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EMPIRICAL STUDY

Learning Novel Words in an Immersive Virtual-Reality Context: Tracking Lexicalization Through Behavioral and Event-Related-Potential Measures

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Abstract: The present study used immersive virtual-reality (iVR) technology to simulate a real-life environment and examined its impact on novel-word learning and lexicalization. On Days 1–3, Chinese-speaking participants learned German words in iVR and traditional picture–word (PW) association contexts. A semantic-priming task was used to measure word lexicalization on Day 4, and again 6 months later. The behavioral findings of an immediate posttest showed a larger semantic-priming effect on iVR-learned words compared to PW-learned words. Moreover, electrophysiological results of the immediate posttest demonstrated significant semantic-priming effects only for iVR-learned words, such that related prime–target pairs elicited enhanced N400

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amplitude compared to unrelated prime–target pairs. However, after 6 months, there were no differences between the iVR and PW conditions. The findings support the embodied-cognition theory and dual-coding theory and suggest that a virtual real-life learning context with multimodal enrichment facilitates novel-word learning and lexicalization but that these effects seem to disappear over time.

Keywords virtual reality; novel-word learning; semantic priming; lexicalization; event-related potentials

Introduction

Vocabulary acquisition in a new language can be a complex task for adults. Learning words not only requires the acquisition of the form and meaning of the new words, but it also includes the process of lexicalization, in which the novel word is integrated and interacts with existing words (Fuhrman et al., 2021; Lei et al., 2022; Liu et al., 2024). Related studies have demonstrated that multimodal enrichment (e.g., through pictures or videos) may promote word learning outcomes (Andrä et al., 2020; Mayer et al., 2015). However, these issues have not been examined in a natural/real-life environment. In this study, we utilize immersive virtual-reality (iVR) technology to simulate a real-life environment and compare novel-word lexicalization when the words are learned in iVR or picture–word (PW) learning contexts.

Background Literature

Novel-Word Learning and Multimodal Enrichment

In a real-life environment, learning of complex skills and knowledge is multimodal in nature (e.g., word learning, interpreting). The presence of multiple sensory and motor information during learning has been referred to as multimodal enrichment (Mathias & von Kriegstein, 2023). In the language learning literature, there is accumulating evidence that multimodal enrichment is superior to a unimodal context with respect to increasing learning performance on recall and recognition tasks (Mathias et al., 2022; Mayer et al., 2015; Suanda et al., 2016). For instance, Andrä et al. (2020) asked participants to learn novel words either in a gesture enrichment condition or in a no-enrichment condition. Learners in the gesture enrichment condition heard novel words accompanied by self-performed gestures, whereas learners in the no-enrichment condition were presented only with translation equivalents. Results showed that learners who had used self-performed gestures outperformed participants who learned through translations, which suggested that a learning context involving social, multisensory, and action–perception processing may increase learning efficiency and memory performance.

Benefits of multimodal enrichment for language processing are supported by the embodied-cognition theory, which emphasizes that whole-body interactions with environments affect formation of experiences and knowledge (Barsalou, 2008; Braxton et al., 2008). This viewpoint has received support from empirical studies examining the interaction between language processing and embodied experiences (Hauk et al., 2004; Wei et al., 2024). For instance, Dudschig et al. (2014) conducted a series of experiments to investigate the association between late-learned second language (L2) word processing and the sensorimotor system. Results showed that the L2 automatically activated motor responses, such as the word *star* facilitating an upward (motor) response, supporting the language–action compatibility phenomenon. Moreover, in a recent event-related potential (ERP) study, Wei et al. (2024) examined the cognitive embodiment of abstract concepts among Chinese–English bilinguals and revealed that trials in which the meanings of first language (L1) high-power words that were congruent with their sensory metaphors (e.g., *king-up*) elicited more positive P300 and fewer negative N400 amplitudes compared to incongruent trials. These findings underscore the role of embodied representations in language processing.

With respect to the language learning literature, compared to the unimodal learning environment (e.g., traditional classroom settings presenting word–word/picture–word associations), whole-body interactions with real-life environments (e.g., moving around, grasping objects) may offer learners an opportunity to establish native-like lexical-semantic representations for novel words and activate relevant brain regions (see the embodied-cognition theory; Barsalou, 2008). For example, in an fMRI study, Mayer et al. (2015) found that novel words learned in an enriched context, particularly through self-performed gestures, were learned more effectively than the words learned in a verbal context. Importantly, the brain activity in specialized visual and motor regions correlated with behavioral learning performance. Moreover, Linck et al. (2009) examined English-speaking learners who were either studying Spanish abroad in Spain or at home in a classroom. The finding that the learners studying abroad outperformed their peers at home highlights the importance of contextualized, whole-body interactions within learning environments.

The dual-coding theory offers another theoretical support of the learning benefits from multimodal enrichment (Jared et al., 2013; Paivio & Csapo, 1969; Wong & Samudra, 2021). The theory proposes that verbal information, such as spoken language, is represented in a verbal modality, and nonverbal information, such as environmental sounds and actions, is represented in a nonverbal modality. Each modality can crossmodally activate the other, resulting in enhanced memory for dually coded information relative to unimodally encoded stimuli. In other words, in addition to the engagement of the verbal modality, the encoding of nonverbal information, such as sensorimotor features, may assist novel-word acquisition (Mathias et al., 2022).

For adults, positive learning outcomes of multimodal enrichment are believed to exceed unimodal learning; however, it is unclear how whole-body interactions in a real-life environment affect novel-word learning. Recent studies have used iVR technology to simulate real-life environments and have demonstrated its effectiveness as a tool for novel-word learning (Fuhrman et al., 2021; Jiao et al., 2024; Legault et al., 2019). For instance, Legault and colleagues (2019) asked learners to learn novel words in either iVR or word–word association conditions. The findings from a lexical-recognition task revealed the benefit of the iVR approach. Until now, studies on novel-word learning in (simulated) real-life environments are limited to recognition/recall performance immediately after learning, such as through lexical-recognition (Legault et al., 2019) or lexical-decision (Jiao et al., 2024) tasks. It is, however, unclear whether similar benefits from an iVR context will emerge for the lexicalization process of novel words over time.

Novel-Word Learning and Lexicalization

The complementary learning systems model hypothesizes that two stages are involved in word learning (Blakeman & Mareschal, 2020; Davis & Gaskell, 2009; McClelland et al., 1995). The first stage involves the hippocampus, in which novel words are encoded as episodic memory traces immediately after learning. The second stage involves the neocortex, where newly learned novel words are gradually integrated into learners' existing semantic memory, a process called *lexicalization*. Examining this lexicalization process (Bakker et al., 2015; Lei et al., 2013) is the focus of the present study.

Lexicalization of novel words is commonly examined by semantic-priming tasks and electroencephalography (EEG; Bakker et al., 2015; Kurdziel & Spencer, 2016). Relevant word-learning studies typically present novel words and existing words in pairs and require learners to identify the semantic relatedness of novel–existing word pairs. In general, successful lexicalization of a novel word implies that the connections between novel words and existing words are strengthened, showing increased semantic-priming effects in behavioral performance (Bakker et al., 2015; Lei et al., 2022; Liu & van Hell, 2020).

Research using EEG has investigated specific ERPs during word learning and lexicalization by focusing on two particular ERP components: the N400 and the late positive component (LPC). N400 effects are closely associated with automatic processes involved in semantic activation, whereas LPC effects have been associated with controlled, strategical processes of semantic retrieval (Kutas & Federmeier, 2011; Liu & van Hell, 2020). Liu and van Hell (2020) trained participants to learn novel words with verbal definitions for two consecutive days followed by a semantic-priming task. The authors found more positive LPC responses for related prime–target pairs compared to unrelated pairs; however, there were no effects on N400. These findings suggest that retrieval of the meaning of novel words that were learned only with verbal information was more controlled and strategic (see also Bakker et al., 2015).

Following the study of Liu and van Hell (2020), Lei et al. (2022) investigated the lexicalization of novel words in a multimodal enriched learning context. In addition to a learning condition with verbal definitions, Lei et al. included a definition–image condition by adding nonverbal image information. The results from a semantic-relatedness judgement test showed better behavioral performance in the definition–image condition but no difference in ERP patterns. To some extent, these findings underscore the behavioral benefits of multimodal enrichment on lexicalization of novel-word meaning (Palma & Titone, 2021). However, it is possible that the absence of changes in ERP patterns might be due to the limited information provided in 2D images. The present study, therefore, employed iVR to simulate a real-life environment in which perceptual and sensorimotor information was embedded.

The Present Study

To our knowledge, the impact of multimodal enrichment on novel-word learning has been limited to recognition/recall performance, especially in VR studies (e.g., a lexical-decision task in Jiao et al.'s study, 2024, and a lexical-recognition task in Legault et al.'s study, 2019). It is unclear whether these findings can inform the researchers' understanding of lexicalization process of novel words. The present study tested whether multimodal enrichment through an iVR context can influence the novel word lexicalization compared to a PW association context. Participants completed learning sessions of German words in iVR and PW contexts on Days 1–3. On Day 4 and 6 months later, we administered a semantic-priming task to measure the lexicalization of the novel words. EEG was utilized during the testing on Day 4. We analyzed ERPs to investigate whether novel-word activation after lexicalization was a more automatic process, as indexed by the N400 component, or a more controlled process, as indexed by the LPC. We note that the to-be-learned novel words in the present study were real German words, different from the pseudowords used in previous studies (e.g., Lei et al., 2022; Liu & van Hell, 2020). Specifically, participants in the present study learned German words for existing concepts that learners already knew and, thus, were able to link German word forms to existing semantic memories.

Two main hypotheses were examined in the present study. The embodied-cognition theory posits that interactions with an environment affect knowledge acquisition (Barsalou, 2008). Hence, learning in an iVR context may provide an opportunity to interact with multiple types of sensorimotor information, and this complementary information is predicted to facilitate encoding and integration of novel words. Consistently, the dual-coding theory emphasizes that the coactivation of verbal and nonverbal modalities can improve encoding and memory retrieval (Paivio & Csapo, 1969). In addition to the engagement of verbal information (e.g., word pronunciation), the nonverbal information provided by an iVR context (e.g., surrounding environment, sensorimotor features) may benefit novel-word lexicalization. On the basis of word-learning studies conducted with iVR technology (Legault et al., 2019), we hypothesize that novel words learned in an iVR context will enhance behavioral patterns of semantic-relatedness judgements compared to PW-learned words, as reflected by reaction times (RTs). Assuming that an N400 semantic-priming effect for target words reflects an automatic retrieval process and that an LPC semantic-priming effect implies a more controlled, strategic retrieval process, we further expect that iVR-learned words, but not PW-learned words, will elicit an N400 semantic-priming effect.

Method

Participants

We recruited 35 Chinese learners of L2 English, who were undergraduate students in China, to participate in the present study. Research ethics committee's approval was received from the research institution where data collection took place, and the participants provided their written informed consent prior to taking part in the study. After the study, they were given a modest payment for their participation. The participants were self-reported right-handed adults, had normal or corrected-to-normal vision, and had no history of neurological or language-related disorders. Five participants were excluded from the data analyses due to the EEG data displaying noncorrectable drifting and excessive line noise (Jiao et al., 2022). Thus, 30 individuals participated in the immediate posttest on Day 4, 23 females, 7 males, $M_{\text{age}} = 19.83$ years, $SD = 1.08$, range:

Table 1 Language background of participants ($N = 30$)

Skills	*M*	*SD*	95% CI
Self-ratings of Chinese (L1) proficiency			
Listening	6.37	0.61	[6.14, 6.60]
Speaking	6.13	0.90	[5.80, 6.47]
Reading	6.40	0.81	[6.10, 6.70]
Writing	6.23	0.68	[5.98, 6.49]
Self-ratings of English (L2) proficiency			
Listening	3.47	0.86	[3.15, 3.79]
Speaking	3.53	0.86	[3.21, 3.86]
Reading	4.20	1.16	[3.77, 4.63]
Writing	4.03	1.07	[3.64, 4.43]
Age of L2 acquisition	9.00	1.73	[8.32, 9.61]

Note. L1 = first language; L2 = second language.

18–23. This sample exceeded the minimum size of 24 calculated by G*Power 3.1: $f = .25$, $\alpha = .05$, power = .80, number of groups = 1, number of measurements = 4. After 6 months, 20 of the participants returned to complete the delayed posttest, 15 females, 5 males, $M_{\text{age}} = 19.65$ years, $SD = 1.14$, range: 18–23.

All participants reported knowledge of an L2, namely English, learned in a classroom environment. We collected participants' self-ratings of Chinese and English language proficiency for listening, speaking, reading, and writing skills on a 7-point scale (1 = *very poor*, 7 = *excellent*; see Table 1). A paired-samples t test revealed that the participants were unbalanced bilinguals whose dominant language was Chinese: $M_{\text{Chinese}} = 6.28$, $SD_{\text{Chinese}} = 0.63$; $M_{\text{English}} = 3.81$, $SD_{\text{English}} = 0.82$, $t = 12.38$, $p < .001$. The participants reported having no experience living abroad. Moreover, all participants had no prior knowledge of German, the language in which they learned novel words in the present study.

Materials

In this study, we asked participants to learn 40 German words (see Appendix S1 in the online Supporting Information). We took into account the familiarity, frequency, visual complexity, and the appropriateness in the virtual environment (i.e., an apartment) when selecting the German words as well as the corresponding 2D/3D materials. The rationale for choosing German as the to-be-learned novel language is that all participants reported no prior knowledge or experience with German. All target words were recorded by a Chinese L1 speaker who majored in German in a soundproof room.

Given that German and English share some orthography and phonology, we controlled for the potential influence of the participants' experience with English on their experience with the novel German words being learned. During the selection of materials, we asked a control group of 21 Chinese–English bilinguals with a similar English proficiency level to that of our participants to assess whether the selected German words sounded like any words they knew in Chinese or English. On the basis of a 5-point scale (1 = *very dissimilar*, 5 = *very similar*), the assessment value of 2.4 suggests that the German words were indeed dissimilar to Chinese or English words, $t = -6.55$, Cohen's $d = -1.04$, 95% CI [−3.10, 1.03], $p < .001$. We conducted correlation analyses between participants' English proficiency and German learning performance (i.e., semantic-priming effect in this study), and observed no significant correlations (see Appendix S2 in the online Supporting Information).

In the learning session, participants learned half of the target words in a traditional PW context accompanied with 2D line drawings and the other half in an iVR context with virtual 3D objects. The 3D objects in the iVR condition and the corresponding 2D line drawings were selected from a standardized 3D object database (Peeters, 2018) and a standardized picture database (Snodgrass & Vanderwart, 1980; Zhang & Yang, 2003), respectively. Moreover, the iVR context included a fully immersive environment that simulated an apartment consisting of a kitchen, bedroom, and living room. This immersive environment was presented and edited using Unity software (https://unity.com). When equipped with headgear and handsets, participants could fully immerse themselves in the virtual environment, physically move throughout the virtual environment, and use the handset to click on target 3D objects.

For the semantic-priming task, the target words were newly learned German words, and the prime words were Chinese real words (Liu et al., 2024). We asked another group of 28 unbalanced Chinese–English speakers, who did not participate in the formal experiment, to assess whether the Chinese prime words were related to the target words on a 5-point scale (1 = *completely unrelated*, 5 = *closely related*). Results showed that the semantic relatedness of related pairs, $M = 4.28$, $SD = 0.21$, was significantly higher than for unrelated pairs, $M = 1.63$, $SD = 0.35$, $t(78) = 41.10$, Cohen's d = 9.17, 95% CI [7.68, 10.65], $p < .001$.

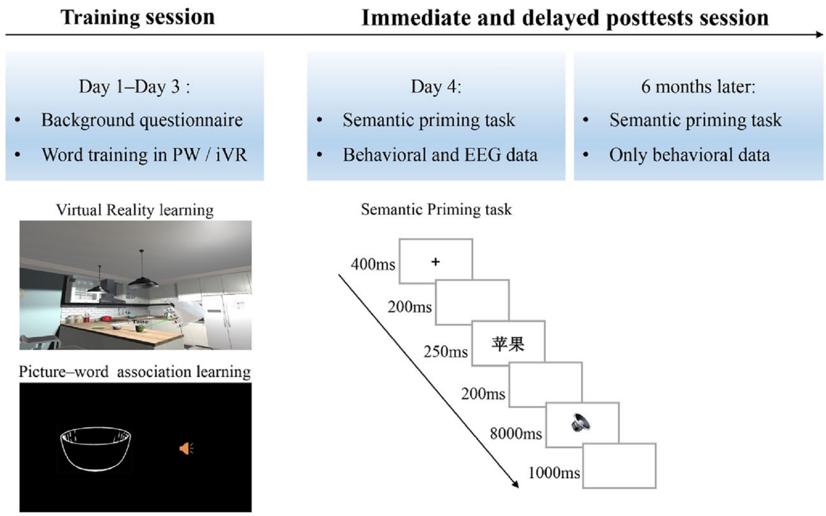

Figure 1 Schematic overview of the tasks. PW = picture–word condition; iVR = immersive virtual-reality condition; EEG = electroencephalography.

Design and Procedure

On Day 1, after providing their informed consent, participants completed the language background questionnaire. Following the questionnaire, participants completed a learning session. On Days 2–3, they again completed learning sessions. We administered a semantic-priming task on Day 4 and once again 6 months later. EEG data were recorded on Day 4. An overview of the procedure can be seen in Figure 1.

Learning Sessions

The participants learned novel words in PW and iVR conditions on Days 1–3. On each day, the participants learned half of the German words (Set 1) in the PW condition and the other half (Set 2) in the iVR condition. The learning conditions and the two sets of words were counterbalanced across participants (i.e., one participant learned Set 1 through PW, and another participant learned Set 1 through iVR). Participants were given a brief break between the two sets to prevent fatigue. For each condition, the participants had the autonomy to learn at their own pace, and the learning procedure lasted 15 minutes per day.

In the PW condition, participants learned German words through pairs of line drawings presented on a computer screen and auditory words. In each trial, participants saw a 2D line drawing and heard its corresponding German word. Participants could hear the word again by pressing the spacebar or could move to the next word by pressing the down arrow key. Before the formal learning session, a practice block of five trials with Chinese words was used to familiarize the participants with the PW learning procedure.

In the iVR condition, the participants learned German words in a fully immersive environment, namely an apartment including a kitchen, bedroom, and living room. When participants wore the HTC VIVE headgear and entered the virtual environment, they could physically move throughout it and see all target objects. Using the handset, participants could place the cursor on objects to hear the corresponding pronunciation of German words. They could repeat this process to hear the target words again. Before the formal learning session, participants were first shown how to use the iVR equipment and were then asked to familiarize themselves with the iVR learning procedure by completing sample trials with Chinese words.

Testing Sessions

The immediate (Day 4) and delayed (6 months later) posttests consisted of a semantic-priming task. There were four types of trials in the semantic-priming task when learning condition (PW, iVR) and semantic relatedness (related, unrelated) were taken into account. Target words were those learned in PW and iVR conditions. We paired each target word with related and unrelated Chinese prime words. There were two blocks in the task, with each block consisting of 80 trials. Each trial began with a 400 ms fixation cross on the screen. Next, a blank screen appeared for 200 ms, followed by an unrelated or related prime word for 250 ms. A blank screen appeared again for 200 ms and was followed by a German target word presented auditorily through the headphones. The participants were required to identify whether the Chinese prime word was related to the target word or not by pressing left or right response keys. Once a response was given or after a maximum duration of 8,000 ms, a 1,000 ms blank screen appeared. Before the formal experiment, the participants were presented with 10 practice trials to become familiar with the procedure.

Electrophysiological Recordings and Preprocessing

EEG data were recorded during the immediate posttest (Day 4) using 64 silver/silver–chloride (Ag/AgCl) electrodes, which were placed according to the extended 10–20 positioning system and referenced online to FCz electrode. All channels were amplified with a band pass of 0.05–100 Hz and a sampling rate of 1,000 Hz. Electrode impedance was kept below 10 kΩ. We preprocessed the EEG data using the EEGLAB toolbox. We resampled the data at a rate of

500 Hz and rereferenced the data offline to the averaged left (TP9) and right (TP10) mastoids. The signal was band-pass filtered at a 0.5–30 Hz. The signals containing eye blinks and other artefacts were corrected for each subject by independent component analysis.

For each participant, we averaged ERPs from 150 ms prior to and 1,000 ms after the target word onset. Baseline correction was performed in reference to prestimulus activity (Liu et al., 2024). For the ERP data, we extracted the mean amplitude of waveforms across the selected time windows of N400 (400–530 ms) and LPC (600–900 ms) from the semantic-priming task. Next, we performed the analysis on the following variables: learning condition (PW, iVR), semantic relatedness (related, unrelated), and anteriority (frontal region, central region, posterior region). We grouped electrodes into three regions of interest: frontal region (F1, Fz, F2), central region (C1, Cz, C2), and posterior region (P1, Pz, P2).

Statistical Analyses

We conducted traditional repeated-measures ANOVAs and Bayes analyses on RTs and mean amplitudes of N400 and LPC (Yin et al., 2023) using JASP (van Doorn et al., 2021). An advantage of choosing a Bayesian approach over frequentist approaches is that the Bayesian approach provides probabilistic evidence for the presence or absence of target effects rather than reporting only a binary test on the null hypothesis. In the Bayes analysis, we tested our hypotheses using Bayes Factor (BF_{10}), which quantifies the strength of evidence in favor of the alternative hypothesis (H1) over the null hypothesis (H0) or vice versa. Table 2 shows the classification scheme used in JASP (Wagenmakers et al., 2018). Moreover, to examine how multimodal enrichment affects the lexicalization process of novel words, we conducted planned ANOVAs on N400 and LPC amplitudes in the PW and iVR conditions separately. We set the alpha level to .05 to evaluate statistical significance and report the 90% confidence interval for the effect size of partial eta squared (Steiger, 2004).

Results

Behavioral Results: The Semantic-Priming Effect

To investigate whether the iVR context significantly enhanced semantic-priming effects of novel words compared to the PW context, we conducted repeated-measures ANOVAs on the learning condition (PW, iVR) and semantic relatedness (related, unrelated). ANOVAs were run separately on the two testing sessions (i.e., immediate posttest on Day 4 and delayed posttest 6 months later). Incorrect responses and trials that were longer than 4,000 ms were

Table 2 A descriptive and approximate classification scheme for the interpretation of Bayes Factor

Bayes factor	Evidence category
> 100	Extreme evidence for H1
30–100	Very strong evidence for H1
10–30	Strong evidence for H1
3–10	Moderate evidence for H1
1–3	Anecdotal evidence for H1
1	No evidence
1/3–1	Anecdotal evidence for H0
1/10–1/3	Moderate evidence for H0
1/30–1/10	Strong evidence for H0
1/100–1/30	Very strong evidence for H0
< 1/100	Extreme evidence for H0

Note. H0 = null hypothesis; H1 = alternative hypothesis.

Table 3 Means (*SD*) by conditions on the immediate and delayed posttests

Condition	Related		Unrelated	
	RT	95% CI	RT	95% CI
Immediate posttest ($n = 30$)				
VR	2,087(271)	[1,986, 2,188]	2,433(309)	[2,318, 2,548]
PW	2,163(275)	[2,061, 2,266]	2,396(296)	[2,286, 2,507]
Delayed posttest ($n = 20$)				
VR	2,047(205)	[1,978, 2,170]	2,399(289)	[2,264, 2,534]
PW	2,048(248)	[1,932, 2,164]	2,369(245)	[2,254, 2,484]

Note. RT = reaction times; VR = virtual-reality condition; PW = picture–word condition.

removed from the RTs analyses. The mean RTs and 95% CI of immediate and delayed posttests are presented in Table 3. Findings from the immediate test showed that despite the main effect of learning condition not being significant, $F(1, 29) = 1.25$, $p = .27$, $\eta_p^2 = .04$, 90% CI [0.01, 0.20], $BF_{10} = 0.36$, there was a significant effect of semantic relatedness, $F(1, 29) = 99.68$, $p < .001$, $\eta_p^2 = .77$, 90% CI [0.64, 0.85], $BF_{10} > 100$. A BF_{10} larger than 100 represents very strong evidence for the existence of the semantic-relatedness effect. Importantly, the Learning Condition × Semantic Relatedness interaction reached significance, $F(1, 29) = 12.15$, $p = .002$, $\eta_p^2 = .29$, 90% CI [0.09,

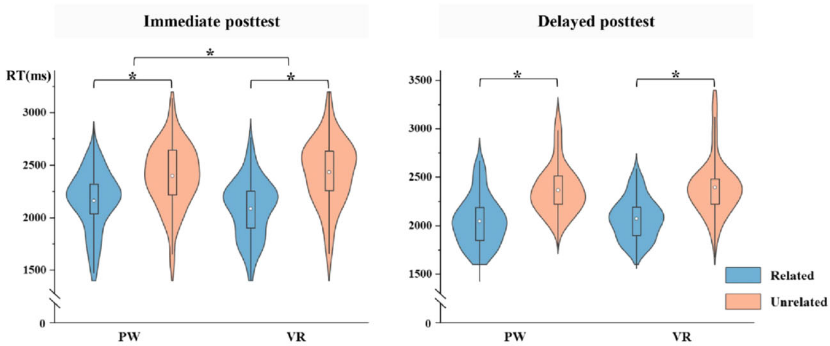

Figure 2 Violin plots for reaction times in immediate (left) and delayed (right) posttests. Box plots show the interquartile range. White dots represent means. PW = picture–word condition; VR = virtual-reality condition; related = related prime–target words; unrelated = unrelated prime–target words.

0.50], $BF_{10} = 51.75$. The BF_{10} of 51.75 again suggests very strong evidence for interactive effects. A simple-effect analysis further showed that semantic-priming effects in the iVR condition, priming effect = 346 ms, $SD = 182.09$, were larger than in the PW condition, priming effect = 233 ms, $SD = 181.66$ (see Figure 2).

The findings from the delayed posttest found a significant main effect only of semantic relatedness, $F(1, 19) = 81.28$, $p < .001$, $\eta_p^2 = .81$, 90% CI [0.66, 0.88], $BF_{10} > 100$, such that participants were faster to respond to related prime–target words than unrelated prime–target words (see Table 3). The main effect of learning condition, $F(1, 19) = 0.99$, $p = .33$, $\eta_p^2 = .05$, 90% CI [0.01, 0.27], $BF_{10} = 0.37$, and the Learning Condition × Semantic Relatedness interaction, $F(1, 19) = 0.004$, $p = .95$, $\eta_p^2 < .001$, $BF_{10} = 0.31$, were not significant.

N400 Semantic-Priming Effect in the Immediate Test

Figure 3 shows the grand average ERP waveforms elicited by the semantic-priming task during the immediate posttest. A repeated-measures ANOVA was run using the learning condition (PW, iVR), semantic relatedness (related, unrelated), and anteriority (frontal, central, posterior) on the N400 amplitude. Results showed that neither the main effect of semantic relatedness, $F(1, 29) = 3.38$, $p = .07$, $\eta_p^2 = .10$, 90% CI [0.01, 0.30], $BF_{10} = 1.15$, nor the main effect of the learning condition, $F(1, 29) = 0.26$, $p = .61$, $\eta_p^2 = .01$, 90% CI [0.01, 0.13], $BF_{10} = 1.22$, reached significance. Importantly, however, the Learning Condition × Semantic Relatedness interaction was significant,

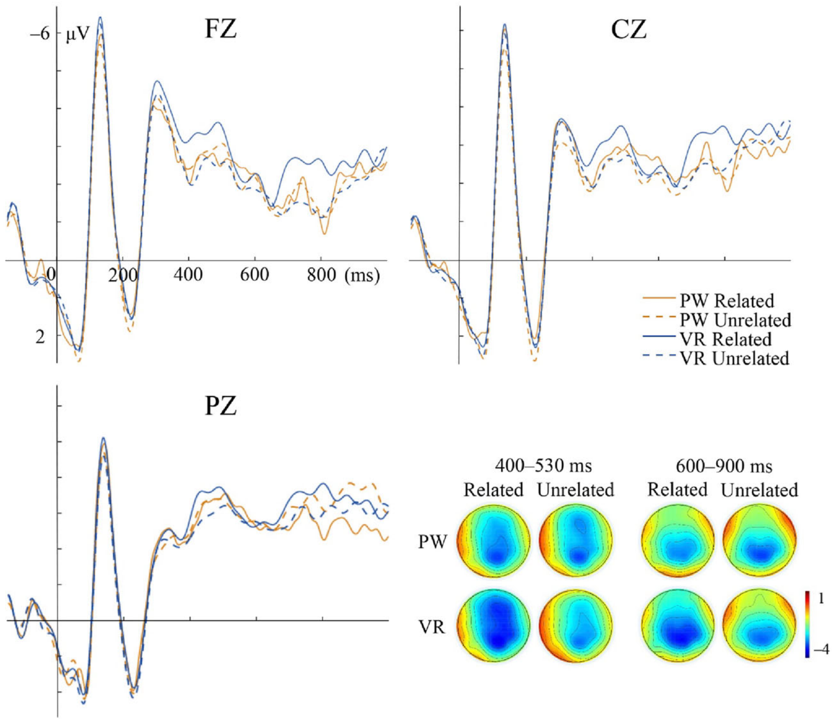

Figure 3 Grand average waveforms and topographic maps of semantic-priming tasks across learning condition. FZ = frontal region; CZ = central region; PZ = posterior region; VR = virtual-reality condition; PW = picture-word condition; related = related prime–target words; unrelated = unrelated prime–target words.

$F(1, 29) = 4.98$, $p = .03$, $\eta_p^2 = .15$, 90% CI [0.01, 0.35], $BF_{10} = 35.37$. Further analyses examining semantic-priming effects in the two conditions were separately conducted in the frontal, central, and posterior regions. Results showed that the semantic-priming effects were significant in the iVR condition across frontal, $F(1, 29) = 6.86$, $p = .01$, $\eta_p^2 = .19$, 90% CI [0.03, 0.39], $BF_{10} = 3.42$; central, $F(1, 29) = 5.46$, $p = .03$, $\eta_p^2 = .16$, 90% CI [0.01, 0.36], $BF_{10} = 2.50$; and posterior regions, $F(1, 29) = 5.19$, $p = .03$, $\eta_p^2 = .15$, 90% CI [0.01, 0.35], $BF_{10} = 1.95$. These neural regions were not significant in the PW condition: frontal, $F(1, 29) = 0.33$, $p = .57$, $\eta_p^2 = .01$, 90% CI [0.01, 0.14], $BF_{10} = 0.23$; central: $F(1, 29) = 0.40$, $p = .53$, $\eta_p^2 = .01$, 90% CI [0.01, 0.15], $BF_{10} = 0.23$; and posterior: $F(1, 29) = 0.22$, $p = .64$, $\eta_p^2 = .01$, 90% CI [0.01, 0.13], $BF_{10} = 0.22$.

Late-Positive-Component Semantic-Priming Effect in the Immediate Test

Another repeated-measures ANOVA was run using the learning condition, semantic relatedness, and anteriority on the mean amplitude of LPC. Results showed a significant main effect of anteriority, $F(1,\ 58) = 4.83$, $p = .01$, $\eta_p^2 = .14$, 90% CI [0.02, 0.27], $BF_{10} = 4.25$. Moreover, the Semantic Relatedness × Anteriority interaction was significant, $F(2,\ 58) = 3.46$, $p = .04$, $\eta_p^2 = .11$, 90% CI [0.01, 0.23], $BF_{10} = 1.40$. However, the BF_{10} of only 1.40 cannot be interpreted as credible evidence against H0.

Planned tests to examine semantic-priming effects in the two conditions were separately conducted on frontal, central, and posterior regions. Results on frontal and central regions showed a numerically significant priming effects in the iVR condition: frontal, $F(1,\ 29) = 6.59$, $p = .02$, $\eta_p^2 = .19$, 90% CI [0.02, 0.39], $BF_{10} = 2.80$; central: $F(1, 29) = 4.64$, $p = .04$, $\eta_p^2 = .13$, 90% CI [0.01, 0.34], $BF_{10} = 1.30$; but a nonsignificant effect in the posterior region, $F(1, 29) = 1.96$, $p = .17$, $\eta_p^2 = .06$, 90% CI [0.01, 0.24], $BF_{10} = 0.47$. Considering the BF_{10} values, these findings were not compelling evidence for the presence of the priming effect in the iVR condition. Moreover, there was no priming effect in the PW condition across the three regions: frontal, $F(1, 29) = 0.03$, $p = .87$, $\eta_p^2 < .001$, 90% CI [0.01, 0.06], $BF_{10} = 0.20$; central, $F(1, 29) = 0.03$, $p = .87$, $\eta_p^2 < .001$, 90% CI [0.01, 0.06], $BF_{10} = 0.20$; and posterior, $F(1,\ 29) = 1.50$, $p = .23$, $\eta_p^2 = .05$, 90% CI [0.01, 0.22], $BF_{10} = 0.38$.

Discussion

In this study, we compared the impact of iVR and PW contexts on the lexicalization process of novel words. As predicted, the behavioral findings support the notion that multimodal enrichment enhances the integration and lexicalization of novel words. These results showed larger semantic-priming effects in the case of iVR-learned words compared to PW-learned words in the immediate posttest (Day 4), but these effects were no longer detected 6 months later. The ERP data collected in the immediate posttest showed semantic-priming effects for iVR-learned words on N400, suggesting automatic processing. These effects did not emerge for PW-learned words.

Our findings support the embodied-cognition theory in which a learner's whole-body interactions with learning environments, which include rich perceptual and sensorimotor information, facilitate learning (Barsalou, 2008). In our study, the iVR setting provided a multimodal enrichment experience in which participants moved around and interacted with the environment, which led to enhanced semantic-priming effects of novel words—a result indicated by behavioral performance and the N400 component. Combined with dual-coding theory (Jared et al., 2013; Paivio & Csapo, 1969), learners who were immersed in a virtual learning context could receive verbal information, such as target word pronunciation, and could collect nonverbal details, such as spatial and motor information. This cross-modal activation in the iVR context enhanced memory encoding and integration relative to the unimodal learning context. These findings suggest that an iVR learning context may benefit lexicalization of novel words, potentially activating an automatic process of semantic retrieval and judgements. However, the findings also showed that these beneficial effects were no longer present 6 months later. We offer a further discussion on the behavioral and electrophysiological patterns in the next subsections.

Behavioral Patterns

Regarding the extent to which novel-word lexicalization is strengthened by an iVR learning experience, the behavioral findings showed that both PW- and iVR-learned words elicited semantic-priming effects, such that there were faster responses to related pairs than to unrelated pairs (see also Andrä et al., 2020). The presence of semantic-priming effects was consistent with our expectation based on the complementary learning system model (Davis & Gaskell, 2009). Specifically, after three learning sessions with sleep intervals, the form/pronunciation of novel words had linked to their meaning and integrated into the learners' mental lexicon, completing the lexicalization of novel words (Lei et al., 2022; Liu & van Hell, 2020).

Importantly, in line with our first hypothesis, the semantic-priming effect of iVR learning was larger than that of PW learning, indicating that the multimodal enrichment experience of iVR learning enhanced novel-word lexicalization. This beneficial effect is consistent with embodied-cognition theory: In the iVR context, novel words were encoded alongside rich sensorimotor information found in the surrounding objects and environments (Barsalou, 2008). From the dual coding perspective, although both iVR- and PW-learned words were encoded verbally, the simulated real-life environment generated nonverbal perceptual-, spatial-, and motor-information encoding (Paivio & Csapo, 1969). However, the superiority effect of iVR learning was absent after 6 months, as evidenced by the less significant interaction of Semantic Relatedness × Learning Condition during the delayed posttest. From the complementary learning system perspective, one possible explanation is that after a longer time interval, all PW- and iVR-learned novel words had been lexicalized and interacted with existing words in a similar fashion. The priming effects similar in numerical magnitude between the two learning contexts provided certain support to our hypothesis; however, this issue merits future testing.

Electrophysiological Patterns

With respect to how the iVR context is more effective in novel-word lexicalization than the PW context, a critical finding in the present study was that we observed an N400 priming effect on iVR-learned words but not on PW-learned words. This finding directly supports the embodied-cognition theory, which posits that accessing concepts from the semantic memory system can activate sensorimotor engagement (Barsalou, 2008). The N400 has been shown to be sensitive to the automatic processing of semantic access (Bakker et al., 2015; Hoshino & Thierry, 2012). Therefore, the observed N400 priming effect in the iVR context indicates that the sensorimotor experience accumulated from the context engages semantic access in an automatic pathway, similar to existing, known words (Liu & van Hell, 2020). Additionally, according to the complementary learning system model, such a multiple sensorimotor experience may be quickly encoded into episodic memory during the initial familiarity stage and then transferred to long-term stable representations during consolidation and lexicalization (Davis & Gaskell, 2009; Liu et al., 2024).

In the previous study by Jiao et al. (2024), unbalanced Chinese–English bilinguals were asked to learn German words in an iVR context, similar to the present study. But the iVR effect in Jiao et al.'s study was observed on N100 and N200, rather than on N400. One possible reason for such a discrepancy is the different task requirements between their experiment and the present study. Specifically, Jiao et al. were interested in lexical-form acquisition measured by a lexical-decision task, in which participants identified whether the target words had been learned or not, rather than by semantic judgements in the present study. Hence, it is not surprising to observe N400 effects in our semantic-relatedness task but not in Jiao et al.'s lexical-decision task.

In addition, studies in immersive learning literature have also focused on cognitive load due to the increased visual information found in an immersive context (Makransky & Petersen, 2021). Relative to word–word/picture–word association learning, learners in iVR contexts must process an abundant amount of subtle details that may not be necessary for word learning; thus, learners must cope with excessive cognitive load (Makransky & Petersen, 2021). Jiao et al. (2024) examined the relationship between iVR learning and cognitive control as measured by a flanker task, but the results failed to show an influence of cognitive load. Combined with the pretraining principle in multimedia learning (Mayer & Pilegard, 2014; Meyer et al., 2019), it is possible that the familiar iVR context and sufficient practice with VR equipment might reduce cognitive load when learners are faced with novel concepts or lessons. This possibility is worthy of further exploration.

Regarding the beneficial effects of multimodal enrichment on novel-word lexicalization, our findings are in line with Lei et al.'s study (2022), in which the multimodal enrichment effect was examined by comparing definition-only and definition–image conditions. Inconsistently, novel-word lexicalization in the definition–image condition of Lei et al. (2022) failed to elicit N400 priming effects. According to the dual-coding theory (Jared et al., 2013; Paivio & Csapo, 1969), involvement of nonverbal information can enhance novel words' encoding and integration. Therefore, the inconsistent N400 effects between the present study and Lei et al.'s (2022) may be associated with degrees of enrichment of nonverbal information, such as through pictures in Lei et al.'s study and through sensorimotor information in the present study. Specifically, the sensorimotor experience provided in an iVR context is richer and facilitates integration of novel words into the mental lexicon, whereas the static presentation of images entails only visual cues, which may not be conducive to memory integration and automatic processing of novel words.

Contrary to our hypotheses, semantic judgements of iVR-learned words did not elicit changes in LPC priming effects compared to PW-learned words. Liu and van Hell (2020) and Lei et al. (2022) observed LPC semantic-priming effects on novel words, which suggests that novel-word lexicalization is a gradual process. Despite observing LPC priming effects in frontal regions for iVR-learned words, combined with the Bayesian analysis, it is hard to draw a reliable conclusion with respect to the LPC priming effect. Overall, the lexicalization process of iVR-learned words is fundamentally more automatic and faster due to its abundant sensorimotor experiences. The multimodal enriched learning processes were strong enough for the forms/meanings of novel words to become fully lexicalized, leading to differences between PW- and iVR-learned words.

Limitations

Our findings showed that when compared to PW-learned words, the beneficial effects of the iVR context on novel-word lexicalization emerged in the immediate posttest (Day 4) but were not present in the delayed posttest (6 months later). A limitation of our study is therefore that our findings were not able to reveal how long the advantages of learning new words in an iVR context last, nor do they explain why differences in learning outcomes between the PW and iVR contexts are no longer significant over time. Although we could speculate that the beneficial effects of learning new words in an iVR context simply dissipate over time, we believe that this is not the case. Instead, it is possible that PW-learned words may also have become lexicalized during this period of consolidation (i.e., 6 months after the learning took place) and thus display similar patterns to iVR-learned words. This said, we acknowledge that the sample size in the delayed posttest was not sufficient. Given the limited number of participants (i.e., $n = 20$) 6 months later, the absence of iVR benefits may reflect a power issue, making it harder to identify the length of such beneficial effects. Hence, future studies should include additional posttests at various time points to examine the trajectories of word learning in iVR and PW contexts.

Conclusion

In the present study, we used EEG technology to examine benefits of multimodal enrichment on lexicalization of novel words. Multimodal enrichment was tested by comparing learning outcomes from a simulated real-life context (iVR) and traditional learning context (PW). Immediately after the learning sessions (Days 1–3), an immediate posttest on Day 4 showed that the multiple sensorimotor contexts improved the lexicalization of iVR-learned novel words compared to the PW contexts. However, this benefit was no longer present in a delayed posttest 6 months later. The results also showed that iVR-learned words were accompanied by an N400 semantic-priming effect. We conclude that our findings support the embodied-cognition theory and dual-coding theory by demonstrating that the multimodal enrichment achieved from an iVR context offers immediate benefits for lexicalization of novel words, in which learners rely more on automatic processes. Future studies should investigate the extent to which these effects persist or dissipate over time.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Accessible Summary

Appendix S1. List of Materials.

Appendix S2. Correlation Analyses Between English Proficiency and Semantic Priming Effects.