



Article

Effects of Semantic and Cross-Language Contextual Variation on Online Processing During Bilingual Novel Word Learning

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Abstract

This study examined how semantic and language-context variability influence online processing during bilingual novel word learning in sentences. Brazilian Portuguese–English bilinguals read novel English–Portuguese cognates embedded in repeated or varied sentences. Each target item was presented a total of four times in participants' first language (L1), second language (L2), or both languages. We examined early (first fixation duration) and late (total reading time) eye-movement measures and assessed semantic knowledge in a post-test relatedness judgment task. The results showed that reading times decreased with repeated exposure across all conditions, reflected in shorter fixation durations and total reading times. Words presented in repeated sentence contexts were read faster than those presented in varied sentence contexts. The language context also modulated online reading behavior. Reading was faster in the L1 condition and longer in the mixed-language condition, particularly during initial exposures. Notably, individual differences in L2 vocabulary proficiency moderated these effects, with more proficient bilinguals showing faster adaptation to linguistic variability. Despite clear differences in online processing, semantic retrieval accuracy in the post-test did not vary across learning conditions, suggesting that differences in online processing did not translate into measurable differences in offline semantic knowledge under the present learning conditions.

Keywords: bilingualism; vocabulary acquisition; semantic context; instance-based learning; eye-tracking

1. Introduction

1.1. Lexical Quality and Novel Word Learning

The human lexicon is a dynamic and continuously developing system. Vocabulary acquisition is a lifelong process in which we constantly encounter and integrate novel items into our lexicon. Central to this integration is the Lexical Quality Hypothesis, which suggests that the quality of a word representation is what determines reading efficiency and comprehension (Perfetti, 2007). High-quality lexical representations are characterized by precise, well-specified, and readily accessible information regarding a word's form, meaning, and its connections to other words. Representations of low lexical quality are typically vague or incomplete and may lead to slower word recognition and diminished comprehension. For bilinguals, this process is uniquely complex, as it can happen in their first language (L1) and second language (L2). As such, understanding the cognitive mechanisms that underly vocabulary acquisition in each language, along with the factors that



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influence the successful integration of new words, is critical for refining theoretical models of vocabulary acquisition, as well as for developing more effective pedagogical strategies.

According to the instance-based framework of novel word learning, learners encode new words along with information about their surrounding semantic contexts, gradually accumulating lexical and semantic information that may facilitate retrieval during subsequent encounters with those words (Reichle & Perfetti, 2003). Encountering words across multiple semantic contexts can lead to wider activation networks, which are useful in applying the meanings of learned words (Bolger et al., 2008). Words encountered in repeated semantic contexts strengthen the existing connections in a developing network, leading to faster recognition but potentially limiting the ability to apply words to novel scenarios. Repeated exposure to novel words across a diverse range of semantic and linguistic contexts can actively engage learners in constructing rich, context-independent knowledge about new vocabulary.

When encountering novel words while reading, the reading times of whole sentences generally decrease with each exposure, as words become more familiar (Lauro et al., 2025). As novel words become more familiar, reading times with each new encounter (during reading) become shorter (Elgort et al., 2018; Godfroid et al., 2018; Joseph et al., 2014; Rayner, 1995). Reduced reading time across multiple encounters may result from increasing familiarity due to its encoding into episodic memory (Reichle & Perfetti, 2003).

Faster reading speed does not, however, necessitate deeper form–meaning links of word knowledge (Laufer & Goldstein, 2004; Pellicer-Sánchez et al., 2021; Perfetti, 2007; Rice & Tokowicz, 2020). In fact, longer reading times of novel words tend to be positively associated with learning (Godfroid et al., 2013, 2018; Williams & Morris, 2004). For instance, longer reading times have been linked positively with higher post-test recall scores (Williams & Morris, 2004), even in L2 (Godfroid et al., 2018). Similar relationships have been observed for post-test word-form recognition (Godfroid et al., 2013) and meaning recognition tasks (Pellicer-Sánchez et al., 2021), suggesting that the extra time spent during learning may reflect deeper processing (Robinson, 1995; Schmidt, 1990). However, evidence from one study indicated that cumulative reading time did not predict word-form recognition or meaning recall (Pellicer-Sánchez et al., 2021).

1.2. Contextual Variability and Semantic Integration

There are several factors that influence how readers extract information about novel words from the surrounding context(s). Within the instance-based framework of novel word learning, the context variability hypothesis posits that each encounter with a novel word creates distinct traces within a lexical–semantic network of knowledge about that word. Therefore, encountering a novel word in distinct semantic contexts results in more distinct traces within that network compared to encountering a novel word repeatedly in the same semantic context (Bolger et al., 2008). Thus, encountering a word in multiple semantic contexts is proposed to support more flexible access to lexical–semantic information, allowing learners to retrieve meaning across a broader range of contexts (Elgort & Warren, 2014; Ferreira & Ellis, 2016; Lauro et al., 2020; Rodríguez-Fornells et al., 2009).

This framework of word learning also suggests that episodic information, such as font size (Rhodes & Castel, 2008), is also encoded into memory during encounters with novel stimuli. Although perceptual characteristics, such as font size, differ substantially from language context in terms of cognitive complexity, both may function as contextual cues that become encoded alongside newly learned information. This conceptualization is also broadly compatible with models of bilingual lexical access (e.g., Dijkstra & Van Heuven, 2002), which posit that language membership is an integral component of lexical processing rather than a surface-level characteristic. One aim of the present study is to

determine whether varying the episodic context in which bilinguals encounter novel words (the language of learning) enriches lexical–semantic networks of recently studied words. Previous research has shown an advantage for semantic variation in L1 and L2 contexts, dependent on the retrieval task, though the effect may be moderated by the learner’s language background (Lauro et al., 2020, 2025). For example, one such study found that while English–Spanish bilinguals showed higher post-test accuracy for words studied in varied semantic contexts, Brazilian Portuguese–English bilinguals, who primarily acquired their L2 in academic settings, showed an advantage in repeated contexts (Lauro et al., 2025).

Moreover, exposing learners to novel words in a multi-language context may introduce desirable difficulty, a cognitive principle where initial learning challenges can foster deeper processing and lead to more robust, long-term retention (E. L. Bjork & Bjork, 2011; R. A. Bjork, 1994). Tasks that demand greater initial cognitive effort, such as inferring the meaning of target words across different linguistic environments, often result in superior learning outcomes.

1.3. Cross-Language Contexts in Bilingual Word Learning

Reading is typically recognized as a highly effective source of vocabulary growth (Krashen, 1989; Nagy & Herman, 1987), even in L2 (Pellicer-Sánchez, 2016; Webb et al., 2023). Bilinguals have the unique opportunity to leverage their existing semantic knowledge in both languages while encountering novel words in one language. Furthermore, exposure to novel words across both languages may offer particularly salient contexts in which bilinguals can extract knowledge. A direct comparison between single-language and mixed-language study phases, in which novel words were encountered across both languages, found that language variability during the study phase served as an additional retrieval cue, leading to higher accuracy in semantic relatedness judgments compared to single-language exposure (Lauro et al., 2025). This suggests that encountering a word across different linguistic environments may provide additional retrieval cues that support later semantic judgments. However, the cognitive mechanisms by which readers successfully infer word meaning from varied linguistic contexts during reading, and how cross-language lexical knowledge affects it, are not well understood.

In addition to semantic variation, the language context in which a novel word is encountered is another factor that can influence the ease with which meanings of novel words are extracted and integrated into lexical–semantic networks, specifically for bilingual learners. The specific language of exposure, much like other episodic features, is encoded into memory alongside the word itself (Cristoffanini et al., 1986; Kintsch, 1970; MacLeod, 1976), potentially shaping subsequent learning outcomes (Lauro et al., 2020, 2025; Lauro & Toassi, 2025). For instance, recent investigations suggest that repeated exposure to a novel word across both of a bilingual’s languages can enhance the accuracy of semantic relatedness judgments, outperforming learning in single-language contexts (Lauro et al., 2025).

A well-studied characteristic of bilingual lexical access is that lexical access is often language non-selective, such that bilinguals may activate representations from both languages, even when only one language is in use (Dijkstra & Van Heuven, 2002). However, the extent of cross-language activation is influenced by factors including language proficiency, age of acquisition, language experience, and task demands. This cross-language interaction can manifest in various ways. For example, high degrees of orthographic or phonological overlap between words that also share meaning (i.e., cognates) typically facilitate lexical processing (Costa et al., 2000). Semantic context has been shown to modulate the extent of this cross-language activation (Lauro & Schwartz, 2017). Critically, the degree of cross-language overlap, ranging from non-cognates to full cognates, appears to moderate online processing. When studying novel words across four separate encounters in both

languages, sentence reading times decreased more rapidly as the degree of orthographic overlap increased (Lauro et al., 2025). This suggests that bilinguals leverage sub lexical similarities to facilitate semantic integration during the learning process.

A unique feature of the current design is the exclusive use of English–Portuguese cognates as target stimuli. Cognates were chosen to provide the highest likelihood of observing cross-language contextual effects. The similarity in form across languages facilitates the initial stages of word recognition by reducing the cognitive effort required for orthographic and phonological mapping (Otwinowska & Szewczyk, 2019). By minimizing the cognitive demands associated with acquiring orthographic form, the present design was intended to better isolate how contextual variability may influence online processing during semantic integration. In this way, cognates should allow participants to manage the high cognitive load of studying novel words in sentence contexts. Using cognates also allows us to maximize the likelihood of observing cross-language contextual interactions during online processing.

In fact, the very act of bilingual cross-language processing can contribute to desirable difficulty during word learning (Bogulski et al., 2019), especially when the language context of vocabulary acquisition is intentionally varied. Bilinguals, constantly engaging in language regulation, frequently demonstrate an advantage over monolinguals in acquiring vocabulary in a new foreign language (Bogulski et al., 2019; Bradley et al., 2013).

Each distinct linguistic context contributes unique orthographic and phonological information. Repeated exposure across languages may encourage learners to process novel words across multiple linguistic environments, potentially supporting the more flexible use of contextual information during subsequent encounters. While the initial cognitive load may be increased due to managing competing cross-language activations of lexical candidates, this increased demand could ultimately promote deeper processing and, consequently, improve memory recall through the mechanism of desirable difficulty (Lauro et al., 2025).

1.4. Eye Movements as an Index of Word Learning

To empirically address the dynamic processes involved in bilingual contextual word learning, eye-tracking may provide a sensitive, online measure of readers' processing during contextual word learning. Although eye movements cannot directly measure lexical–semantic representations or lexical quality, they provide indirect behavioral indices of processing efficiency as readers encounter novel words in context. By manipulating the type (repeated or varied semantic contexts) or the language (L1 or L2) of repeated exposures, we may observe subtle changes in eye movements that reflect changes in online processing as readers repeatedly encounter novel words during learning. Eye-tracking also measures implicit processing, rather than secondary or offline measures of semantic knowledge. Furthermore, eye-tracking is a natural and ecologically valid measure of lexical access and semantic integration of novel words.

Importantly, eye-movement measures provide indirect behavioral indices of the cognitive processes engaged during reading. Although fixation duration measures are widely interpreted as reflecting lexical access and semantic integration during reading (Rayner, 1998, 2009), they have also been used to examine online processing during second language vocabulary learning (Elgort et al., 2018; Godfroid et al., 2018). Nevertheless, they do not directly measure the quality of the underlying lexical–semantic representations. Consequently, the present study interprets eye-movement differences as evidence of differences in online processing efficiency during learning rather than direct evidence of lexical knowledge itself.

Eye movements in reading reflect the learning effort associated with reading unfamiliar words. Readers typically make more and longer fixations when they experience processing difficulty (Rayner, 2009). Longer reading times on unfamiliar words are often interpreted as more effortful learning, including orthographic encoding of word forms (Lowell & Morris, 2014), and inferring meaning and integration of meaning into the surrounding context (Chaffin, 1997; Chaffin et al., 2001). Low-frequency words are more difficult to process than high-frequency words (Brysbaert et al., 2011, 2018; Monsell et al., 1989), resulting in slower, more effortful processing. Novel words that have not been encountered previously have zero frequency and remain low frequency in the early stages of learning (Elgort et al., 2018; Godfroid et al., 2018). As such, novel words are read more slowly and with more effort because they are difficult to process.

1.5. Individual Differences in Bilingual Vocabulary Learning

Readers' pre-existing lexical knowledge can also significantly modulate contextual word learning and reading efficiency. General vocabulary ability and primary language (L1 vs. L2) have been shown to impact reading times (Kuperman et al., 2023; Kuperman & Van Dyke, 2011) and the success of contextual word learning (Elgort et al., 2015; Elgort & Warren, 2014; Frishkoff et al., 2008). A robust general vocabulary appears particularly beneficial for inferring meanings of recently encountered novel words or pseudowords, especially when the surrounding context lacks explicit dictionary-style definitions (Elgort et al., 2024).

Finally, bilinguals' L2 proficiency also mediates the efficiency of reading and the effectiveness of word learning in L2 contexts. Lower L2 proficiency is typically associated with more effortful reading, longer fixation durations, shorter saccades, and fewer word skips (Cop et al., 2015; Dirix et al., 2020; Godfroid et al., 2013; Pellicer-Sánchez, 2016), reflecting slower lexical access and greater cognitive load compared to L1 reading. This is often attributed to less robust L2 lexical representations and a reliance on lower-level processing (Kuperman et al., 2023). Higher proficiency in L2 can facilitate the inference of word meanings from semantic context, as more advanced learners utilize their larger existing vocabulary and stronger grammatical knowledge as leverage during meaning extraction (Webb et al., 2023). However, even with proficient learners, the demands of processing novel words within a less dominant language can still elicit distinct eye-movement patterns compared to L1 learning (Berzak & Levy, 2023; Cop et al., 2015).

1.6. Present Study

The present study aimed to investigate how semantic and language context influence online processing during bilingual novel word learning, using eye-movement measures as indirect indices of processing efficiency. Specifically, we are interested in how different types of repeated exposures to novel words (varied semantic contexts or repeated semantic contexts; L1, L2 or both language contexts) influence online processing during repeated encounters with novel words as reflected in real-time reading behavior. The primary goal was to examine how processing effort during reading varies across semantic and language contexts, and whether these online processing differences are associated with performance on a subsequent semantic relatedness task. Critically, we manipulate two key aspects of the learning environment: (1) the semantic context in which novel words are read, and (2) the language context in which novel words are encountered.

We hypothesize that repeated semantic contexts will initially facilitate lexical access, as measured by early eye-tracking measures (first fixation duration) of the novel word. As such, reading times should decrease at a faster rate across repeated semantic contexts, reflecting increased familiarity with the repeated sentence context and target word. How-

ever, for later-stage measures (total reading time), we hypothesized that varied semantic contexts would support more efficient semantic integration during later stages of processing. Sentence-level total reading times were additionally examined to assess broader adaptation to repeated semantic and language contexts during reading. In later-stage measures of reading times, reading times should decrease more rapidly for words studied in varied semantic contexts. Regarding the effect of language context on reading times, reading times should be faster in L1 contexts compared to L2 contexts. In mixed-language contexts, in which readers encounter novel words and sentences twice in L1 and twice in L2, we predict slower initial reading times, reflecting the increased cognitive demands of language switching and cross-language activation. However, we predict that this initial processing cost will diminish with repeated exposure, such that by later encounters (e.g., the fourth exposure), the differences in overall sentence reading times between mixed and single-language conditions will be attenuated.

We also hypothesized several key interactions. First, we predict an interaction between the semantic context and language conditions. The mixed condition requires the learner to manage both semantic shifting and language-set switching simultaneously. Therefore, we expect significantly longer reading times in the mixed-language condition than in the single-language condition. Second, repeated semantic contexts should lead to a rapid decrease in reading times across subsequent encounters with the same word. We expect the rate of reduction in reading times for varied semantic contexts to be more gradual. Finally, we predict that these interactions will be moderated by L2 proficiency. Specifically, there should be a smaller variability cost in the mixed language condition as L2 proficiency increases, demonstrating a greater capacity to utilize cross-linguistic cues during repeated encounters with novel words.

2. Materials and Methods

2.1. Participants

This study included 30 Brazilian Portuguese–English bilinguals (43% male, $n = 13$). Participants ranged in age from 18 to 49 years ($M = 29.8$, $SD = 9.8$). All participants reported English as their second language (L2). L2 age of acquisition ranged from 5 to 18 years old ($M = 11.77$, $SD = 3.50$). Most reported learning English at school ($n = 25$) and independently ($n = 22$), with fewer reporting acquisition at home ($n = 14$) or with friends ($n = 5$). Participants could choose more than one method of acquisition.

Eight participants had a master's degree, two held a specialization degree, fifteen had a bachelor's degree, and five were currently enrolled in an undergraduate program. Most participants were studying Languages and Literature (with an emphasis on English) ($n = 24$). The remaining participants reported study areas of translation studies ($n = 2$), linguistics ($n = 2$), cinema ($n = 1$), and psychology ($n = 1$).

L2 proficiency was assessed both subjectively and objectively. Subjective proficiency was measured via self-ratings across four domains on a 7-point scale (1 = very poor, 7 = excellent). Descriptive statistics for subjective self-ratings are reported in Table 1. Objective proficiency was measured using a computerized adaptation of the vocabulary sub-test of the Shipley-2 Institute of Living Scale (Shipley et al., 2009), in which participants completed 40 multiple-choice synonym trials of increasing difficulty. The number of correct trials and the response times (RTs) for correct trials are reported in Table 1.

Table 1. L2 (English) proficiency and acquisition information.

Subjective L2 (English) Proficiency		
	<i>M (SD)</i>	<i>Range</i>
Speaking	5.17 (1.42)	2–7
Listening	5.27 (1.17)	3–7
Writing	5.07 (1.36)	2–7
Reading	5.77 (0.97)	3–7
Objective L2 (English) Proficiency		
	<i>M (SD)</i>	<i>Range</i>
Vocabulary Score	23.37 (3.91)	14–30
Correct RT (ms)	2806	900

Note. Proficiency self-ratings were provided on a 7-point scale (1 = very poor, 7 = excellent). Vocabulary proficiency was assessed using an adapted version of the vocabulary sub-test of the Shipley-2 Institute of Living Scale (Shipley et al., 2009); RT = response time for correct trials.

2.2. Stimuli and Materials

2.2.1. Target Words

Seventy-two rare target English–Portuguese cognates were selected based on the degree of cross-language overlap, word frequency, and word length. Target cognates were divided into two lists (36 target words per list). The orthographic similarity of target cognates was quantified using normalized Levenshtein distances (Schepens et al., 2012). The Levenshtein distance (Levenshtein, 1966) counts the minimum number of substitutions, insertions, and deletions to edit one word into another. To normalize the Levenshtein distances, the following formula was used ($\text{score} = 1 - (\text{Levenshtein distance} / \text{maximum word length of target word(s)})$). The average normalized Levenshtein distance for English–Portuguese cognates was 0.71 ($SD = 0.17$). The normalized Levenshtein distances were not significantly different across experimental lists, (List 1: $M = 0.70$, $SD = 0.14$; List 2: $M = 0.71$, $SD = 0.21$), $t(70) = -0.10$, $p = 0.92$.

The target word length did not differ significantly in English ($M = 6.54$ letters, $SD = 1.46$ letters) or Portuguese ($M = 6.94$ letters, $SD = 1.42$ letters), $t(142) = 1.82$, $p = 0.07$. There were no significant differences in word length across experimental lists, p 's > 0.05.

Word frequency (words per million; wpm) was measured using the SUBTLEXus database (Brysbaert & New, 2009) for English and SUBTLEX-PT database (Soares et al., 2015) for Portuguese words. If a target word did not appear in the database, it was assigned a value of 0.0 ($n = 14$ in English; $n = 13$ in Portuguese). The average frequency for English target words ($M = 6.54$ wpm, $SD = 1.46$) was slightly less than the average frequency for Portuguese target words ($M = 6.94$ wpm, $SD = 1.42$), $t(71) = -3.23$, $p = 0.002$. However, the frequencies did not differ across experimental lists for English target words, nor for Portuguese target words, p 's > 0.07.

2.2.2. Study Sentences

Experimental lists were counterbalanced across participants such that each participant saw 36 target words embedded in sentence contexts. Participants were exposed to each target word four times, reading a total of 144 sentences. In 1/3 of the trials, they were exposed to English-only contexts (across each of the four exposures); in 1/3, they were exposed to Portuguese-only contexts; and participants read two sentences in English and two sentences in Portuguese in 1/3 of the trials. Across participants, the target items were counterbalanced across all semantic and language conditions.

There was no significant difference in sentence length for Portuguese ($M = 15.21$ words, $SD = 3.71$ words) and English ($M = 14.80$ words, $SD = 4.07$ words) sentences, $t(286) = 0.89$, $p = 0.37$. Additionally, half of the trials repeated the same sentence across each of the four

exposures, and half of the trials varied the sentences in which target words were embedded, resulting in six possible conditions: English-only, repeated semantic context; Portuguese-only, repeated semantic contexts; English-only, varied semantic contexts; Portuguese-only, varied semantic contexts; both languages, repeated semantic contexts; and both languages, varied semantic contexts. Each participant was exposed to each condition. There was a minimal but significant difference in sentence length across experimental lists, $t(286) = 2.24$, $p = 0.026$. Sentences in List 1 ($M = 15.52$ words, $SD = 4.04$) were approximately one word longer on average than sentences in List 2 ($M = 14.50$, $SD = 3.68$).

2.2.3. Comprehension Questions

Each participant answered 14 comprehension questions throughout the task. The average accuracy was 90% ($M = 0.90$, $SD = 0.10$), with scores ranging from 57% to 100%.

2.2.4. Post-Test Semantic Relatedness Task Design

To assess novel word learning, participants completed a semantic relatedness task, which was an adaptation of the semantic decision paradigm using the software PsyToolkit 3.7.0 (Stoet, 2010, 2017). In this task, participants judged whether pairs of words were semantically related or unrelated. Thirty-six studied words were each paired with either a semantically related synonym or an unrelated non-studied word. Accurate identification of the related pairs and rejection of the unrelated pairs indicated successful semantic learning.

To control for prior knowledge and potential response biases, 36 non-studied low-frequency words (drawn from the unstudied item pool) were also included in the semantic relatedness task, each paired with either a semantically related or unrelated word. These filler items were randomized among the experimental trials. Although the target words were low-frequency cognates, the present study did not include an explicit pre-test of item familiarity. Instead, low-frequency cognates were selected to maximize cross-language overlap while reducing the likelihood of substantial prior knowledge, thereby allowing examination of contextual and cross-language influences on emerging lexical representations.

2.2.5. L2 Proficiency Vocabulary Test

Following the semantic relatedness task, participants completed an English vocabulary assessment using a computerized adaptation of the vocabulary sub-test of the Shipley-2 Institute of Living Scale (Shipley et al., 2009) using the PsyToolkit software (Stoet, 2010, 2017). This test was used to quantify participants' general L2 lexical knowledge. The assessment consisted of 40 multiple-choice synonym trials of increasing difficulty. Each trial presented a target word and four response options, from which participants selected the synonym that best matched the target. Both the number of correct responses and the response times (RTs) for correct trials were recorded (see Table 1).

2.3. Procedure

Participants provided informed consent, approved by the ethics committee (approval #: 7.148.736). The study session consisted of novel words presented in sentence contexts. Eye movements were recorded using the Tobii Pro Spark eye-tracker at a sampling rate of 60 Hz and an average spatial accuracy of 0.45° and precision of 0.26° RMS. Participants completed a 5-point binocular calibration to ensure accurate gaze estimation on the display screen. Re-calibration was conducted as needed throughout the session if drift was detected or if participants shifted positions significantly.

Each trial began with a fixation cross. The sentence appeared once a stable fixation was detected. Participants pressed the spacebar when they had finished reading and understood the sentence. Simple yes/no comprehension questions were presented throughout the trials. Sentences were presented in randomized order.

Immediately following the study session, participants completed a post-test semantic relatedness task. For this task, participants were presented with a target word (previously encountered in the study session) and a probe word. In half of the trials, the probe word was a semantically related synonym, and in the other half, the probe word was a semantically unrelated word. Participants had to determine whether the two words were semantically related or unrelated in meaning. Response times and accuracy were recorded.

Finally, participants completed an English vocabulary assessment using the Shipley-2 Vocabulary Test (Shipley et al., 2009), which quantified their general L2 lexical knowledge.

2.4. Eye-Movement Measures

Three eye-movement measures were analyzed to capture different stages of processing during contextual word learning. The first fixation duration (FFD) on target words was used as an index of early lexical access and initial processing difficulty. The FFD is commonly interpreted as reflecting early stages of word recognition that are sensitive to lexical familiarity and processing efficiency (Rayner, 1998, 2009). The total fixation duration (TFD) on target words was analyzed to capture later and more integrative stages of lexical-semantic processing, including reanalysis and semantic integration during sentence reading.

In addition to word-level fixation measures, total sentence reading times (TRTs) were analyzed to capture broader sentence-level processing associated with contextual word learning. Fixation durations on target words primarily reflect local lexical access and integration processes. Sentence-level TRTs may reflect more global semantic integration and adaptation to repeated linguistic environments during reading. In bilingual reading, processing difficulty associated with novel words may extend beyond the target region and influence integration across the entire sentence. Prior research on bilingual contextual word learning has similarly examined sentence-level reading measures to examine how repeated exposures influence broader reading efficiency (e.g., Lauro et al., 2025). Thus, sentence-level TRTs allowed us to examine whether repeated semantic and language contexts influenced localized processing of target words, as well as broader sentence-level adaptations across repeated encounters.

2.5. Statistical Analysis Plan

2.5.1. Reading Times of Study Sessions

Linear mixed-effects regression models were analyzed using the lme4 package (Bates et al., 2015) in R 4.4.1 (Baayen, 2008; Baayen et al., 2008). To address the factor structure, predictors were non-orthogonally coded to allow for the interpretation of main effects averaged across levels. Language context was Helmert-coded (Contrast 1: L1 vs. L2; Contrast 2: single- vs. mixed-language), and semantic context was deviation-coded (-0.5 = repeated; 0.5 = varied). Presentation order (first, second, third, fourth) and L2 vocabulary score (Shipley-2) were treated as continuous variables and centered prior to the analysis. Presentation order was modeled as a continuous linear predictor to estimate overall changes in processing across repeated encounters with novel words. Our primary interest was in testing average changes in processing over repeated exposures rather than characterizing the precise functional form of learning trajectories.

The models included the fixed effects of language context, semantic context, presentation order, and L2 vocabulary score, along with all possible interactions.

Random-effects structures were selected to appropriately account for repeated observations within participants while maintaining model convergence and interpretability (Bates et al., 2015). Random intercepts for participants and items, as well as random slopes for within-subjects factors, were included and retained if the model fit improved and the model converged. The full model is reported, as it provided the best fit for the data while

accounting for critical individual differences in L2 proficiency. Therefore, the final model reflects the maximal random-effects structure that converged. Then, estimated marginal means (EMMs) (for the linear mixed-effects models) were calculated using the emmeans package (Lenth, 2016) based on the final model.

2.5.2. Post-Test Semantic Relatedness Task

Linear and logistic mixed-effects models were used to examine the response times (RTs) and accuracy rates using the same package in R (Baayen, 2008; Baayen et al., 2008; Bates et al., 2015). The same predictors included in the reading time analyses were also included in the analyses of post-test RTs and accuracy rates. Additionally, the relatedness condition (related vs. unrelated) of the post-test trial was included as an additional predictor. The same model comparison approach was applied using log-likelihood ratio tests to assess model fit.

3. Results

3.1. Reading Times While Studying

To investigate the online processing of novel words, two eye-movement measures on the target word region were analyzed: first fixation durations (FFDs) and total fixation duration. The final models included language context (Contrast 1: L1 vs. L2; Contrast 2: single- vs. mixed-language), semantic context (repeated vs. varied), presentation order, and L2 vocabulary scores as fixed effects, including all possible interactions (Table 2). The final model for FFD included random intercepts for participants and target words. Random slopes for language and semantic contexts did not converge. The final model for the TFD made on target novel words included random intercepts for participants and target words, with random slopes for semantic context at the participant level. The final model for the analysis of the whole duration of fixations made on target novel words included random intercepts for participants and target words, with random slopes for semantic context at the participant level.

Table 2. Linear mixed-effects models for target word eye movements and total sentence reading times.

Predictor	First Fixation Duration			Total Fixation Duration			Sentence Total Reading Time		
	<i>b</i> (SE)	<i>t</i>	<i>p</i>	<i>b</i> (SE)	<i>t</i>	<i>p</i>	<i>b</i> (SE)	<i>t</i>	<i>p</i>
Fixed Effects									
(Intercept)	264.54 (10.32)	25.69	<0.001	626.27 (168.51)	3.72	<0.001	3958.43 (340.70)	11.62	<0.001
L1 vs. L2	4.77 (4.94)	0.97	0.337	−37.44 (26.03)	−1.44	0.155	−358.49 (148.96)	−2.41	0.019
Single vs. Mixed	4.21 (62.96)	1.45	0.150	75.33 (15.04)	5.01	<0.001	363.75 (86.48)	4.21	<0.001
Repeated vs. Varied	6.14 (298.13)	0.76	0.450	98.57 (48.00)	2.05	0.044	894.26 (270.87)	3.30	0.001
Presentation Order	−22.14 (62.85)	−7.75	<0.001	−156.15 (7.99)	−19.53	<0.001	−575.33 (32.61)	−17.64	<0.001
L2 Vocabulary Score	7.16 (389.75)	0.74	0.469	−11.46 (65.62)	−0.18	0.863	−279.43 (312.90)	−0.89	0.379
L1 vs. L2 * Presentation Order	0.23 (93.42)	0.07	0.947	33.51 (9.76)	3.43	<0.001	108.76 (39.88)	2.73	0.006

Table 2. Cont.

Predictor	First Fixation Duration			Total Fixation Duration			Sentence Total Reading Time		
	<i>b</i> (SE)	<i>t</i>	<i>p</i>	<i>b</i> (SE)	<i>t</i>	<i>p</i>	<i>b</i> (SE)	<i>t</i>	<i>p</i>
Single vs. Mixed * Presentation Order	1.10 (52.06)	0.53	0.594	−13.45 (5.68)	−2.37	0.018	−51.64 (23.10)	−2.24	0.025
Repeated vs. Varied * Presentation Order	7.43 (115.71)	1.30	0.193	67.04 (15.99)	4.19	<0.001	565.99 (65.22)	8.68	<0.001
L1 vs. L2 * L2 Vocabulary	2.21 (73.32)	0.66	0.507	28.36 (9.77)	2.90	0.004	143.83 (39.73)	3.62	<0.001
Single vs. Mixed * L2 Vocabulary	1.30 (31.94)	0.67	0.535	−14.07 (5.66)	−2.48	0.013	−91.54 (23.02)	−3.98	<0.001
L1 vs. L2 * Repeated vs. Varied * L2 Vocabulary	11.60 (196.64)	1.75	0.081	−57.16 (19.54)	−2.93	0.003	−203.39 (79.45)	−2.56	0.011
Single vs. Mixed * Presentation Order * L2 Vocabulary	1.51 (51.94)	0.78	0.437	12.06 (5.67)	2.13	0.034	16.47 (23.05)	0.72	0.474
Random Effects	Variance (SD)			Variance (SD)			Variance (SD)		
Target Word (Intercept)	601.82 (24.53)			27,959.00 (167.20)			1,006,216.00 (1003.10)		
Participant (Intercept)	2614.00 (51.13)			127,227.00 (356.70)			3,036,100.00 (1742.40)		
Context (Intercept)	—			14,868.00 (121.90)			416,116.00 (645.10)		
Residual	28,488.71 (168.79)			269,839.00 (519.50)			4,430,851.00 (2105.00)		

Note. The linear mixed-effects regression models were constructed with unstandardized fixed effects coefficients for language context, semantic context, presentation order, L2 vocabulary score, and all possible interactions. Language context was Helmert-coded (L1 vs. L2; single- vs. mixed-language), and semantic context was deviation-coded (repeated = −0.5; varied = 0.5). Continuous predictors were centered, and categorical predictors were non-orthogonally coded prior to analysis.

3.1.1. First Fixation Duration

The model for FFD revealed a significant main effect of presentation order, $p < 0.001$, indicating that the time spent on the initial encounter of a word significantly decreased across subsequent exposures. There were no main effects of either language contrast, nor the semantic context factor, nor were there any significant interactions (see Table 2).

3.1.2. Total Fixation Duration (of Target Words)

The analysis of TFD, that is, the sum of all fixations on the target word, demonstrated significant effects of experimental manipulations and individual differences. There was a main effect of presentation order, $p < 0.001$, with total reading times decreasing approximately 156 ms per exposure. There was a significant main effect of language context, reflecting overall longer processing times in the mixed-language condition compared to the single-language condition, $p < 0.001$. Additionally, a main effect of semantic context revealed that varied contexts elicited longer fixations than repeated contexts, $p < 0.001$ (Table 2).

There were also several interactions with presentation order, reflecting the rate of learning differences by experimental conditions. The interaction between presentation order and language context (L1 vs. L2) suggests that the rate of learning (i.e., reduced reading times) was steeper for the L2 condition than the L1 condition, $p < 0.001$. The interaction between presentation order and the other language contrast (single- vs. mixed), demonstrated that the mixed condition had a steeper rate of learning than the single-language condition, $p < 0.001$. Finally, the interaction between presentation order and semantic context yielded steeper reductions in reading time for repeated semantic contexts relative to varied semantic contexts, $p < 0.001$ (Figure 1).

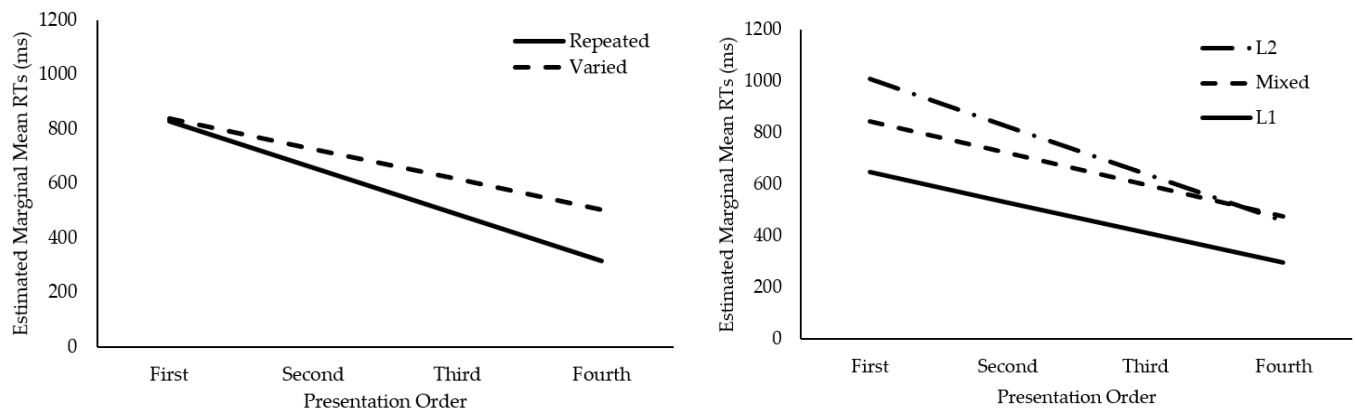


Figure 1. Total duration of fixations on target novel words (in milliseconds) (estimated marginal means).

Individual differences in L2 proficiency also significantly modulated processing. There was a significant interaction between L2 proficiency and language (single vs. mixed), $p = 0.01$, as well as a three-way interaction between L2 proficiency, language (L1 vs. L2) and semantic context, $p = 0.003$. Higher L2 vocabulary scores were associated with a significant reduction in the processing cost of target words embedded in L2 with varied sentences. Additionally, there was another three-way interaction between L2 proficiency, language (single vs. mixed) and presentation order, $p = 0.034$. As L2 proficiency increased, the decrease in reading time across exposures in the mixed-language condition became significantly steeper, facilitating a more rapid reduction in switching costs across successive exposures.

3.1.3. Total Reading Time of Sentences

The analysis of total fixation durations for the entire sentence revealed several significant main effects and higher-order interactions. There was a main effect of presentation order, reflecting a decrease in reading times across successive encounters, $p < 0.001$. Significant main effects were also observed for both language contrasts (L1 vs. L2, $p = 0.019$; single vs. mixed, $p < 0.001$), with faster reading times for L1 sentences compared to L2 sentences and longer reading times for mixed-language contexts compared to single-language contexts. Additionally, the main effect of semantic context was significant, $p = 0.001$. Repeated semantic contexts were read faster than varied contexts.

These main effects were qualified by several significant two-way and three-way interactions. A significant interaction between language (L1 vs. L2) and presentation order yielded steeper decreases in L1 sentence reading times across each exposure compared to L2, $p = 0.006$. Furthermore, the decrease in reading times was also more pronounced in single-language rather than mixed-language sentences across each exposure, $p = 0.025$. Additionally, the faster reading times of repeated semantic contexts accelerated at a greater rate than varied semantic contexts across each exposure, $p < 0.001$ (Figure 2).

L2 proficiency significantly moderated these patterns. A significant three-way interaction emerged between language (L1 vs. L2), semantic context, and vocabulary score, $p = 0.01$, indicating that reading time lags for L2-varied sentences (i.e., longer processing/reading times) were significantly attenuated as L2 proficiency increased. Additionally, two-way interactions were observed between vocabulary score and both language contrasts (both p 's < 0.001). Higher L2 proficiency was associated with a reduction in the processing costs typically associated with L2 and mixed-language environments. No other interactions reached the threshold for significance.

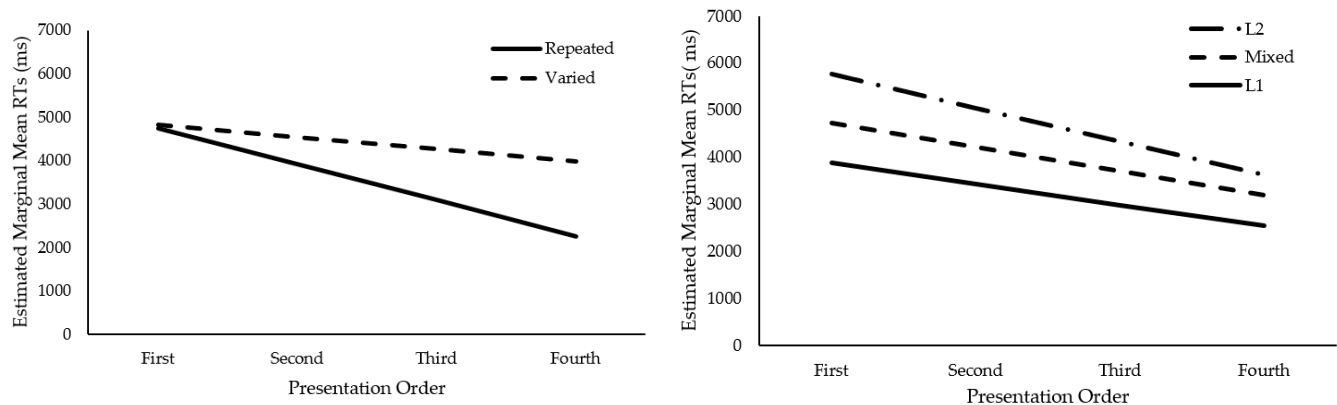


Figure 2. Estimated marginal means of sentence reading times (ms) across encounters.

3.2. Post-Test Semantic Relatedness Task Performance

A linear mixed-effects model was conducted to examine the effects of study language, study context, and semantic relatedness condition on response times (RTs). The model included random intercepts for participants and target word. The only significant effect observed was for the semantic relatedness condition (related vs. unrelated trials), $p = 0.002$, in which RTs were faster for related trials. There was no significant effect of language or semantic contexts, p 's > 0.05 . There were no significant interactions.

A logistic mixed-effects model was performed to assess the accuracy rates using the sample predictors. Random intercepts were included for participants and target word. Again, the only significant effect observed was the semantic relatedness condition (related vs. unrelated trials), $p = 0.033$, demonstrating higher accuracy for related trials compared to unrelated trials. There were no significant effects of the study language conditions or the study semantic context conditions, p 's > 0.05 . There were no significant interactions.

4. Discussion

The present study examined how semantic variability and language context jointly influence bilingual novel word learning during sentence reading. Eye-movement findings demonstrated that repeated semantic contexts facilitated more efficient online processing across repeated encounters, whereas semantically varied contexts elicited greater processing demands, particularly during later stages of lexical–semantic integration. Language context further modulated these effects, such that reading in the dominant language facilitated more efficient processing than reading in the non-dominant language or across mixed-language contexts. Together, these findings suggest that semantic and linguistic variability influence online processing during bilingual novel word learning. However, because no differences were observed in the offline semantic relatedness task, these effects are most appropriately interpreted with respect to processing efficiency during learning rather than as direct evidence of stronger lexical–semantic representations.

Consistent with prior work related to lexical familiarity (Elgort et al., 2018; Godfroid et al., 2018), as well as our initial hypothesis, repeated exposure to novel words reduced processing times across all eye-tracking measures. This effect was more pronounced in the later-stage measures, suggesting that, in addition to aiding lexical access, repetition supports the efficient semantic integration of novel information over time. The similar patterns observed for total fixation duration and total reading time are not unexpected. Both measures incorporate later stages of processing, including continued lexical–semantic integration and rereading. Varied semantic contexts demonstrated an initial processing cost during early encounters with novel words, and the interaction between semantic context and presentation order demonstrated that the decrease in reading time across each

exposure was slower when the semantic context varied across encounters, suggesting that processing demands of semantic variation were persistent. These findings are broadly consistent with the desirable difficulty framework (E. L. Bjork & Bjork, 2011; R. A. Bjork, 1994), which proposes that more effortful learning conditions can promote deeper encoding and more flexible representations.

However, the first fixation duration primarily reflects earlier stages of lexical processing and may therefore be less sensitive to the contextual manipulations employed in the present study (Rayner, 1998, 2009). The absence of significant effects for the first fixation duration suggests that the contextual manipulations primarily influenced later stages of lexical–semantic integration rather than early stages of lexical access. Furthermore, the lack of significant differences on the post-test semantic relatedness task suggests that the processing cost associated with semantically varied sentences did not translate into immediate improvements in semantic retrieval. One possibility is that the benefits from varied semantic contexts may emerge after a longer consolidation period (Laufer & Goldstein, 2004; Robinson, 1995).

Although the present findings are broadly consistent with an instance-based account of contextual word learning, alternative mechanisms may also have contributed to the observed facilitation for repeated contexts. Specifically, repeated sentence contexts may reduce processing demands through repetition priming and episodic memory for previously encountered sentence contexts, independent of changes in lexical–semantic processing. Therefore, the present design cannot fully disentangle facilitation arising from semantic contextual repetition from facilitation attributed to broader sentence-level repetition effects. Future research could isolate these mechanisms by varying the semantic context while minimizing the repetition of the surrounding sentence contexts or by independently manipulating semantic and episodic sources of repetition.

Regarding the role of language context, the online processing of novel target words, as well as whole sentences, was faster in L1 than in L2. Additionally, the rate of decrease in RTs across encounters was steeper in L1 compared to L2. This is consistent with previous research on bilingual reading processes (Cop et al., 2015; Kuperman et al., 2023). The present findings are consistent with more efficient online lexical processing during L1 reading and may reflect more efficient lexical access and semantic integration. Furthermore, consistent with our prediction, a processing cost associated with reading in both languages was found for the word-level TFDs, suggesting increased word-level processing demands, possibly due to language-switching costs and cross-language competition (Kroll & Tokowicz, 2005). However, participants with higher L2 proficiency demonstrated greater reductions in processing time across mixed-language encounters, suggesting that bilingual readers adapt to dual-language contexts over repeated exposures. This may be consistent with increased efficiency in managing cross-language activation as lexical representations become more familiar. However, this interpretation should be considered within the context of the present participant sample. Although L2 proficiency significantly moderated several effects, bilingual lexical access is known to vary as a function of proficiency, age of acquisition, language experience, and task demands (Dijkstra & Van Heuven, 2002).

An important finding from the present study was the dissociation between online processing measures and offline semantic relatedness performance. Although semantic and language context influenced eye-movement behavior during reading, these effects did not translate into significant differences in post-test semantic retrieval. One possible explanation is that eye-tracking measures are sensitive to subtle and incremental learning-related processes that occur during contextual word learning, whereas the offline semantic relatedness task provides a more conservative assessment of whether those online processing differences resulted in stable lexical–semantic knowledge. From an instance-based

perspective, lexical learning emerges through repeated contextual encounters, and the observed eye-movement differences likely reflect this ongoing process. However, although reliable differences emerged in the eye-movement data, these processing differences did not translate into superior offline vocabulary learning. As such, the present findings should be interpreted as demonstrating how semantic and language context influence online processing during bilingual word learning, rather than as direct evidence that these manipulations produced stronger lexical–semantic representations. However, prior work using a similar semantic relatedness task did observe condition-level differences in post-test accuracy (Lauro et al., 2025), suggesting that the effects of contextual variability on offline learning outcomes may depend on factors such as exposure schedule, degree of contextual variation, language context, or the strength of lexical representations formed during learning. It is also possible that the present semantic relatedness task was less sensitive to subtle differences in semantic depth than measures requiring active recall or meaning generation.

The present findings generally support instance-based accounts of word learning (Reichle & Perfetti, 2003), which propose that lexical representations emerge gradually across repeated encounters and are shaped by the contextual and episodic characteristics of those encounters. The persistence of semantic contextual effects, even after multiple exposures, suggests that variability may increase processing demands during the early stages of learning. Additionally, the role of language context supports models of non-selective bilingual lexical access (Dijkstra & Van Heuven, 2002) and demonstrates that language-switching during word learning results in an initial processing cost that interacts with learners' L2 proficiency.

Several limitations should be acknowledged. First, the post-test may not have captured the full extent of semantic knowledge. Research has demonstrated different effects for semantic recall and recognition (Pellicer-Sánchez et al., 2021). Future research may use recall or meaning-generation tasks to extract deeper semantic knowledge of the recently studied words. Alternatively, a delayed assessment could be used to investigate the long-term effects of contextual variability. Future studies may also employ nonlinear modeling approaches to more precisely characterize how processing changes over the course of repeated word exposures. Another limitation is that repeated semantic contexts necessarily involved repeated sentence contexts, making it difficult to parse out the effects of semantic contextual consistency from sentence-level repetition and episodic priming.

Finally, the present study used cognates to control form overlap across languages. Participants may have been, at least partially, familiar with some target items prior to the experiment. Cognate overlap likely reduced orthographic learning demands and may have facilitated semantic inference across contexts. Consequently, the present findings may reflect contextual modulation of lexical–semantic integration under conditions of high cross-language support, rather than stable lexical–semantic knowledge. Future work should compare cognates and non-cognates directly to determine whether contextual variability effects differ as a function of cross-language overlap.

5. Conclusions

Despite these limitations, the present study demonstrates that bilingual vocabulary learning is influenced not only by repetition frequency but also by the semantic and linguistic variability of learning contexts. By combining eye-tracking measures with semantic and cross-language contextual manipulations, the present findings suggest that online processing measures can provide a sensitive index of learning-related processing during bilingual novel word learning, even when stable differences are not detectable in offline behavioral measures. Together, these findings highlight the importance of considering both semantic and cross-language variability in models of bilingual lexical processing

and vocabulary acquisition while providing a foundation for future research examining how these online processing differences can develop into more stable lexical–semantic representations over time.

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