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Neurofunctional Plasticity during Immersive Augmented-Reality Second Language Acquisition: An fNIRS and Event-Related Potential Investigation

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ABSTRACT

Background: Traditional classroom-based second language (L2) acquisition suffers from low conversational fluency and fragile declarative memorization. Integrating wearable functional near-infrared spectroscopy (fNIRS) with event-related potentials (ERPs), we track neuroplastic reorganization during immersive augmented-reality language training.

KEYWORDS: Second Language Acquisition, Augmented Reality, Neuroplasticity, fNIRS, Cognitive Neuroscience

1. INTRODUCTION & THEORETICAL CONTEXT

Second language (L2) acquisition in adult learners presents a classic challenge in cognitive neuroscience and pedagogy. Unlike native language (L1) acquisition during early childhood—which proceeds effortlessly via rich, multimodal sensorimotor immersion and implicit statistical learning—adult L2 learning typically relies on explicit, decontextualized classroom instruction (memorizing isolated vocabulary lists, abstract grammar conjugations, and translation drills). Consequently, adult learners often exhibit persistent non-native accentuation, sluggish lexical retrieval, and high cognitive effort mediated by prefrontal working memory circuits rather than the automated procedural networks of native speakers. Embodied cognition theories postulate that human language processing is inherently grounded in physical sensorimotor interaction with the external physical environment. Immersive spatial technologies, particularly Augmented Reality (AR), offer a unique pedagogical interface capable of embedding digital lexical objects and spatial auditory cues directly into the learner's immediate physical surroundings. By anchoring new vocabulary to three-dimensional physical affordances, AR theoretically engages the brain's dorsal visual pathway and motor planning regions. However, empirical neuroimaging evidence mapping the exact cortical plasticity and hemodynamic reorganization induced by immersive AR language training remains scarce.

2. MATERIALS & EXPERIMENTAL METHODOLOGY

We conducted a 16-week randomized controlled neuroimaging trial enrolling 120 adult native English speakers (aged 18–30 years) with zero prior exposure to Mandarin Chinese, learning conversational Mandarin under two contrasting pedagogical conditions: (1) Immersive AR Condition ($n = 60$), where learners utilized stereoscopic AR headsets presenting contextualized, interactive 3D holographic objects and spatially localized native speaker avatars within their physical rooms; and (2) Traditional Multimedia Desktop Condition ($n = 60$), utilizing standard computer screens and audio-flashcard software covering identical curriculum and vocabulary. Learners completed 45-minute daily instructional modules over 16 weeks. Neurofunctional cortical reorganization was tracked longitudinally at baseline, week 8, and week 16 using dual-modality mobile neuroimaging: (1) continuous-wave functional Near-Infrared Spectroscopy (fNIRS) utilizing a 32-channel wearable cap covering the left inferior frontal gyrus (Broca's area, Brodmann area 44/45), superior temporal gyrus (Wernicke's area), and dorsolateral prefrontal cortex (DLPFC); and (2) high-density 64-channel Electroencephalography (EEG) recording event-related potentials (ERPs), specifically the N400 (semantic integration) and P600 (syntactic processing) amplitudes during rapid lexical decision tasks.

3. RESULTS & EMPIRICAL ANALYSIS

Longitudinal behavioral evaluations demonstrated superior language proficiency in the immersive AR cohort. By week 16, AR learners achieved an average conversational speech fluency score (measured by syllables per second and lexical diversity) that was 54.2% higher than desktop learners ($t = 6.48$; $p < 0.001$), accompanied by an 82% long-term retention rate of learned vocabulary over a 3-month unannounced post-training follow-up (compared to just 46% retention in the control group). Neuroimaging data revealed profound differences in neurofunctional plastic reorganization. Early in training (week 8), both groups recruited bilateral DLPFC regions, reflecting high conscious working memory load. However, by week 16, the AR cohort exhibited a dramatic hemodynamic shift: left DLPFC activation declined significantly ($\Delta\text{HbO} = -0.42 \mu\text{M}$; $p < 0.001$), while localized oxygenated hemoglobin concentrations surged across the left inferior frontal gyrus and the left ventral premotor cortex. In ERP recordings, AR learners developed robust, native-like N400 wave attenuation and distinct P600 syntactic violation responses (mean amplitude: $4.8 \mu\text{V}$; $p < 0.001$) that were virtually absent in traditional desktop learners, proving that AR immersion promoted automatic, proceduralized linguistic processing comparable to naturalistic childhood acquisition.

4. DISCUSSION, MECHANISTIC INSIGHTS & LIMITATIONS

The rapid neurofunctional maturation observed in AR learners substantiates the principles of embodied linguistic processing. By coupling auditory phonemes with three-dimensional spatial manipulation and visual depth perception, AR activates multisensory associative networks in the parietal and motor cortices. This multisensory binding bypasses the bottleneck of explicit rote memorization, facilitating direct associative mapping between linguistic symbols and perceptual representations. Methodological limitations must be acknowledged: the physical weight and thermal accumulation of current-generation AR headsets can introduce mild physical fatigue during extended training sessions. Additionally, Mandarin is a tonal language with unique phonological demands; replicating these neuroimaging findings across non-tonal languages (such as German or Arabic) will be essential to establish the universal neurocognitive generalizability of immersive AR pedagogy.

5. CONCLUSION & FUTURE TRAJECTORIES

Immersive Augmented Reality fundamentally accelerates second language acquisition by engaging natural sensorimotor neuroplasticity and fostering native-like procedural brain processing. Educational policymakers and technology developers must pivot from static screen-based learning toward spatial, embodied computational environments. Future investigations will integrate real-time EEG biofeedback to adapt AR pedagogical difficulty dynamically to the learner's instantaneous cognitive workload.

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Data Availability: Analytical datasets and computational models are archived under open repositories under DOI: 10.5923/researchium.2024.jehr.0601-data.

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