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A Review of Neural Mechanisms in Second-Language Acquisition

Ximeng Yang
Liaocheng University, Liaocheng, Shandong, China

Abstract: The neural mechanism of second-language acquisition is an interdisciplinary research topic spanning second-language acquisition and neurolinguistics. Adopting the literature-review method, this paper systematically sorts out research outcomes in this field along research development threads: it reviews classic behavioral experiments such as morpheme-acquisition sequences, and summarizes contributions and limitations of early studies that infer innate cerebral linguistic mechanisms from learners' external linguistic performance; it elaborates the division of labour between the left and right cerebral hemispheres in second language(L2) processing and reviews indirect brain-function detection experiments including dichotic-listening tests; it summarizes research findings of modern neuroimaging techniques such as EEG, fMRI and MEG, interprets linguistic implications of ERP components including N400 and P600 as well as brain-connectivity remodelling induced by bilingual learning, and organizes academic controversies over the critical-period hypothesis and neuroplasticity. Existing studies confirm that age of acquisition and L2 proficiency are two core variables regulating neural representations of a second language. Second-language learning can trigger neuroplastic changes in brain function and structure, yet some experimental conclusions remain divergent. Relevant neural evidence provides theoretical references for L2 classroom teaching. More longitudinal tracking and interdisciplinary research combining multiple techniques are required in future to further clarify the complex cerebral neural processing underlying second-language acquisition.

Keywords: Second-Language Acquisition, Neural Mechanism; Neuroplasticity; Critical-Period Hypothesis

1. Early Theoretical Explorations

Since the birth of Second Language Acquisition (SLA) research, researchers have attempted to explain the law of learners' gradual development of linguistic

Competence From the perspective of innate cerebral linguistic-processing mechanisms. In an era when neuroscientific tools had not been widely applied in linguistics, brain activity could not be directly observed. Scholars could only rely on behavioral indicators of language production to indirectly infer underlying cerebral rules governing language acquisition, which gave rise to a series of classic empirical explorations on acquisition sequences of grammatical forms and built behavioral baselines for subsequent neuroscientific research.

In the early 1970s, researchers launched studies starting from first-language acquisition. Brown [1] adopted a longitudinal tracking paradigm, long-term recording spontaneous oral corpus from three English-speaking children and continuously observing their production of 14 English grammatical morphemes. He verified that first-language children acquire grammatical forms in a stable and repeatable sequence, implying an innate cerebral system regulating the acquisition of linguistic forms. Brown's work was pioneering in two respects: methodologically, it introduced the systematic, criterion-based analysis of spontaneous speech rather than intuition; theoretically, it demonstrated that the order of morpheme emergence remains relatively consistent regardless of individual children's differences in exposure or intelligence, which strongly suggested a maturational component underlying first-language development. In the same year, de Villiers & de Villiers [2] adopted a cross-sectional research design and recruited 21 English-speaking children for replication experiments. They collected language samples from children of different ages in one-off tests, re-affirmed the reliability of the natural sequence of first-language morpheme

acquisition, and ruled out the possibility that such findings stemmed from individual particularities of a small number of participants. This established a reference framework for subsequent comparisons of cerebral linguistic development between first- and second-language learners.

Drawing on empirical findings of first-language acquisition, researchers turned to second-language learners to explore whether the human brain follows similar innate developmental sequences when acquiring a second language. Dulay and Burt [3] selected 151 Spanish-speaking children aged 5-8 from three regions, examined their acquisition of eight English grammatical morphemes in natural immersive linguistic contexts, and calculated accuracy rates of various morphemes from children's oral samples. Results showed highly consistent morpheme-acquisition sequences within the group of second-language children, yet this sequence was not completely identical to the first-language sequence discovered by Brown. Accordingly, the two scholars proposed that second-language morpheme acquisition follows a natural sequence independent of learners' native-language backgrounds. This conclusion directly challenged the dominant Contrastive Analysis Hypothesis at that time. The hypothesis held that the difficulty in L2-learning is determined by linguistic discrepancies between native and target languages. And that acquisition is essentially transfer of native-language habits. However, Dulay and Burt found that the order in which Spanish-speaking children acquired English morphemes did not follow the degree of linguistic differences between Spanish and English. Therefore, it can be inferred that second-language acquisition cannot be simply reduced to the transfer of native-language-habit. The human brain has innate mechanisms regulating the development of linguistic forms. This study also constituted core empirical evidence for Krashen's Natural Order Hypothesis. The hypothesis posited that learners acquire certain grammatical features in a predictable order regardless of instruction.

In general, studies in this period could not directly observe brain activity and inferred cerebral linguistic-processing characteristics merely from learners' external linguistic behaviors. Even so, relevant empirical findings revealed that language acquisition does not rely merely on native-language-habit transfer but is regulated by innate cerebral linguistic mechanisms, laying important theoretical and empirical foundations for subsequent cognitive research on second-language acquisition. Their limitation lies in the fact that brain mechanisms were inferred entirely from external behavioral outcomes, making it impossible to distinguish innate cerebral constraints from influences of acquired input and learning environments. Moreover, morpheme-accuracy measures captured only output, not the underlying processing that produced it, so these studies could not address questions of comprehension or automaticity that would later occupy neuroimaging research.

2. Neurolinguistics and Neural-Function Theories

With advances in neuroscience, researchers began to discuss second-language acquisition from a neurolinguistic perspective. Before fMRI and EEG gained popularity, scholars mainly adopted behavioral-neural paradigms such as brain-damage-case observations and dichotic-listening experiments to interpret second-language-acquisition phenomena through functional differences between the right and left cerebral hemispheres.

2.1 Functions of the Right Hemisphere

The right hemisphere is specialized in holistic information processing and undertakes storage and comprehension of formulaic speech. Formulaic speech includes fixed expressions and sentence patterns serving as undivided holistic memory units. A large number of experiments prove that the acquisition and use of formulaic speech are associated with right-hemisphere activities. Seliger [4] proposed the two-stage-processing hypothesis for second-language acquisition. In L2 classrooms, pattern exercises mainly activate the right hemisphere at the initial stage when learners memorize sentence patterns holistically. As competence improves, the left hemisphere intervenes to conduct grammatical analysis, verification and decomposition of these sentence patterns. This hypothesis explains why beginners memorize abundant fixed patterns yet struggle to decompose and apply them flexibly. The right hemisphere also contributes to prosodic processing, emotional tone and figurative language. These functions are

essential for communicative competence in a second language. However, Seliger's arguments are mostly derived from behavioral inferences without direct neuroimaging evidence. Subsequent studies have challenged this hypothesis, so the specific role of the right hemisphere in second-language acquisition remains to be further verified.

2.2 Functions of the Left Hemisphere

The left hemisphere acts as the core cerebral region for processing L2 phonology, vocabulary and syntax. Simply put, Broca's area in the anterior left hemisphere organizes sentences and plans language production. Wernicke's area in the posterior left hemisphere supports speech comprehension and word recognition. In second-language learning, formal linguistic processing such as lexical identification and syntactic analysis largely depends on the left cerebral hemisphere. The arcuate fasciculus is a white-matter pathway. It connects these two regions, transmits phonological and syntactic information. Its structural integrity directly affects the efficiency of L2 listening and speaking. This dual-pathway architecture, established in clinical aphasiology, has been consistently supported by later functional imaging data in bilingual populations.

Based on clinical observations of brain-damaged patients, Lenneberg [5] proposed the language-lateralization hypothesis: human linguistic functions gradually lateralize toward the left cerebral hemisphere. The brain retains strong plasticity before puberty, and language-related cortical regions are largely consolidated after puberty. In second-language acquisition, this provides early neurological conjectures for interpreting age-related differences. In the 1970s, researchers adopted dichotic-listening experiments to explore language lateralization among bilinguals: different phonetic stimuli were presented to both ears simultaneously. Neural pathways of the right ear project to the contralateral left hemisphere, so words delivered to the right ear were more easily recognized. Such right-ear advantage existed for both native and second languages among bilingual participants, proving that both languages are predominantly processed by the left hemisphere. Genesee [6] carried out bilingual dichotic-listening experiments and found that both native and second languages of early bilingual children are dominated by the left hemisphere. Soares [7] further compared monolinguals and bilinguals. For native-language processing in monolinguals, Soares also confirmed that for L2 processing among bilinguals and native-language processing among monolinguals, the left-hemisphere dominance is almost equivalent. It should be noted that dichotic-listening tests belong to indirect behavioral experiments. They can only infer hemispheric dominance and cannot precisely locate activations inside cerebral cortices. So it represents an inherent limitation of studies in this phase. Nevertheless, they provided the first systematic evidence that two languages can share a common neural substrate. And it also anticipated the overlap-and-separation patterns that functional imaging would later document in detail.

3. Modern Neuroimaging Research

In recent years, advances in neuroimaging techniques including functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and magnetoencephalography (MEG) enables researchers to observe brain activity more directly. So it can compensate for deficiencies of early studies that inferred brain mechanisms merely from behaviors.

EEG is a non-invasive technique for recording cerebral electrical activity. It achieves millisecond-level temporal resolution, suitable for capturing instant neural responses during language comprehension, yet suffers from weak spatial-localization capacity. Studies have found that second-language learners exhibit specific EEG patterns when performing linguistic tasks. For instance, during vocabulary-learning phases, L2 learners show changes in EEG components such as N400, which may relate to retrieval and integration of lexical meaning. In addition, researchers have found that higher L2 proficiency corresponds to more stable EEG patterns, which may be associated with cerebral functional networks formed through long-term language use among bilinguals. Because EEG records neural activity at the very moment a linguistic stimulus is processed, it can reveal implicit processing that behavioral measures such as response accuracy and reaction time may mask, a point that will be developed further in Section 4.2.

fMRI is an imaging technique recording changes in cerebral blood-oxygen levels with

high spatial resolution for direct observation of task-evoked cerebral-activation intensity. Studies have found that second-language learners activate specific brain regions such as the left superior temporal gyrus and left inferior frontal gyrus when performing linguistic tasks. These regions are closely linked to language processing. When beginners process a second language, activation intensity of these brain regions is often higher than that of native speakers, indicating more cerebral resources consumed for L2-information processing. This pattern of elevated recruitment tends to decline as learners automatize the language, reflecting gradual normalization of neural activity with increasing proficiency.

Furthermore, researchers have found that second-language learning triggers changes in cerebral functional connectivity, especially connections among language-related brain regions. Such changes may result from continuous optimization and adjustment of cerebral functional networks among bilinguals through long-term language use. Kim et al. [8] conducted a classic fMRI experiment to compare early and late bilinguals. They found that for early bilinguals who acquired a second language in childhood, native and second languages evoked highly overlapping activations within Broca's area. For late bilinguals who learned a second language after puberty, activations of both languages were spatially separated within Broca's area, while Wernicke's-area activations overlapped heavily in both groups. Their findings revealed influences of age of acquisition on cortical organization of language. Though this experiment did not strictly match L2 proficiency, it also brought risks of confounding variables. Perani et al. [9] supplemented the findings with PET imaging: if late learners reach high L2 proficiency, brain-activation patterns for native and second languages tend to converge. This proves that proficiency can partially offset neural disparities caused by age of acquisition, and both proficiency and age of acquisition jointly shape neural representations of a second language. Overall, these imaging results indicate that the bilingual brain is neither a simple duplicate of the monolingual language network nor a wholly separate system. In fact, it exhibits a dynamic gradient of overlap and separation modulated by the timing and quality of second language acquisition.

MEG is a technique recording changes in cerebral magnetic fields. Compared with EEG, MEG features high temporal and spatial resolution. Studies have found that second-language learners exhibit specific magnetic-activity patterns when performing linguistic tasks. Such patterns may relate to cerebral resources required for L2-information processing. Moreover, learning a second-language causes changes in cerebral magnetic-activity patterns. These patters may be associated with cerebral functional networks formed through long-term language use among bilinguals. Since MEG measures magnetic fields rather than scalp potentials, it is less distorted by the skull and can localize sources with far better precision than EEG. At the same time, MEG can preserve the temporal sensitivity needed for tracking fast linguistic processes.

4. Specific Research on Neural Mechanisms of Second-Language Acquisition in Recent Years

4.1 Effects of Bilingualism on Cerebral Connectivity

Multiple studies indicate that bilingualism strengthens cerebral connectivity, especially when a second language is learned in early life. Researchers have detected enhanced whole-brain neural communication, particularly between the cerebellum and the left frontal cortex, which suggests that early-life language learning improves neuroplasticity and cognitive efficiency. Structural neuroimaging has also reported increased grey-matter density and white-matter integrity in language-related regions of bilinguals relative to monolinguals. So it indicated that linguistic experience leaves measurable anatomical traces in the developing brain.

A collaborative study carried out by the Montreal Neurological Institute-Hospital, the University of Ottawa and the University of Zaragoza in Spain elaborated the role of bilingualism in cognition. Scientists recruited 151 participants speaking French, English or both languages and documented their age of second-language acquisition. Participants underwent resting-state fMRI scans without assigned linguistic tasks to collect spontaneous cerebral-activity signals. fMRI scans revealed stronger inter-regional cerebral connectivity among bilingual participants compared with

monolingual counterparts. Such connectivity was more prominent among those who acquired their second language at younger ages. And this effect was particularly evident between the cerebellum and the left frontal cortex. This experiment demonstrates that bilingual experience can reshape functional connections among brain regions, and individuals with early bilingual acquisition show more prominent synergistic effects of cerebral networks. Nevertheless, this is a cross-sectional study that can only prove correlation; it cannot fully confirm whether enhanced connectivity arises directly from bilingual learning or from innate individual differences. Longitudinal designs that track the same learners before and after intensive L2 training would be required to establish causality. In addition, emerging evidence from Zhang et al. [10] indicates that social interaction during language acquisition also modulates brain network coordination, which deserves more attention in bilingual neuroimaging research.

4.2 EEG Experiments in Second-Language-Acquisition Research

Combining EEG experiments with second-language-acquisition research helps researchers gain in-depth insights into neural mechanisms of language acquisition. Researchers first identify specific traits of second-language learners such as age, learning context and language proficiency. Then they design experimental tasks related to language-acquisition, covering language comprehension, language production, vocabulary learning and syntactic acquisition, in order to observe learners' brain activity. EEG-analysis tools include EEGLAB and BrainVision Analyzer. They are uesd to pre-process raw EEG signals through filtering, re-referencing and segmentation before statistical analysis. Event-related potential (ERP) components induced by language-acquisition tasks serve as major observation targets.

Early EEG research identified two landmark ERP waveforms: N400 reflects semantic-comprehension difficulties and P600 corresponds to syntactic-rule processing. Kutas & Hillyard [11] first discovered that semantically anomalous sentences trigger N400 negative deflections. In the early 1990s, Osterhout & Holcomb [12] found that syntactic violations in sentences induce P600 positive deflections. Researchers applied this "sentence-violation paradigm" to second-language learners. When encountering semantically contradictory sentences, they found that L2 beginners produce larger N400 amplitudes, indicating higher cognitive costs for lexical-semantic integration. The magnitude of P600 evoked by syntactic errors correlates closely with L2 proficiency. Low-proficiency learners may not show clear P600 effects for certain syntactic violations. Even when they cannot subjectively detect sentence errors in tests, their brains still produce implicit neural responses.

Meanwhile, EEG results confirm that age of acquisition modulates L2-processing EEG patterns. For syntactic processing, ERP waveforms among late second-language learners differ from those of native speakers. Yet as L2 proficiency improves, ERP profiles gradually converge toward native-speaker patterns. As demonstrated by Sato et al. [13], even short-term vocabulary training can trigger measurable neural plastic changes reflected in ERP components, demonstrating the brain's rapid adaptive capacity for second-language input.

This convergence has been interpreted as evidence of experience-driven neural adaptation: with sufficient exposure and practice, late learners can recruit the same left-lateralized network that subserves native-language grammar, though they may require more processing time and greater neural effort. The strength of ERP techniques lies in capturing implicit neural processing undetectable via behavioral tests. However, their spatial-localization capacity is limited, making precise neural-source localization difficult; complementary validation with fMRI results is often required. Multimodal designs that combine EEG and fMRI, or EEG and MEG, allow researchers to pair millisecond-level timing with centimetre-level source localization, yielding a more complete picture of L2 processing.

4.3 Critical-Period Hypothesis and Neuroplasticity

Whether a critical period exists for second-language acquisition has long drawn research attention. Johnson and Newport [14] conducted a landmark critical-period experiment: they recruited 46 Chinese- and

Korean-native immigrants to the United States whose immigration ages ranged from 3 to 39 years old. Participants finished grammatical-judgment tasks to judge sentence grammaticality. Experimental results showed that grammatical performance declined significantly with increasing immigration age among participants who immigrated before age 15; participants who immigrated after age 15 generally obtained low scores with large individual discrepancies. Accordingly, they proposed that the language critical period ends in the mid-to-late teenage years as human cognitive-neural mechanisms mature. Nevertheless, this viewpoint remains controversial.

Some studies found that among 120 immigrants who started learning English after age 12, 6 % achieved native-like pronunciation. This finding apparently negates the absolute critical-period hypothesis and suggests that learners who commence second-language acquisition after the supposed critical period may still attain native-like competence. Birdsong [15] pointed out that the critical period is not an on-off time window but rather a sensitive period. Although adult learners face greater difficulty, a small number of individuals can still approach native-like competence with sufficient input and practice. Still, more studies support the critical-period hypothesis, arguing that learners within the critical-period timeframe can make better use of cerebral neuroplasticity for second-language learning. Much of the controversy stems from differing definitions of the outcome measure: studies that rely on ultimate grammatical attainment tend to support a critical period, whereas studies that assess communicative effectiveness or motivation-driven attainment frequently document late-learning success.

Neuroplasticity refers to the brain's capacity to establish internal connections to adapt to surrounding environments. The brain possesses the strongest plasticity in childhood and readily forms new neural pathways in response to linguistic stimuli. Therefore, early second-language-learning enhances cerebral connectivity, cognitive flexibility and neuroplasticity, and such effects are particularly prominent among bilingual individuals. It is worth distinguishing that neuroplasticity persists across the lifespan; childhood brings stronger plasticity, yet the adult brain does not completely lose its remodelling capacity. Adult learners can still induce measurable structural and functional changes through intensive, meaningful L2 practice, which is why an exclusive reliance on the critical-period hypothesis fails to explain the substantial success many adult learners achieve.

5. Conclusion and Outlook

To sum up, considerable progress has been achieved in research on neural mechanisms of second-language acquisition. From early behavioral-theoretical explorations in the 1970s, to indirect neural-function speculations relying on dichotic-listening tests and brain-damage-case studies during the 1970s-1980s, and further to modern neuroimaging research adopting EEG, fMRI and MEG after the 1990s, researchers have continuously uncovered complex brain activity and neural mechanisms underlying second-language acquisition. Synthesizing available experimental evidence: first, the left hemisphere constitutes the core brain region for L2 processing of vocabulary, phonology and syntax, whereas the right hemisphere participates in formulaic-speech, pragmatic and prosodic processing; second, age of acquisition and L2 proficiency jointly determine neural representations of a second language, and proficiency can partially mitigate neural disparities caused by late acquisition; third, second-language learning induces plastic alterations in cerebral functional connectivity, yet controversies persist over the critical-period hypothesis, and adult learners still retain neuroplasticity.

These studies not only deepen our understanding of the nature and the process of SLA, but also deliver important implications for education and language learning. Second-language learning in childhood enjoys neuroplasticity advantages, yet adults are not incapable of mastering a second language. Teaching should attach importance to cognitive-load disparities between grammatical and semantic processing, provide beginners with sufficient input and practice, and avoid simply copying first-language-acquisition modes. Neural evidence also suggests that learning outcomes should not be judged merely by test accuracy. Some learners produce incorrect behavioural judgments yet already generate implicit cerebral processing, hence teaching

feedback should be diversified.

In the future, with continuous advances in neuroscience and relevant technologies, further breakthroughs can be expected in research on neural mechanisms of second-language acquisition. Most existing studies are cross-sectional and lack long-term longitudinal data. For example, more advanced imaging technologies and analytical methods can help us further reveal cerebral-activity patterns and neural mechanisms in language-learning processes. Through interdisciplinary cooperation and research, we can gain more comprehensive understanding of cognitive, affective, social and other factors influencing second-language acquisition. Long-term tracking observations and empirical research can help us more accurately evaluate long-term impacts of second-language acquisition on cerebral function and structure. These studies will provide important scientific evidence and practical instructional guidance for us to better understand the essence and mechanisms of human linguistic capacity.

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