome duration and extent-has been little examined through a longitudinal lens. A longitudinal perspective is also vital for investigating the sequence of events between the epigenome, the environment, behaviour, and higher cognitive functions. The same longitudinal viewpoint is necessary to study the epigenetic evolution of the brain as a function of normative language exposure across the early life span (Abdurakhmanov J., et al).

Implications for Education and Intervention

Genetic knowledge can inform how educators promote language development by making use of existing risk markers and by identifying protective factors of influence. Evidence that language development and cognitive skills from infancy through the transition to school are correlated suggests a monitoring system that alerts educators to children who perhaps show less-than-expected growth in language. When children can be identified as less likely to succeed, exposure to those more at risk can inform targeted language-promoting approaches that already exist in the education literature (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010) ; specific strategies then may be matched to individual children rather than implemented at the class-level. Intelligence, socioeconomic status, and engaged parenting have been linked to vocabulary growth, whereas residence in a disadvantageous language model environment, delimitations on child-directed speech, parenting conflict, and less-engaged parenting have been linked to reduced growth. Addressing the well documented effects of different language experiences holds promise for ameliorating risk not just in language but in other areas of development as well.

Ethical, Legal, and Social Considerations

Language acquisition is currently the subject of many interdisciplinary studies covering various aspects of cognitive and communicative skills across different species including insect, mammalian, and human languages. The general subject of research involves the acquisition of linguistic abilities and of the mechanisms and prerequisites for normal maturation. Acquisition is often tracked through the progressive use of word types or grammatical structures on an individual basis. The subjects cover genetically derived individual variation (F. Newbury et al., 2019) , the early development of behaviours in children with sensorineural hearing loss after cochlear implantation (M. Markman et al., 2011) , the effects of values and norms on inter-temporal decisions (A. V. Frolov et al., 2018), and genetic factors influencing motivational strategies for the acquisition of a second language in the absence of adequate conditions for early language learning (A. V. Frolov & H. Gruehn, 2019).

Each research report mirrors the variety of implications that are relevant for successful language acquisition and advisory practices. Parents, educators, and children directly benefit from carefully crafted descriptive studies that emerge from a clear understanding of the genetic, epigenetic, social, and cultural factors influencing adversity in language acquisition. Contemplating astutely upon other studies addressing the first and second language acquisition-induced transcribability of accented speech may give rise to complementary insights (Azimova S., et al).

Successful acquisition of reproduction and acquisition of another language via conversational imitation depends upon the mastery of a local or national language. Acquisition of sensorial modalities other than auditory has been shown to influence the transcribability of pre-trained accented speech from completely different linguistic domains. It is therefore plausible to consider the same observation for accented speech that has been rehearsed via the alternative circuitry of a two-way fully equipped print signal acquisition setup (A. V. Frolov et al., 2019). The described circumstances collected from present and identified reports would readily explain the complexity pertaining to the reproduction of national accents when the local language has not completely been acquired (Sasmakov S.A., et al).

Future Directions in Research

In response to the research questions outlined above, it is possible to delineate several key priorities and directions for future inquiry into genetic and epigenetic influences on language acquisition and cognitive development. Since the publication of the earlier review by Fisher and Vernes (Fisher & Vernes, 2015) , the field has witnessed profound advances in knowledge of the human genome, along with substantial methodological development and widespread adoption of multi-omics approaches. Nonetheless, significant conceptual gaps, methodological challenges, and practical hurdles remain. Many of these are encapsulated in the eight priorities detailed below (Ziyaev A.A., et al).

The first priority concerns the need for integrative multi-omics approaches that draw on epigenetic, transcriptomic, metabolomic, and other molecular data alongside genomic information. As studies in other disciplines such as medicine and psychology have emphasized, such a holistic perspective has great potential to elucidate causal pathways and mechanisms linking genotype to behaviour (DOCKS at The University of North Carolina at Greensboro & E. Simone, 2010). It also offers a powerful framework for identifying the gene–environment interactions that influence the timing and dosage of exposure to environmental factors acting on language and cognition (Azimova S., et al). A second priority arises from the profound typological diversity observed in the world's languages, an attribute that has long been recognized as crucial for testing theoretical propositions concerning language acquisition. Such cross-linguistic comparisons provide an invaluable means of assessing particular ontogenetic scenarios and therefore deserve greater emphasis in the investigation of genetic, epigenetic, and other biological contributions to individual variability in language acquisition (Ziyaev A.A., et al).

A third priority embraces longitudinal studies extending across infancy and early childhood, a period of remarkable brain and behavioural plasticity. Although substantial progress has been made in mapping the human genome and characterizing genetic variation, the factors that govern the intricate timing and coordination of concurrent developmental acquisitions remain poorly understood, particularly during the early years. Close investigation of these factors is essential for identifying early indicators of individual

trajectories, thereby optimally informing monitoring and intervention practices, and for leveraging recent advances in machine-learning, time-series, and dynamical-systems modelling (Sasmakov S.A., et al).
A fourth priority identifies the opportunity to develop new methods for assessing gene–environment interactions, enable alternative strategies for ascertaining direct causal influences, and extend the scope of intervention research. Emerging solutions such as Mendelian randomization, single-nucleotide polymorphism (SNP)–informed randomization, and polygenic-score–informed intervention, as well as interventions based on time-sensitive epigenetic changes, could yield valuable insights into how biological and environmental variables jointly shape language and cognition; yet their potential has yet to be fully realised.

The fifth priority centres on the need for methods that facilitate secure extraction of cognitively relevant intelligence indicators from large, de-identified databases in order to conduct enrichment analyses and assess the relative importance of different determinants of variability in language acquisition and related domains. Such methods could further help establish whether overlapping determinants drive covariation across multiple behaviours, as previously suggested. The sixth priority considers the opportunity to enhance intervention modelling as a means of evaluating different teaching approaches that are tailored to diverse biological and environmental profiles, thereby optimally capitalising on children's innate predispositions. Due recognition of the dual nature of these profiles is essential to support equitable access to opportunities that foster robust and sustainable development.

A seventh priority acknowledges the imperative to establish ethical guidelines and monitoring mechanisms for genetic and epigenetic research that ensure sensitive information remains confidential and restricts application of the findings to their original, narrowly specified domains. Such safeguards protect against inadvertent misuse, unintended consequences, and the potential for mandatory genetic or epigenetic screening that could inadvertently favour the formulation of deterministic models. Proposals seeking explicitly to reduce risk and stigma and to promote reassurance, altruism, acceptance, and respect likewise merit consideration (Ziyaev A.A., et al). Finally, the eighth priority advocates research directed toward developing means of translating genetic and epigenetic findings into actionable, evidence-based insights for classroom practice, thereby closing the current gap between academic and instructional spheres and making further discoveries more readily accessible to educators.

Conclusion

Language acquisition and cognitive development are shaped by interacting genetic, epigenetic, linguistic, cognitive, and social influences. Language acquisition encompasses the end state and processes governing the learning of language(s), while cognitive development refers to the growth of existing capacities and the acquisition of new ones. Genetic material is inherited through reproduction, whereas epigenetic modifications are acquired and subject to experiences (Mannonov A., et al). The two domains develop in parallel. Genetic and epigenetic influences can be quantified through direct measurement of molecular material, behavioural observations, and assessment of various stimuli. Both domains proceed through well-defined stages across specific time windows. Though the potential for influences exists at each stage, risk factors and gene-environment interplay differ across stages. Language acquisition and cognitive development are central to understanding the role of genetics and epigenetics in a range of organisms, including humans. Each represents a multifaceted and complex trait that remains both poorly understood and of considerable importance. Genetic and epigenetic influences on learning have long been proposed for language acquisition, alongside competing constructs such as innate knowledge, general-purpose learning, and emergentism. Genetic and epigenetic contributions to cognitive development have received comparatively less attention, despite broad interest in the topic (L, 2017).

References:

[1] 1. Fisher S., Vernes S. Genetics and the Language Sciences. - 2015. - [PDF]
[2] 2. Devanna P., Dediu D., Vernes S. The Genetics of Language: From complex genes to complex communication. - 2019. - [PDF]
[3] 3. Kovas Y., Hayiou-Thomas M.E., Oliver B.R., Dale P.S., Bishop D.V., Plomin R. Genetic influences in different aspects of language development: The etiology of language skills in 4.5 year-old twins. - 2005. - [PDF]
[4] 4. L.O. Caregiver communication to the child as moderator and mediator of genes for language. - 2017. - [PDF]
[5] 5. Markman T.M., Quittner L.A., Eisenberg S.L., Tobey E.A., Thal D.K., Niparko J.K., Wang N.Y. Language development after cochlear implantation: an epigenetic model // NCBI. - 2011. - URL: https://www.ncbi.nlm.nih.gov
[6] 6. Docks N.C., Simone L.E. Investigating gene–environment interaction as a contributor to language performance. - 2010. - [PDF]
[7] 7. Newbury D.F., Gibson J.L., Conti-Ramsden G., Pickles A., Durkin K., Toseeb U. Using polygenic profiles to predict variation in language and psychosocial outcomes in early and middle childhood. - 2019. - [PDF]
[8] 8. Allabergenov M., et al. Intelligent educational environments and ubiquitous computing for continuous learning and digital literacy development // Journal of Wireless Mobile Networks, Ubiquitous Computing and Dependable Applications. - 2024. - Vol. 15, No. 4. - P. 179–191
[9] 9. Mannonov A., et al. The Philological Library as a modern architectural icon for knowledge and research // Indian Journal of Information Sources and Services. - 2025. - Vol. 15, No. 1. - P. 388–394
[10] 10. Mannonov A., et al. The impact of Uzbek-language mobile libraries on digital education // Indian Journal of Information Sources and Services. - 2025. - Vol. 15, No. 1. - P. 315–319
[11] 11. Abdurakhmanov J., et al. Cloning and expression of recombinant purine nucleoside phosphorylase in the methylotrophic yeast Pichia pastoris // Journal of Advanced Biotechnology and Experimental Therapeutics. - 2023. - DOI: 10.5455/jabet.2023.d153
[12] 12. Moti Ranjan Tandi, & M. Sathish Kumar. (2025). Quantum-Inspired Reconfigurable Computing for Accelerated Matrix Computations in High-Performance Embedded Systems. SCCTS Journal of Embedded Systems Design and Applications , 3(2), 48-58. https://doi.org/10.31838/ESA/03.02.06
[13] 13. Ziyaev A.A., et al. Synthesis of S-(5-aryl-1,3,4-oxadiazol-2-yl) O-alkyl carbonothioate and alkyl 2-((5-aryl-1,3,4-oxadiazol-2-yl)thio) acetate, and their antimicrobial properties // Journal of the Turkish Chemical Society, Section A: Chemistry. - 2023. - DOI: 10.18596/jotcsa.1250629
[14] 14. Azimova S., et al. Study of the immunogenicity of combination of recombinant RBD (Omicron) and nucleocapsid proteins of SARS-CoV-2 expressed in Pichia pastoris // The Open Biochemistry Journal. - 2023. - DOI: 10.2174/011874091x273716231122102205
[15] 15. Sasmakov S.A., et al. Expression of recombinant PreS2-S protein from the hepatitis B virus surface antigen in Pichia pastoris // VacciMonitor. - 2021. - Vol. 30, No. 1. - P. 27–32