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Explaining Age-Related Effects in Bilingual Language Acquisition: The Interplay of Neurodevelopment, Language Exposure, and Learning Mechanisms

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Abstract. For decades, the age-related disparity in second language learning outcomes has remained one of the most debated core topics in bilingual acquisition research, with long-standing disagreements over whether observed differences stem from immutable biological critical periods, variable environmental input, or distinct cognitive learning patterns across life stages. This literature review examines how age shapes differences in bilingual language acquisition between child and adult learners by considering three dimensions: brain development, learning environment and cognitive processes. Research on neurodevelopment suggests that children and adults both have different linguistic advantages in phonological and grammatical development. Studies of language exposure indicate that quantity, quality, and richness of input significantly shape bilingual development. Research on cognitive and learning processes further suggests that children and adults may both acquire a second language under implicit and explicit conditions. Drawing on existing literature in child and adult linguistic studies, the literature argues that age-related differences in bilingual acquisition are not completely determined by biological development but emerge from interactions among neurodevelopmental plasticity, environmental exposure and learning awareness.

Keywords: Bilingualism, Age of Acquisition, Critical Period, Cognitive Processing

1. Introduction

The differences between child and adult second language (L2) acquisition have been studied for decades. A central question that has been discussed is whether children possess an age-related advantage that allows them to learn additional languages faster or even better than adults. Traditionally, such gaps have have been explained through the Critical Period Hypothesis (CPH), which proposes that learning a language changes across development and that earlier acquisition is generally associated with more native-like ultimate attainment. Age of acquisition (AoA) has therefore become an important variable in research to measure whether there is a gap between child and adult learners. However, previous findings also show the belief that younger learners are universally more successful in acquiring a second language is complicated. Age effects vary across linguistic domains and individual learners, while some late learners can also achieve high levels of

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L2 proficiency. As a result, age alone may be insufficient to explain the variation observed in bilingual development.

This literature review examines age-related differences in bilingual and L2 acquisition through three interacting dimensions: neurodevelopment and critical period effects, the quantity and quality of language exposure, and cognitive processing and learning mechanisms. Earlier research provided influential theoretical frameworks or empirical evidence, while recent studies reconsider these explanations through experimental research and updated methods. Understanding these differences can contribute to theoretical and educational implications. Bilingual development can expand individuals' opportunities for communication, education, and participation in a global perspective. Identifying how learning conditions differ across developmental stages may help educators design class instruction that responds to the strengths and weaknesses of learners at different ages.

2. Neurodevelopmental factors in age-related language acquisition

Scholars have increasingly debated whether a critical or sensitive period exists in second language acquisition and how strongly age influences bilingual language development. Earlier research often emphasized the advantages of studying language learning at a younger age, linking early acquisition to greater neuroplasticity and higher ultimate attainment. However, the relationship between age and language acquisition is more complex than the assumption that "younger is always better or faster."

2.1. The critical/sensitive period and age of acquisition

Age of acquisition (AoA) has been widely considered an indicator of second language attainment and is closely associated with the Critical Period Hypothesis. AoA is understood not simply as the irreversible period at which language learning begins, but as a "meta-variable" that reflects learners' cognitive, neurological, linguistic, motivational, and experiential characteristics at the onset of sustained L2 acquisition. Earlier AoA is often associated with greater neurocognitive plasticity, reflected in age-related developmental processes in myelination and neural activation patterns associated with language processing, which may partly explain the advantages among younger learners. However, neurocognitive plasticity is not the determining factor; its developmental timing can also interact with biological and experiential factors, including bilingual experience. Importantly, age-related effects are not uniform across linguistic domains because pronunciation and morphosyntax may show different developmental trajectories. Therefore, AoA should be understood as a more complex predictor of L2 attainment rather than a fixed determinant [1]. Large-scale empirical evidence further demonstrates the complexity of the relationship between age and L2 attainment. In a study of native and non-native English speakers, researchers found that grammar learning ability remains relatively stable until approximately age 17.4, although learners generally need to begin by age 10-12 to achieve native-like proficiency. These findings suggest that language acquisition is a prolonged process and requires sufficient time before learning ability declines, and age alone cannot be explained as an early-childhood advantage [2]. Nevertheless, this age-related decline still does not allow for a clear definition of the critical period, and academic debate continues regarding the intrinsic interpretation of the age effect.

2.2. Rethinking the critical period

While previous studies interpret their findings as evidence for the onset of a critical period, other researchers have questioned whether age-related patterns reflect a distinct critical period. Other scholars challenge this interpretation by distinguishing a general age effect from the specific non-linear pattern predicted by the Critical Period Hypothesis (CPH). Although younger learners

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generally achieve higher ultimate L2 attainment, a continuous decline in attainment with increasing AoA does not provide sufficient evidence for a critical period. Instead, support for the CPH requires a noticeable change in the AoA attainment relationship before and after the proposed critical-period boundary. However, researchers point out that many previous studies utilized statistical approaches that were not appropriate for detecting those changes, such as comparisons of correlation coefficients to infer differences in slopes. Thus, these findings suggest that age-related declines in L2 attainment should not be used to predict a clearly defined critical period. Such linguistic domain variation makes it difficult to identify a specific age boundary that can represent a universal critical period for all aspects of language acquisition [3]. Building on efforts to identify the boundary of a critical period, recent research has shifted focus toward examining the mechanisms that could produce critical period effects (CPE). A study computationally training GPT-2 and RoBERTa language models from scratch under different bilingual exposure schedules. By varying when models were exposed to L1 and L2, the researchers recorded differences in age of L2 exposure while controlling the amount of language input. The models did not naturally exhibit a human-like Critical Period Effect, challenging the idea that such effects inevitably emerge from successful statistical learning. When the researchers explicitly reduced model plasticity through Elastic Weight Consolidation, CPE emerged [4]. These findings suggest that developmental changes in plastics contribute to human CPE, although the research team emphasizes that their results provide only limited evidence for a biologically programmed mechanism.

2.3. Neuroplasticity and the developing bilingual brain

Previous computational modelling studies have revealed that dynamic changes in neuroplasticity can give rise to critical-period-like effects; however, the conclusions of these models still require verification through empirical evidence from the human brain. On this basis, the potential role of plasticity in L2 acquisition highlighted by previous discussion provides a possible neurodevelopmental explanation for age-related differences in bilingual language acquisition. Neuroplasticity is defined as the brain's capacity to reorganize functionally and structurally in response to experience. Although this capacity continues throughout the lifespan, its extent and patterns may change depending on the age at which learning begins. Bilingual language acquisition therefore provides a useful model for examining how early and late language experiences differentially shape the developing brain. Berken et al. argue that language development is influenced by both biological maturation and linguistic experience. Infants initially have a broad capacity to discriminate phonemes across languages, but their perception begins to narrow toward native phonemic contrasts at approximately six months. By twelve months, phonetic perception becomes increasingly tuned to the language to which they are exposed. These early developmental differences are also performed in the organization of bilingual language networks. Simultaneous bilinguals demonstrate greater functional connectivity between the left and right inferior frontal gyri and other regions involved in language control, whereas sequential bilinguals tend to recruit greater neural activity when producing their later-learned L2. Earlier AoA is associated with stronger and more distributed functional connectivity, which reflects greater neural efficiency when producing language [5]. However, reduced plasticity with age does not mean that neuroplasticity disappears in adulthood. A recent longitudinal study that followed adult learners during six months of intensive L2 learning found significant changes in white-matter connectivity with language-related networks, which demonstrates neural changes correlating with L2 performance [6]. These findings suggest that the adult brain retains plasticity during second language learning through past experience

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3. Environmental factors: language exposure and experience

3.1. Beyond age: experience and ultimate attainment

The learning experience becomes particularly important when learners with contrasting AoA and exposure histories are compared. A study examined this issue by comparing Greek English heritage speakers (HSs) and late L2 learners with Greek and English monolingual controls. The two bilingual groups followed contrasting exposure trajectories. HSs were exposed to Greek from early childhood, whereas the late L2 learners were exposed to English at an average age of 8.0 and later moved to the UK at an average age of 28.4. At the time of testing, they had lived in the UK for an average of 10.7 years, providing substantial exposure to English through immersion. The groups were matched for age and educational background. The researchers found that HSs performed similarly to English monolinguals in English, but showed lower performance than Greek monolinguals in their heritage language: only 19.4% of HSs performed within or above the normal native-speaker range in Greek, with average performance 5 SDs below the Greek monolingual mean. In contrast, 34.3% of the late bilinguals performed within the normal native-speaker range on the English grammatical judgement task [7]. These results challenge the original assumption that early exposure guarantees native-like attainment or that late onset necessarily prevents it, suggesting that ultimate attainment reflects learners' continuing language experiences rather than accounting age alone. Another study further identifies the specific individual and environmental factors that contribute to the variation in bilingual attainment. Drawing on ten years of research with over 300 early English L2 learners of different ages, researchers challenge the common assumption that children acquire a second language quickly, effortlessly, and with relatively uniform outcomes. Rather, early L2 learners may require years to approach monolingual levels of performance and show individual variation across different linguistic domains. Such variation is influenced by factors including age, L1 background, cognitive capacities, and the amount of exposure to the language environment. This also suggests that language exposure involves not only its quantity but also its quality and richness [8].

3.2. Quantity and quality of language exposure

Differences in the amount of language input can also substantially shape bilingual development. De Houwer examines the language input environments of younger bilingual children rather than treating bilingual exposure simply as the presence of two languages. The researcher conceptualizes the input environment through several dimensions, including the duration and frequency of exposure, the distribution of languages between parents, and parental interaction strategies. Preliminary data in the article suggest that greater exposure is generally associated with stronger productive ability in the language. Moreover, De Houwer argues that absolute frequency, the actual amount of language input a child receives, may provide a more informative measure than relative frequency, which only describes the proportion of language exposure. Two children with the same 50/50 exposure ratio may receive different total amounts of linguistic input [9]. Therefore, evaluating bilingual development requires attention not only to when exposure begins, but also to the cumulative opportunities children have to hear and use each language. Beyond the quantity of language input, the richness and characteristics of children's language environments can also predict individual differences in long-term L2 outcomes. A longitudinal study was conducted with 21 Chinese L1 English L2 children, following their development from approximately 4.5 to 6.5 years of English exposure. The results showed that different aspects of the language environment predicted different L2 abilities. Greater length of English exposure and richer English environments were

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associated with stronger vocabulary, grammatical, and lexical-semantic performance, while the amount of English that children used on their own additionally predicted lexical-semantic knowledge. Maternal English fluency and education were also associated with better global English comprehension [10]. These findings demonstrate that bilingual development cannot be simply defined by when L2 exposure begins. Rather, the amount, richness, and opportunities for active language use continue to shape L2 attainment even after years of exposure.

4. Cognitive and learning processes across age groups

Beyond neurodevelopment and environmental exposure, age-related differences in bilingual acquisition may also reflect differences in how children and adults process and learn from linguistic information. Children are generally considered to rely more on implicit learning, whereas adults have greater access to explicit learning strategies and metalinguistic knowledge. These differences do not directly indicate that one group has greater learning advantages. Instead, apparent child-adult gaps may partly depend on cognitive demands of language processing and how linguistic knowledge is measured.

Poor grammaticality judgments among late L2 learners may reflect limitations in language processing rather than the effects of learning beyond CPH. Early research examined three possible sources of difficulty: limited L2 working-memory capacity, weaker lexical decoding ability, and slower L2 processing speed. Late L2 learners performed more poorly than native speakers on these processing measures and on grammaticality judgments, while working memory and decoding ability were associated with judgement performance. Their difficulties were also selective rather than uniform. For example, word order and question structures were relatively easier, while article and past-tense morphology were more difficult. Moreover, when native speakers completed similar grammaticality judgments under processing stress, particularly noise or high memory load, their performance showed patterns resembling those of late L2 learners [11]. These findings suggest that poorer adult performance may partly reflect difficulty in processing and applying grammatical knowledge under processing demands, rather than a complete absence of that knowledge.

Subsequent research has further confirmed the crucial role of cognitive processing load. Kromos argues that second-language processing relies heavily on working memory and attentional resources, particularly when language encoding has not yet become automated; consequently, individual differences in working memory directly influence learners' ability to retrieve and apply grammatical knowledge in demanding tasks [12]. Testing procedures and grammatical types can also account for performance differences between native speakers and second-language learners. Dabrowska compared native speakers, late immersion learners and classroom-based second-language learners and found that, in modified grammar judgement tasks (GJTs) focusing on tense and agreement markers, both groups of learners exhibited significant weaknesses; whereas in functional grammar picture-selection tasks (PSTs) focusing on semantic-syntactic contrasts, there were no significant differences in performance across the three groups. Implicit and explicit learning provide another important perspective for understanding the differences between child and adult L2 learners. Implicit learning is learning that occurs without awareness of the regularities being acquired, while explicit learning involves an intention to learn and the conscious use of knowledge during the learning process. Lichman investigated whether children are primarily implicit language learners because of maturational constraints or because they are typically exposed to more implicit learning environments. The study results show that adults recalled more vocabulary and were more accurate than children in word order and article production. However, there was no significant effect of training condition on overall language performance, in which both children and adults were able to produce novel sentences and judge grammaticality successfully under either condition. These findings challenge the assumption that children are inherently restricted to implicit learning mechanisms. It also suggests that the differences between child and adult learning strategies may partly demonstrate differences in instructional environments rather than maturation alone. Therefore, implicit and explicit should not be considered as spectator processes but rather as interconnected strategies that are automatically generated within learning conditions, awareness, and resulting knowledge.

5. Conclusion

Differences between early and late L2 learners cannot be explained by a single factor alone. Children and adults may each have distinct advantages, depending on the linguistic domain, learning

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context, and type of task being assessed. Children often benefit from earlier neuroplasticity and extensive naturalistic exposure, while adults may draw more effectively on working memory, metalinguistic knowledge, and grammatical rules. Therefore, the child-adult gap in L2 acquisition is better understood as the result of an interaction among neurodevelopment, language exposure, cognitive processing, and learning mechanisms rather than a single hypothesis or measurement. Meanwhile, previous research has several limitations. First, age is not completely isolated from other developmental and environmental variables. Second, a single standard cannot be able to define successful L2 acquisition. Studies assess different outcomes, including grammatical accuracy, vocabulary, processing efficiency, and ultimate attainment, while performance itself can vary across assessment tasks. Furthermore, linguistic domains do not necessarily develop at the same rate, which means that an age advantage observed in one domain may not apply to another. Finally, some learning mechanisms can be isolated under controlled conditions in experimental studies, while short-term training or artificial-language tasks may not fully represent long-term bilingual development. Future research should therefore move beyond simple comparisons between younger and older learners. Longitudinal studies that follow learners across multiple stages of development may help distinguish initial learning speed from long-term attainment, while including other possible variables such as input unity, quality and cognitive resources within the same participants. Researchers should also use multiple measurements across different linguistic domains rather than defining proficiency through a single task.

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