ABSTRACT

Title of Dissertation:	EXPLORING VISUAL WORD RECOGNITION IN LATE SECOND LANGUAGE LEARNERS: A FOCUS ON LETTER TRANSPOSITION
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Previous studies in the first language (L1) revealed that letter-transposed (TL) primes (e.g., baisc for basic) have a significant advantage over letter-substituted (SB) primes, although this advantage accompanies a significant cost when compared to identity (ID) primes. These phenomena are often cited as evidence for position-flexible yet precise lexical processing in L1. The present study investigated whether Korean L2 learners of English employ the same processing abilities as native speakers. A lexical decision task using the masked priming paradigm was conducted with 144 English words and 144 nonwords. Targets were preceded by four prime types: ID, TL, SB, and unrelated (UN) primes. Both native speakers and L2 learners exhibited significant TL advantage and cost. However, the two groups differed significantly in the repetition priming effect as well as in the differences between TL and UN conditions, and between the SB and UN

conditions. These findings in the L2 learners were not entirely compatible with either the Lexical Tuning Hypothesis (Castles, Davis, Cavalot, & Forster, 2007) or the Multiple Route Model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger, Lété, Bertand, Dufau, & Ziegler, 2012; Grainger & Ziegler, 2011). Instead, the L2 learners' performance was primarily influenced by the formal similarity in terms of letter identity and letter position. Thus, high formal similarity between prime and target pairs resulted in faster and more accurate responses to word targets, regardless of prime lexicality. Given that the TL advantage and cost were comparable to native speakers, the results highlight the need for diverse comparisons to appropriately examine L2 visual word recognition.

EXPLORING VISUAL WORD RECOGNITION IN LATE SECOND LANGUAGE LEARNERS: A FOCUS ON LETTER TRANSPOSITION

by

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

I dedicate this study to my beloved parents, Jeongho Kang and Seonok Lee, who, provided me with unyielding support despite facing their own difficult times.

To my beloved sister Seonim Kang, thank you for your constant sustenance.

Acknowledgements

It is a true honor and personal pleasure for me to have completed this dissertation. I am sincerely indebted to many individuals who contributed to its realization.

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I also wish to extend my gratitude to Dr. Megan Masters, who shared invaluable perspectives on the present study, particularly during its early developmental stages. My appreciation also goes to Dr. Branson Hui for his generous and insightful guidance with the statistical analysis. I sincerely thank Dr. Ekaterina Sudina, who meticulously reviewed the present study and offered crucial revisions that I might have overlooked otherwise. Finally, my heartfelt thanks go to Dr. Min Wang, who eagerly agreed to serve as a committee member and the dean's representative, providing a valuable additional perspective on the interplay between L1 and L2.

Beyond my committee, I would also like to thank the many other individuals who helped me with this dissertation. Dr. Kichan Park shared valuable guidance pertaining to the Korean L2 learners of English. Dr. Mi Jeong Song and Dr. Yong-Yae Park at Seoul National University graciously provided me with opportunities, upon my request, to visit their classes and recruit participants, which was pivotal to this study. Last but not least, I am deeply appreciative of Dr. Jonghyun Lee, whose generous permission for pilot studies in his classes was absolutely indispensable to my dissertation.

It is my hope that this dissertation contributes to the field of Second Language Acquisition. Whereas I am deeply grateful for all the advice, support and guidance I have received, any remaining errors or omissions are my sole responsibility.

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List of Abbreviations

AD: advantage

CO: cost

ID: identity

GLMMs: generalized linear mixed-effects models

L1: the first language

L2: the second language

ms: millisecond (1 ms = 0.001 second)

PR: priming

RP: repetition

SB: letter substitution

SOA: the stimulus onset asynchrony

TR: letter transposition

UN: unrelated

Chapter 1. Introduction

Reading is one of the highly complex linguistic activities, which includes multi-level cognitive processes of visual stimuli. It requires the interpretation of images on the retina in such a way that language-related symbols (e.g. script) are detected and analyzed. These symbols are encoded with a culturally language-specific system[1] to represent a language in which they are written (Rastle, 2007). Hence, readers must have an acquired skill to identify what linguistic information can be extracted, and how this information can be integrated in the mind, based on the knowledge of how a language is represented visually.

A word is one of the most important minimal units in various reading activities (Balota, 1994; Grainger, 2018). The importance of a word can be seen through young children's development of literacy. For instance, children do not learn how to read by adopting a complete bottom-up approach, which analyzes the phonetic or phonemic value of a single letter. Instead, they utilize their pre-existing knowledge of a word, including its sound value and meanings, so that they develop skills to identify the roles of relevant letters and to form connections among phonemes, graphemes, and ultimately meanings (Ehri, 2020). Indeed, reading often requires not only the retrieval of the sounds, but also the appropriate interpretation of what the letters represent; however, non-logographic scripts do not usually encode the meanings in their visual forms. Thus, it is no wonder that readers rely on words and their lexical information in such a way that the visual cues from letters are integrated with the morphological and semantic information in the mental

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[1] A language and its characteristics do not mandate the use of a specific orthographic system. For example, the Korean language can be and has been transcribed not only in the Korean script, but also in the Latin or Cyrillic scripts. The widespread use of the Korean script was determined by the history and culture of Korean speakers.

lexicon. Hence, a study on visual word recognition offers a great opportunity to observe how a human mind can handle various aspects of a language in real time (Balota, Yap, & Cortese, 2006; Grainger, 2018).

One of the major questions in the research of visual word recognition is what automatic or unconscious processes are involved in the recognition of written words (Coltheart et al., 2001; Grainger & Ziegler, 2011). A single glance of a word is sufficient for skilled readers to extract and utilize various kinds of information that contribute to a meaningful understanding. For these readers, the activation of lexical information is close to an automatic or unconscious process; the "Stroop Effect" (Stroop, 1935) has been often cited as a notable example of this automaticity (see Parris, Hasshim, Wadsley, Augustinova, and Ferrand (2022) for the recent review).

There have been major discussions on the automatic or unconscious aspects of visual word recognition in the first language (L1), such as the effect of *letter transposition*. Letter transposition, here, refers to a condition where the positions of some (often two) letters in a word are switched while the identities of letters remain intact, which Grainger and Whitney (2004) encapsulated in the title of their study: "*Does the huamn mnid raed wrods as a wlohe*?" Although these letter-transposed strings are no longer real words (consider 'mnid'), a human mind seems to be capable of retrieving the lexical information of the relevant (or pre-transposed) words even without conscious effort. This, however, does not mean that the letter positions do not matter in such a way that only the letter identities make a significant contribution to word recognition and meaning retrieval. The sequence of letters does play a crucial role in meaning differentiation (Norris, Kinoshita, & van Casteren, 2010) as in *save* and *vase*, *trail* and *trial*, or *fried* and *fired*, yet the human mind can cope with transposed strings of letters in certain conditions, activating the corresponding mental lexical representations. This effect of letter transposition has helped many researchers to investigate in what manner letter identities and positions are related to mental lexical representations, or how “a word” is represented and processed in the mind.

The present study, therefore, focuses on letter transposition in visual word recognition, with special regard to whether and how second language (L2) learners differ from native speakers. Based on the research and observations of L1 speakers’ responses to letter-transposed stimuli, it will be investigated whether late L2 learners exhibit the same type of effects related to letter transposition as native speakers do. This comparison between late L2 learners and L1 speakers will shed additional light on how the late acquisition of a second language affects the processes or representations of newly acquired language, when the L1 is firmly established in the mind.

Chapter 2. Literature Review

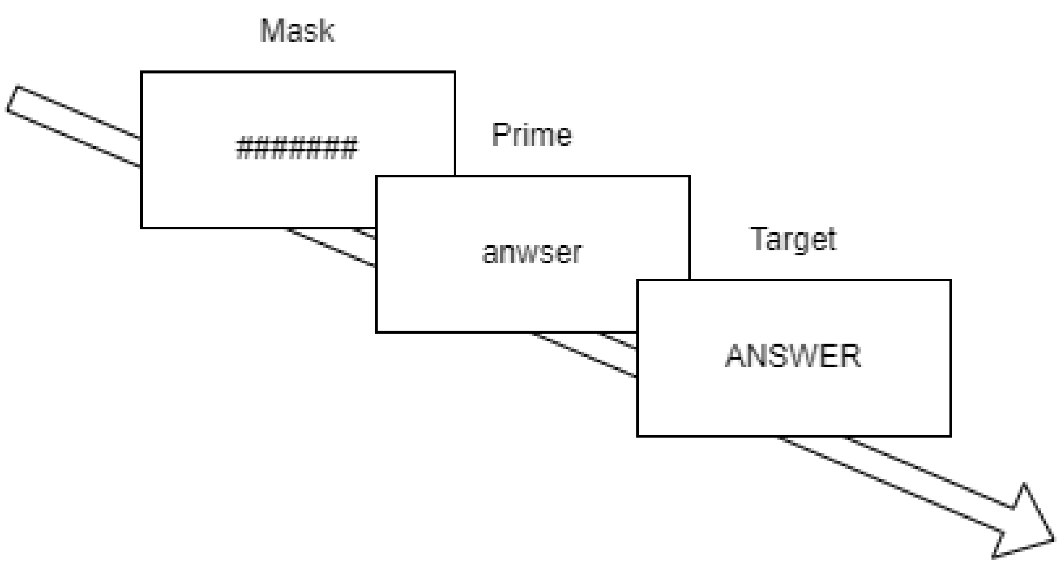
2.1. Letter Transposition in the L1 Visual Word Recognition

An examination of letter transposition as a means of studying visual word recognition began with the study reported by Forster, Davis, Schoknecht, and Carter (1987). They discovered that the recognition of a word was facilitated by a certain type of string generated by transposing letters of the word. Two additional major findings have emerged in the past 30 years. They are the *letter transposition advantage* over letter substitution, and the *letter transposition cost*. Almost all of these findings have been obtained through the masked priming paradigm.

The masked priming paradigm is specifically designed to tap into the automatic aspects of visual word recognition rather than conscious decision making processes (Forster et al., 1987). The procedures of this experimental method are illustrated in Figure 1 below.

Figure 1.

Example of the Masked Priming Paradigm (Forward Mask Only)



Note. Each square represents a computer screen, and the arrow represents a flow of time.

In this paradigm, a sequence of symbols such as hash marks (#####) is presented on the screen for a certain amount of time. This particular sequence of symbols is called a *mask*. The mask is specifically designed to appear on the position in such a way that it can obscure the following stimulus. When the mask disappears, the first stimulus, called a *prime*, is shown very briefly, usually for around 50 milliseconds (ms) in a visual type of task. The human brain can initiate the visual processing of the prime within this short span of time, but the brief presentation does not last long enough for conscious identification of the prime. Then, another stimulus, called a *target*, is presented on the screen. The participants are requested to perform a task on each target. This presentation method of two stimuli prevents the conscious perception of primes while participants process primes unconsciously (Forster & Davis, 1984; Segui & Grainger, 1990). In this manner, the masked priming paradigm enables researchers to investigate the effect of primes on targets, particularly regarding how the unconscious processing of primes influences the word recognition of targets.

There are two important findings that received researchers' attention in the masked priming studies of the letter transposition in visual word recognition. The first one is the *letter transposition advantage* over letter substitution, which refers to significantly faster reaction times in the letter-transposed prime condition compared to the letter-substituted prime condition. This advantage was first highlighted by the work by Perea and Lupker (2003). The second finding is the *letter transposition cost*, the difference of reaction times between letter transposition and identity conditions, which was first noted by Rayner, White, Johnson, and Liversedge (2006). These two findings have directed researchers' attention toward the re-evaluation of visual word recognition. In this chapter, the present study will revisit the major discoveries and their implications in the L1 studies, which have been found through a manipulation of letter transposition.

2.1.1. Discovery of Letter Transposition Priming in L1

One of the earliest groundbreaking observations on the effect of letter transposition was made by Forster et al. (1987). Their primary goal was to investigate formal factors that could have an impact on visual word recognition, as they assumed that certain types of related forms might facilitate word recognition. To address the hypothesis, an experimental method called a *lexical decision task* was adopted, in which participants were requested to judge whether a given string of letters was a real word or not. The task was conducted in English by Forster et al. (1987) since they recruited native speakers of English. For example, the participants responded with 'yes' to a target stimulus such as 'INCLUDE' (a real word in English), whereas they answered with 'no' to a target stimulus like 'LUTNICE' (a nonword in English).

In one of the experiments (Experiment 1), Forster et al. (1987) focused on the participants' reactions to letter transposition. They were particularly interested in the behavioral measurements of the reactions to misspelled words such as 'anwser' instead of 'answer.' The letter-transposed misspelled stimuli shared the same letters as the corresponding words although letter transposition caused two of the letters misaligned. Therefore, it was expected that the letter-transposed condition might produce facilitation of word recognition at a certain cost of the misalignment in letter position.

To prevent conscious decision making, Forster et al. (1987) utilized the masked priming paradigm. If their task allowed the participants to consciously observe all the stimuli, the measured reactions would only indicate the general knowledge about correct spelling, as in old-fashioned spelling tests. Thus, the obtained results might reflect conscious decision-making processes rather than visual word recognition. Forster et al. (1987) addressed this issue by well-designed priming conditions; as mentioned, primes were presented for such a short time span that they initiated unconscious processing of information without conscious identification of the stimuli. This masked priming paradigm enabled the researchers to estimate the word recognition processes that primarily involved unconscious and automatic mechanisms.

Specifically, four experimental conditions were prepared: (1) identity, (2) letter transposition, (3) letter substitution, and (4) control. The primes in the identity condition were the same word as their targets (e.g. a prime 'answer' for the target 'ANSWER'). The letter transposition condition consisted of the primes in which transposition occurred in two internal letters of the targets (e.g. anwser for ANSWER[2]). In the letter substitution condition, targets were preceded by the primes which were created by substituting a single letter of the targets (e.g. antwer for ANSWER). Lastly, the control condition used the primes that were completely different from their targets (e.g. dinner for ANSWER). All the primes were presented for 60 ms, followed by their targets. All the four conditions had the same targets in order to ensure that the observed differences resulted from the experimental conditions. Four different groups participated in the lexical decision task, and they received a list of stimuli in such a way that each of the groups was exposed to different combinations of primes and targets; that is, no participants saw the same target item twice or more. Then, the question was whether the presentation of letter-transposed primes (e.g. anwser for ANSWER) could provide facilitation of target word recognition.

The remarkable finding of Forster et al. (1987) was that they obtained significant priming effects of 62-63 ms in letter transposition, $p < 0.01$. Compared to the control condition, the lexical decision was faster by 63 ms in higher frequency words, and by 62 ms in lower frequency words when letter-transposed primes preceded the targets. These effects of facilitation were not

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[2] A prime 'anwser' for the target 'ANSWER;' from now on, an exemplar word of prime A for the corresponding target item B will be notated as (A for B).

statistically significant from those in the identity condition (61-66 ms), $p > 0.05$. The data from the nonword, on the other hand, revealed no significant effect of priming in either the identity or letter transposition conditions.

The results suggested that (1) letter-transposed primes significantly facilitated the word recognition of their corresponding targets, and (2) this facilitation must be related to the lexical processing. The primes with letter transposition, per se, were not the lexical representations as 'anwser' was not the correct form of the word 'answer.' Nevertheless, these primes provided lexical access as rapidly as the identity primes did. This phenomenon could not have resulted from formal similarity between primes and targets because nonword stimuli failed to show the same rapid access to targets (e.g. anksen for ANSKEN). Thus, it seemed reasonable to conclude that lexical representations were activated even by a sequence of letters that were not in the correct order if the letters were present in their targets (Forster et al., 1987). From this conclusion, Forster et al. (1987) postulated that successful word recognition might not require the stimuli that were exactly matched with the mental representations.

By using the masked priming paradigm, the study by Forster et al. (1987) discovered strong evidence that information about letter position might be processed leniently in visual word recognition. There were a few studies that manipulated letter transposition before, such as Chambers (1979) or O'Connor and Forster (1981). However, the results of these previous studies were difficult to interpret because they did not control for the involvement of conscious decision-making processes. In Forster et al. (1987), primes were not consciously recognized by participants in such a manner that they were unconsciously processed. Therefore, it was likely that the facilitation of letter transposition did not originate from conscious or strategic decision making. The findings of Forster et al. (1987)'s opened a possibility to investigate whether and how the automatic and unconscious activation of lexical representations is resilient to violations or misalignment of letter position.

A few follow-up studies examined letter transposition in visual word recognition. Humphreys et al. (1990) conducted a perceptual identification task in which participants were asked to identify targets. In this task, targets followed their primes, but they also disappeared. The results showed that participants were less accurate when letter-transposed primes were present than when identity primes appeared. Andrews (1996) conducted a naming task with the masked priming paradigm (the presentation duration of primes: 56 ms) in which participants verbally spoke out targets. Here, letter transposition failed to demonstrate the same type of facilitation that Forster et al. (1987) found. Letter-transposed primes resulted in statistically non-significant but slower responses than unrelated primes by 9 ms. Furthermore, Andrews (1996) found no statistically significant interaction between target types (words and nonwords) and priming conditions; thus, her results indicated that the observed patterns might not have been caused by lexical factors. However, the results of these studies may require caution in interpretation. Due to the nature of their tasks, the outcomes might have been influenced by intervening factors such as individual differences of memory capacity or motor skills. It is also worth noting that these two studies involved word production as well as word recognition.

The discussion about letter transposition was rekindled by Perea and Lupker (2003)'s study. As mentioned above, the reported results at the time were still inconclusive regarding letter transposition since Forster et al. (1987)'s study. Hence, Perea and Lupker (2003) aimed to verify the facilitation effect of letter-transposed primes. To control relevant factors, they implemented two manipulations. (1) First, they manipulated the letters of stimuli in two different positions: word-internal and word-final positions; this was designed to control the amount and position of orthographic overlap between primes and targets. This manipulation also allowed the researchers to investigate whether a specific position mattered in the effect of letter transposition. (2) Second, they included two-letter-substituted primes as the orthographic controls for letter-transposed primes; for instance, 'ufner' for USHER was created as a match with a letter-transposed prime 'uhser' for USHER in the word internal position. These control primes served as a measure for the form priming effects based on the orthographic overlap between primes and targets; 'ufner' had the same amount of orthographic overlap with 'uhser' by showing letter sequences of 'u' and 'er.' As in Forster et al. (1987), Perea and Lupker (2003) conducted a lexical decision task with the masked priming paradigm, but the presentation of masks and primes was modified. A forward mask appeared for 500 ms, and it preceded a prime that was shown for 40 ms. Then, a backward mask followed for 40 ms, and a target was finally provided for participants to judge[3].

The results of Perea and Lupker (2003) proved that the letter transposition conditions were significantly faster than their orthographic control conditions, particularly in the word internal position. In their first experiment, word-internal letter-transposed primes produced faster responses by 30 ms than letter-substituted primes, $p < .001$. In word-final position, however, the letter transposition condition marginally differed from the corresponding letter substitution condition by 13 ms, $p < .07$. Regardless of the manipulation position, letter-transposed primes showed faster responses than the unrelated word primes by 14 ms (word-internal) and 16 ms (word-final). The same facilitation of responses was not observed in the letter substitution condition: word-internally, letter-substituted primes were slower than the unrelated word primes

[3] For the sake of simplicity, the presentation of a mask(s) and a prime will be notated in the following fashion: (mask: 500 ms, SOA: 80 ms with a backward mask of 40 ms). SOA refers to the stimulus onset asynchrony in experimental psychology, which indicates a temporal gap between a prime and a target.

by 16 ms, and word-finally, letter-substituted primes were faster than the unrelated word primes only by 3 ms. Perea and Lupker (2003)'s third experiment confirmed the aforementioned results. Word-internal letter-transposed primes demonstrated a significant advantage of 44 ms over letter-substituted primes, $p < .001$. Word-final letter-transposed primes were marginally faster than letter-substituted primes by 12 ms, $p = .05$. Again, the letter transposition conditions resulted in consistently faster responses than the unrelated word conditions by 35 ms (word-internally) and 25 ms (word-finally). However, the letter substitution condition was only faster than the unrelated word condition in word-final position by 13 ms, not in word-internal position (9 ms slower). It should be noted that Perea and Lupker (2003) did not provide statistical analyses of the differences either between the letter transposition and unrelated word conditions or between the letter substitution and unrelated word conditions; these differences were not their main focus of interest. In both word-internal and word-final positions, nonword stimuli failed to present significant facilitation in letter-transposed primes.

Therefore, Perea and Lupker (2003) discovered strong evidence for significant facilitation of letter transposition in visual word recognition. The observed effects of letter transposition were marginal in word-final position, but statistically significant in word-internal position. What Perea and Lupker (2003) emphasized was that the facilitation of letter transposition remained significant even if they controlled for the orthographic overlap between primes and targets by introducing letter-substituted primes. This significant facilitation suggested that the priming effect of letter transposition was not driven primarily by formal similarity. It was also important that nonword stimuli did not exhibit any such effect related to letter transposition. Therefore, Perea and Lupker (2003) concluded that letter-transposed primes aided participants in retrieving the relevant lexical information, and that these primes with letter transposition were able to result in patterns of lexical activation similar to what the identity primes could do.

Furthermore, Perea and Lupker (2003) demonstrated the importance of letter substitution condition as the orthographic control for letter transposition condition. In their second experiment, they removed the identity and unrelated word conditions. Instead, they introduced a new condition: unrelated nonword primes (e.g. bacse for USHER). As in the other experiments, the same lexical decision task was conducted on another group of participants. In the statistical analysis, Perea and Lupker (2003) could not find any significant interaction, but they observed an interesting pattern. When the unrelated nonword primes were used as the baseline, the sizes of facilitation seemed similar in both word-internal (22 ms) and word-final (19 ms) positions. On the other hand, the advantage of letter-transposed primes over letter-substituted primes was twice as large in word-internal position (22 ms) than in word-final position (11 ms). By revising and increasing the materials, Perea and Lupker (2003) investigated this baseline issue again in their third experiment. They finally found statistically significant differences between the letter substitution and unrelated nonword conditions. With the unrelated nonword primes as the baseline, the facilitation of letter transposition was measured to be 44 ms (word-internal) and 39 ms (word-final), which replicated the pattern in their second experiment. However, letter-transposed primes enjoyed a statistically significant benefit over letter-substituted primes in word-internal position (44 ms), $p < .001$. In word-final position, the advantage of letter transposition only reached the significance level (12 ms), $p = .05$ (as explained above). Thus, one could obtain a statistically significant effect of letter transposition where others might find statistically marginal or non-significant facilitation depending on which position and what baseline they chose. As Schoonbaert and Grainger (2004) noted later, the introduction of letter substituted controls in Perea and Lupker (2003)'s provided a key instrument to appropriately identify the conditions where letter transposition had a significant effect.

Since the seminal work of Perea and Lupker (2003), researchers have agreed that letter transposed primes are indeed capable of activating lexical representations, even though they are not real words. Research interest has shifted toward the relevance of this phenomenon in visual word recognition, particularly on the condition where letter transposition can induce significant facilitation. Therefore, it is no wonder that researchers have focused on comparing the conditions of letter transposition and letter substitution; for this comparison provides more precise measurements of the effects related to letter transposition, as Perea and Lupker (2003) demonstrated.

2.1.2. Letter Transposition Advantage in L1

2.1.2.1. Letter Transposition Advantage in L1 Adults

Following Perea and Lupker (2003), recent research has directed its attention to the processing advantage of letter-transposed primes over letter-substituted primes. As briefly mentioned in the introduction, the present paper adopts the term ‘advantage,’ which is used to refer to the significant difference between the letter transposition and letter substitution conditions in Perea and Lupker (2003). When clarification is needed, this paper specifies the difference as ‘advantage of letter transposition’ or ‘letter transposition advantage.’ The reason why the term ‘priming effect of letter transposition’ is not chosen is that this term can be ambiguous in terms of which condition or baseline is compared to the letter transposition condition.

In Indo-European languages, it has been consistently reported that letter-transposed primes enjoyed a significant advantage over letter-substituted primes: in English (Colombo, Spinelli, & Lupker, 2020; Lupker, Acha, Davis, & Perea, 2012; Lupker, Perea, & Davis, 2008; Meade, Mahnich, Holcomb, & Grainger, 2021; Norris et al., 2010; Perea & Lupker, 2003; Yang & Lupker, 2020), Italian (Colombo et al., 2020), and Spanish (Perea & Acha, 2009; Perea & Carreiras, 2008; Perea, Duñabeitia, & Carreiras, 2008; Perea & Lupker, 2004). The letter transposition condition (e.g. uhser for USHER) resulted in significantly faster reaction times than the letter substitution condition (e.g. ufner for USHER).

In English, Norris et al. (2010) (Experiment 1) recruited 25 native speakers of English and conducted a lexical decision task using the masked priming paradigm (mask: 500 ms, SOA: 53 ms). When they investigated the results from 100 five-letter words, they confirmed a significant 21 ms advantage of letter transposition over letter substitution. In Lupker et al. (2012) (Experiment 2), 56 native speakers of English performed a lexical decision task with the masked priming paradigm (mask: 550 ms, SOA: 55 ms), involving 96 words with 6-9 letters. Significant advantages of 23-28 ms were found in letter transposition over letter substitution. A recent masked priming study by Colombo et al. (2020) (Experiment 3) analyzed the lexical decision responses to 96 words with 7-8 letters (mask: 500 ms, SOA: 50 ms), which were obtained from 77 native speakers of English. The results, again, confirmed a significant 20 ms advantage of letter transposition over letter substitution. Lastly, Meade et al. (2021) observed a significant advantage of letter transposition by 25-33 ms in a lexical decision task of 100 five-letter words (mask: 300 ms, SOA: 70 ms with a backward mask of 20 ms).

The letter transposition advantage has also been reported in Spanish and Italian. Perea et al. (2008) (Experiments 1 and 2) examined lexical decision responses from 44 and 36 native speakers of Spanish. They investigated the responses to 240 words (7-11 letters) by using the masked priming paradigm (mask: 500 ms, SOA: 66 ms). Compared to the letter-substituted primes, the (adjacent) letter-transposed primes showed significant 27-36 ms advantages, mirroring the patterns observed in English. Another study by Perea and Carreiras (2008) (Experiment 1) used 96 shorter Spanish words of 6-7 letters for a lexical decision task with the masked priming (mask: 500 ms, SOA: 50 ms). The results revealed a 26 ms advantage of letter transposition over letter substitution, when transposed letters constituted illegal bigrams (e.g. comsos for COSMOS). This study further investigated the lexical decision of 138 Spanish words of 6-11 letters (Experiment 2). With these stimuli of diverse lengths, the researchers observed a significant 21 ms advantage of letter transposition. Perea and Acha (2009) (Experiment 1) conducted a lexical decision task of 104 six-letter Spanish words (mask: 500 ms, SOA: 50 ms). They also confirmed a 14 ms advantage of letter transposition when they manipulated consonant letters (e.g. catrel for CARTEL). The recent study by Lupker et al. (2012) (Experiment 3 and 4) analyzed the lexical decision data from 28 and 44 native speakers of Spanish (mask: 500 ms, SOA: 50 ms), which was conducted on 128 Spanish words of various lengths (6-10 letters). This study concluded that letter transposition had significant advantages of 13-17 ms even in the stimuli of various lengths. In Italian, Colombo et al. (2020) (Experiment 2) conducted a lexical decision task with the masked priming (mask: 500 ms, SOA: 50 ms). They provided 94 Italian words (7-10 letters) for 36 native speakers of Italian. Their results showed a significant 14 ms advantage of letter transposition over letter substitution.

Studies on non-Indo-European languages also revealed a significant advantage of letter transposition over letter substitution: in Chinese (Yang, Chen, Spinelli, & Lupker, 2019), Japanese (Perea & Pérez, 2009; Yang et al., 2020), and Thai (Perea, Winskel, & Ratitamkul, 2012). The crucial point here is that (1) all of these languages are typologically different, and (2) their orthographies are neither the same nor Roman-alphabetic. Specifically, Chinese is an analytic Sino-Tibetan language with a logographic script (Hanzi) whereas Japanese is an agglutinative Japonic language with a logographic script (Kanji) and syllabaries (Hiragana and Katakana). Thai is an analytic Kra-Dai language written with an abugida script. The existence of significant advantage in these languages implies that the effect of letter transposition is not unique to either the Latin script or Indo-European languages.

In Chinese, Yang et al. (2019) conducted four experiments with 40, 44, 60, and 34 native speakers of Chinese. They measured the participants' lexical decision on 4 letter Chinese character words (mask: 500 ms, SOA: 50 ms). Since Chinese characters are not alphabetic, these researchers transposed and substituted two Chinese characters, instead. For example, two characters in the second and third positions were transposed as follows: a prime of /you3 bu4 suo3 tong2/ (ACBD type) for the target of /you3 suo3 bu4 tong2/ (ABCD type). The substitution was implemented in a similar manner; two characters in the second and third positions were substituted. For example, a prime of /you3 pu1 zou3 tong2/ (AEFD type) was generated for the target of /you3 suo3 bu4 tong2/ (ABCD type) [4]. The results revealed a significant advantage of transposition in all of their four experiments: 46 ms, 41 ms, 56 ms, and 50 ms.

In Japanese, Perea and Pérez (2009) investigated one of the Japanese syllabaries: Katakana. The letters of this syllabary are based on a syllable-like structure called a mora. For example, a single moraic character of /me/ has an orthographically different shape from /ma/ even though they share the consonant of /m/[5]; i.e. the script is not alphabetic. In a lexical decision task of 240 four-moraic words (mask: 500 ms, SOA: 50 ms) (Experiment 1), they found a significant 19 ms advantage in the letter transposition condition (e.g. /a.ri.me.ka/ for /a.me.ri.ka/) compared to the letter substitution condition (e.g. /a.ka.ho.ka/ for /a.me.ri.ka/). Another study by Yang et al. (2020)

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[4] Transposition prime: 有不所同 for 有所不同
Substitution prime: for 有扑走同 for 有所不同

[5] /me/ メ and /ma/ マ

(Experiment 5) further included 80 logographic Kanji words as well as 80 Katakana words in their lexical decision task (mask: 500 ms, SOA: 50 ms). In the results from 96 native speakers of Japanese, they found significant 25 (Kanji) and 42 (Katakana) ms advantages of letter transposition over letter substitution.

In Thai, Perea et al. (2012) recruited 33 native speakers of Thai for a lexical decision task with 180 Thai words for a lexical decision task (mask: 500 ms, SOA: 50 ms). The Thai script has three unique characteristics that differ from the Latin script. First, some vowel letters are represented as diacritics, not as stand-alone letters. Second, there are several vowel letters that precede their consonant(s) but must be read as if they follow the consonant(s); written as /eb/, but read as /be/. Lastly, spaces are usually omitted in such a way that readers have to distinguish the beginning and end of each word. Still, Perea et al. (2012) could identify a significant 10ms advantage of letter-transposed primes over letter-substituted primes. What should be noted is that they manipulated the letters in word-initial positions; nonetheless, a significant advantage was confirmed. The effect of letter transposition in this position might seem irrelevant to what other studies discovered. However, this significant effect of letter transposition was not completely unexpected given the fact that the Thai language does not use spacing to distinguish words; the letters in word-initial positions can be written as if they were the word-internal letters in Indo-European languages.

Another important discovery was that several studies confirmed a significant advantage of transposition in non-adjacent letters. In English, Lupker et al. (2008) (Experiment 1a) investigated 52 native speakers with regard to their performances in a lexical decision task of 80 words with 6-9 letters (mask: 500 ms, SOA: 47 ms). Notably, they transposed letters that were not adjacent to each other (e.g. aminal for ANIMAL). Still, the researchers obtained a significant 24 ms advantage when consonant letters were exchanged in position. Yang and Lupker (2020) conducted three experiments with 60, 72, and 44 native speakers of English. Three lexical decision tasks were used for 80 words with 6-9 letters (mask: 500 ms, SOA: 47 ms), and non-adjacent letters were manipulated (e.g. specutale for SPECULATE). Similar to Lupker et al. (2008), Yang and Lupker (2020) found significant transposition advantages of 21 ms, 19 ms, and 20 ms in all the three experiments. In Spanish, Perea and Lupker (2004) conducted three lexical decision tasks for native speakers (mask: 500 ms, SOA: 50 ms). Likewise, non-adjacent letters were transposed (e.g. caniso for CASINO) or substituted (e.g. caviro for CASINO). The researchers discovered significant 12-21 ms advantages, except for when only non-adjacent vowel letters were transposed. In one of the aforementioned studies, Perea and Carreiras (2008) (Experiment 2) addressed the non-adjacent letter transposition with 22 native speakers of Spanish, and 138 words of 6-7 letters. They also observed a significant 21 ms advantage of letter transposition. Lastly, one of the aforementioned studies, Perea et al. (2008) (Experiments 1 and 2), reported significant 14-17 ms advantages in the transposition conditions of non-adjacent letters. As Perea and Carreiras (2008) pointed out, a significant advantage of letter transposition could be found in non-adjacent positions, even across syllables.

The studies on letter transposition, therefore, have proven that a significant advantage of letter transposition exists over letter substitution in L1. As observed in Perea and Lupker (2003)'s early study, the significant letter transposition advantage may require specific conditions for it to occur significantly such as in word-internal positions. The following section addresses the important conditions and factors that were found to be critical in the letter transposition advantage.

2.1.2.2. Conditions and Factors of the Letter Transposition Advantage

The first condition of the letter transposition advantage is the position of letter manipulation;

a significant advantage is often observed in word-internal position. As Perea and Lupker (2003) noted above, the letter transposition condition could be smaller in word-final position (12 ms) compared to that in word-internal position (44 ms). Perea and Lupker (2003) suggested that letter-substituted primes could provide as much lexical activation in word-final position as letter-transposed primes. In word-final position, for instance, both 'ushno' (letter substitution) and 'ushre' (letter transposition) for USHER retained a letter sequence of 'ush' at the beginning of the strings. The interruption of irrelevant letters could be only effective at the end of strings in letter substitution condition; therefore, readers might obtain enough information required to activate lexical items even from letter-substituted primes. In word-internal position, however, the letter substitution condition included primes such as 'ufner' for USHER, which shared only the letter of 'u' with its target; a sequence of irrelevant letters 'fn' could interrupt lexical interaction significantly. Hence, the interruption of irrelevant letters occurred earlier in word-internal position than in word-final position, which ultimately led to slower responses to letter substitution. The aforementioned studies on letter transposition, in fact, examined the letter transposition advantage in word-internal position, except for Perea et al. (2012)'s in Thai.

The size of letter transposition advantage also depends on the distance between manipulated letters; the transposition of adjacent letters shows a larger advantage than that of non-adjacent letters. Perea et al. (2008) (Experiments 1 and 2) compared the sizes of letter transposition advantages between adjacent and non-adjacent positions. The observed advantages were significantly larger in the transposition of adjacent letters (27 ms and 36 ms) than in the transposition of non-adjacent letters (14 ms and 15-17 ms). As mentioned earlier, however, the transposition advantages of non-adjacent letters were still statistically significant. One interesting finding of Perea et al. (2008) (Experiment 2) was that the sizes of letter transposition advantages were statistically non-significantly different between the non-adjacent conditions of 1- and 2- letter distances—such as cholocate for CHOCOLATE (1-letter) and choaolcte for CHOCOLATE (2-letter). That is, the letter transposition advantage might not necessarily decrease in proportion to the number of the intervening letters. Thus, Perea et al. (2008) suggested that the effect of letter transposition might not arise from a certain graded activation pattern, through which the size of facilitation was proportionally determined by the distance between the positions of the transposed and transposing letters.

Another interesting finding is that the letter transposition advantage can be mediated by letter frequency. In the investigation of non-adjacent letter transposition, Lupker et al. (2008) (Experiment 2) compared two conditions related to letter frequency: transposition with highly-frequent letters and transposition with less-frequent letters. In a lexical decision task of 72 words with 6-10 letters (mask: 500 ms, SOA: 47 ms), a significant interaction was observed between the factors of transposition and letter frequency. The transposition of less frequent letters had a significant 34 ms advantage, whereas that of high-frequency letters (11 ms) failed to reach the significance level, $p = .12$. Caution, however, should be taken in generalizing the effect of letter frequency on letter transposition. Lupker et al. (2008) investigated the transposition of non-adjacent letters, which was shown to have a significantly smaller advantage than the transposition of adjacent letters, as previously discussed in Perea et al. (2008)'s study. Therefore, a lack of significant effect might have only suggested a lack of statistically adequate sample sizes. Nonetheless, if Lupker et al. (2008)'s finding held true, highly-frequent letters might be more position-sensitive in the mental lexicon (Lupker et al., 2008).

There is another orthographic property that might be involved in the letter transposition advantage: bigram legality. As mentioned earlier, Perea and Carreiras (2008) (Experiment 1) discovered a significant transposition advantage in Spanish only when the transposed letters constituted an illegal bigram. Specifically, they included two conditions of bigram frequency in their experiment: strings with legal bigrams, and strings containing an illegal bigram. No significant advantage of letter transposition was found if the primes were consisted of legal bigrams (e.g. vebral for VERBAL); in fact, there was statistically non-significant disadvantage of 6 ms. On the other hand, a significant 26 ms advantage of letter transposition arose from letter-transposed primes with an illegal bigram (e.g. vednal for VERBAL). Perea and Carreiras (2008), however, did not strongly argue that the bigram legality was the crucial factor for a significant letter transposition advantage. Bcasue all their letter-substituted primes contained an illegal bigram, they instead suggested that the bigram legality might affect the processing speed in the letter transposition conditions: 682 ms with legal bigrams, and 634 ms with an illegal bigram. That is, word-like letter-transposed primes might be less effective in the lexical activation of their targets than the letter-transposed primes with an illegal sequence of letters.

One may question whether neighborhood density can affect the letter transposition advantage significantly if word-like letter-transposed primes are less effective, thinking that these primes might inhibit the lexical activation as if they were neighbors. However, Meade et al. (2021)'s study found no evidence supporting the effect of neighborhood density on the letter transposition advantage in behavioral results. Letter-transposed primes resulted in significant facilitation in both high-density (25 ms) and low-density targets (33 ms). Only in the data from electroencephalography did the researchers find a significant interaction between neighborhood density and letter manipulation conditions; the difference of negative 250 was smaller between letter transposition and letter substitution conditions in high-density targets, but not the difference of negative 400. Meade et al. (2021) interpreted the interaction in negative 250 as the difference in the transition from prelexical to lexical processes. However, as they noted, this neurological difference did not manifest as the letter transposition advantage in reaction time.

In addition, there is one debatable phenomenon concerning the letter transposition advantage. A few studies reported that no significant advantage was found if vowel letters were transposed. Perea and Acha (2009) (Experiment 1), for instance, were unable to find a significant difference between the vowel-letter transposition (e.g. craota for CROATA) and substitution (e.g. creita for CROATA) in a Spanish lexical decision task. Perea and Lupker (2004) (Experiments 2 and 3) investigated the transposition of non-adjacent vowel letters in Spanish, but they also failed to observe any significant advantage of transposition over substitution in both shorter 6 letter words (e.g anamil and anomel for ANIMAL) and longer 7-10 letter targets (e.g. absuloto and abselito for ABSOLUTO). Lupker et al. (2008) (Experiment 1a) reached a similar conclusion in English; non-adjacent vowel-letter transposition (e.g. anamil for ANIMAL) did not facilitate the target recognition significantly more than non-adjacent vowel-letter substitution (e.g. anemol for ANIMAL).

However, it is still presumptuous to generalize the results concerning the vowel letter transposition. In the three experiments by Yang and Lupker (2020), non-adjacent vowel letters were shown to consistently generate significant advantages of 12 ms - 25 ms in the letter transposition in English (e.g. specalute for SPECULATE). Yang and Lupker (2020) pointed out that a lack of significant advantage in vowel-letter transposition might have been Spanish-specific, considering that they were unable to replicate the null effect reported by Lupker et al. (2008) in English. They also suggested that the transposition of vowel letters in Spanish might be highly destructive because Spanish has simpler syllabic patterns, and more transparent orthography than English. Thus, the suggestion of Lupker et al. (2008) might raise a question whether phonology was one of the main factors contributing to the letter transposition advantage.

However, experimental evidence has indicated that phonology is not a decisive factor for the letter transposition advantage. For example, Colombo et al. (2020) found no evidence of significant differences between the transpositions of consonant-consonant, consonant-vowel, and vowel-consonant pairs in both English and Italian. Further evidence came from Perea and Pérez (2009)'s study (Experiment 2) which utilized the unique traits of the Katakana script in Japanese. Instead of transposing letters, they switched two phonemes in such a way that the manipulation resulted in the transposition of phonemes, and the substitution of letters: e.g. /a.re.mi.ka/ for /a.me.ri.ka/[6]. The phoneme-transposed condition (e.g. /a.re.mi.ka) had the same level of phonological overlap as the letter-transposed condition (e.g. /a.ri.me.ka/). However, phoneme-transposed primes failed to show a significant advantage over substitution. In Thai, Perea et al. (2012) investigated the misaligned vowel letters that orthographically precede, but phonemically follow the onset letter (e.g. a string written as 'ebn' must be pronounced /ben/). When these misaligned letters are transposed, the letter strings with transposition were matched with the phonemic sequence of targets (e.g. a transposed string of 'ben' is the same as the pronunciation /ben/ of the word written as 'ebn'). Perea et al. (2012) compared the transposition of misaligned letters with the transposition of consonant-vowel and vowel-consonant pairs. They, however, found no significant differences among the conditions, even though the transposition of misaligned letters provided phonemically better cues than the others. Lupker et al. (2012) (Experiment 1, 2, 3, and 4) manipulated graphemes in such a way that transposed letter strings were unable to constitute a single phoneme (e.g. anhtem for ANTHEM). Still, they found no evidence of any confounding

[6] /a.re.mi.ka/ アレミカ and /a.me.ri.ka/ アメリカ

effects from their grapheme manipulation; the letter transposition advantage was consistently observed regardless of whether a grapheme was manipulated or not. Lastly but most importantly, Perea and Carreiras (2008) (Experiment 2) examined two different conditions of letter transposition: the one that changed the pronunciation of the adjacent consonant letter (e.g. racidal for RADICAL), and the other which involved no such change (e.g. cholocate for CHOCOLATE). In the results, the researchers were unable to detect statistical differences between these two conditions; Significant advantages were observed regardless of whether letter transposition might affect the phonological processing of primes.

As Colombo et al. (2020) suggested, a lack of phonology-related effects in letter transposition did not imply that phonological traits were unimportant in visual word recognition. The evidence reported above could be summarized as follows: The orthography-related processing affected the letter transposition advantage, whereas phonology might play a minor or even non-significant role in the phenomenon (Perea & Carreiras, 2006, 2008).

Here, it should be noted that the letter transposition advantage is not universal. Studies on Semitic languages have not found strong evidence for a significant advantage of letter transposition. Velan and Frost (2009) performed a lexical decision task (mask: 500 ms, SOA: 40 ms) with 80 native speakers of Hebrew. Their task was carefully manipulated in such a way that it was designed to replicate the experiments on the letter transposition advantage in Indo-European languages. One exception was the manipulation method to generate letter-transposed primes. They created two types of letter-transposed primes: a type in which transposed letters could be identified as another existing root (e.g. s.l.x 'to send' > x.s.l. 'to strengthen'), and the other type in which transposed letters constituted nonsensical or non-existing roots. The results indicated a significant inhibition of 11 ms in the former, and no significant transposition advantage in the latter. In Arabic, Boudelaa et al. (2019) analyzed the lexical decision data from 59 native speakers of Arabic (mask: 1000 ms, SOA: 50 ms), which were conducted on 60 Arabic words. They also failed to detect any significant advantage of transposition. Regarding a lack of significant advantage of letter transposition, Perea et al. (2010) suggested that the order of root-constituting letters might be highly important in Semitic languages in such a way that the letter transposition was more destructive in visual word recognition than in other languages.

2.1.2.3. Implication of the Letter Transposition Advantage in L1

Given that letter-transposed primes can provide significantly more facilitated lexical access to their targets than their orthographic controls (i.e. letter-substituted primes), it has been noted that the processing of visual word recognition is flexible in dealing with positional information (Lupker et al., 2008; Norris et al., 2010; Perea & Carreiras, 2006; Perea et al., 2008, 2012; Schoonbaert & Grainger, 2004). If we assume that identity and position of letters are processed equally, it is difficult to explain why letter-transposed primes have a significant advantage over letter-substituted primes. For instance, a letter-transposed prime 'uhser' has two disruptions of letter position (h and s). while its corresponding letter-substituted prime 'ufner' causes two disruptions of letter identity (f and n). Therefore, no significant advantage of letter transposition is expected if both types of disruptions are equally interfering. An alternative explanation is that the disruption of letter position is less interfering than that of letter identity. This explanation, however, does not imply either that the information of letter position is irrelevant in visual word recognition or that lexical representations are encoded without the information of letter position (Perea & Lupker, 2003). The alternative rather implies that transposed letters—in which the information of letter identity is intact—are capable of activating their corresponding lexical representation.

It is worth noting that the presence of significant letter transposition advantage is not primarily conditioned by phonological processing. Similar to one of the alternative explanations in Lupker et al. (2008), one might argue that letter-transposed primes have more phonological similarity to their targets than letter-substituted primes, which ultimately gives rise to a significant processing advantage. For example, a letter-transposed prime ‘uhser’ may share more phonological traits with the target ‘USHER’ than its letter-substituted prime ‘ufner;’ the parsed result of ‘hs’ in ‘uhser’ (e.g. /hs/) is phonologically closer to that of ‘sh’ in ‘USHER’ (e.g. /ʃ/) than that of ‘fn' in ‘ufner’ (e.g. /fn/). However, many studies involving phonology-related manipulation failed to provide significant differences in the letter transposition advantage (Colombo et al., 2020; Perea & Carreiras, 2008; Perea & Pérez, 2009; Perea et al., 2012; Yang & Lupker, 2020). In particular, the results of Perea and Carreiras (2008) demonstrated that no significant differences were found between two types of letter transposition, one of which alters the pronunciation, and the other of which maintains it. These results implies that phonology has a limited role in letter transposition, and it seems rather reasonable that orthographic processing is significantly involved in the letter transposition advantage (Perea & Carreiras, 2006, 2008).

The exact processing mechanisms behind the letter transposition advantage are still debatable (Yang & Lupker, 2020), but the researchers reached a general agreement that the violation of letter identity is more stringently treated than that of letter position (Lupker et al., 2008; Norris et al., 2010; Perea & Carreiras, 2006; Perea et al., 2008, 2012; Schoonbaert & Grainger, 2004). Given that primes are briefly masked and presented before their targets, it is suggested that position-flexible activation occurs at the early stage of visual word recognition (Norris et al., 2010; Perea & Lupker, 2003, 2004). For example, the letter ‘s’ in a letter-transposed prime ‘uhser’ may activate the ‘s’ in the mental representation of ‘USHER’ in such a way that the lexical activation is not a strict one-by-one and left-to-right matching between visual stimuli and their mental representations (Norris et al., 2010). Alternatively, the information of letter position may be processed or integrated leniently (Perea & Lupker, 2003; Schoonbaert & Grainger, 2004). For instance, a rapid check of letter identity occurs much earlier than the integration of positional information in such a way that the initial identity check provides a significant advantage for letter-transposed primes, which include all the letters of their targets, over letter-substituted primes, which contain two mismatching letters.

To summarize, the previous research has found that letter transposition can induce orthography-based and position-flexible activation of lexical representations. This implies that linguistic brains possess a certain flexibility in the processing of letter-positional information so that visual word recognition may prioritize the identification of letters over the integration of positional information. The present study will further examine whether this flexibility is an innate ability or a result of language development.

2.1.2.4. Letter Transposition Advantage in L1 Children

Several developmental studies discovered the advantage of letter transposition over letter substitution among children. Acha and Perea (2008) recruited Spanish-speaking children with the mean ages of 7 and 11, as well as adults. They conducted a lexical decision task (mask: 500 ms, SOA: 50 ms), which included 128 Spanish words with 6-9 letters. Their results found significant advantages of letter transposition: 53 ms in 7-year-old children and 9 ms in 11-year-old children. These advantages did not differ statistically from the letter transposition advantage of 11 ms in the adults; the global analysis showed no significant interaction between age and advantage of letter transposition.

Ziegler, Bertrand, Lété, and Grainger (2014) also confirmed significant advantages of letter transposition among a wide range of French children in terms of their biological ages: 7, 8, 9, 10, and 11. Slightly differing from Acha and Perea (2008), they used the sandwich priming method. In their lexical decision task, a fixation mark of * was shown at first (for 1000 ms), followed by a very brief presentation of a target (for 27 ms). The target was replaced by a prime (for 70 ms), and subsequently, the target appeared on the screen again. Ziegler et al. (2014) manipulated 36 French words with 5-6 letters for their task, and they found that all the age groups showed significant advantages of letter transposition, ranging between 62 ms and 101 ms. In addition, a significant interaction was observed between age and letter transposition advantage. Because the reaction time data was transformed for statistical analysis, Ziegler et al. (2014) conducted a post-hoc analysis of effect size, and they concluded that the letter transposition advantage increased with the children's age.

Comesaña, Soares, Marcet, and Perea (2016) (Experiments 2 and 3) was another study that presented the evidence for the letter transposition advantage among children. They used 120 Spanish words with 7-12 letters for their lexical decision task with the masked priming (mask: 500 ms, SOA: 50 ms). Their results (Experiment 2) suggested that children had significant advantages of letter transposition in consonant-consonant (23 ms) and vowel-vowel pairs (21 ms). In the same task with the same stimuli, adults (Experiment 1) had significant 21 ms advantage of letter transposition only in consonant-consonant pairs, but not in vowel-vowel pairs. As in Ziegler et al. (2014), Comesaña et al. (2016) conducted additional experiments with the same stimuli, but used the sandwich priming method; a target was shown before the presentation of a prime (for 33.3 ms). They still obtained a significant advantage of letter transposition: 47 ms (consonant-consonant pairs) and 40 ms (vowel-vowel pairs).

There was also empirical evidence from English-speaking children. Kezilas, McKague, Kohnen, Badcock, and Castles (2017) recruited 8-, 9-, and 11-year-old children as well as a control group of adults, all of whom spoke English. They performed a lexical decision task with 72 English words of 5 - 6 letters (mask: 500 ms, SOA: 50 ms). All the children exhibited significant 12 - 45 ms advantages of letter transposition, and no interaction was found between age and letter transposition advantage even when adults were included; the adults had a significant 9 ms advantage.

A recent study by Spinelli, Colombo, and Lupker (2022) (Experiment 1) confirmed significant advantages of letter transposition among Italian-speaking children. Their participants were 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} graders, whose ages ranged from 7 to 12, as well as adults. In the first experiment, three transposition conditions were created: consonant-consonant (e.g. puslante for PULSANTE), and consonant-vowel (e.g. pulasnte for PULSANTE), and vowel-consonant pairs (e.g. plusante for PULSANTE). Spinelli et al. (2022) conducted a lexical decision task with 96 Italian words of 6-8 letters, and they used the sandwich priming method; the fixation point of * was presented for 1000 ms, the initial presentation of a target for 27 ms, and a prime for 67 ms before the final presentation of the target. All the children and adults demonstrated significant 14 ms - 118 ms advantages of letter transposition. A significant interaction between age and letter transposition advantage was found; each group differed from another except for between 3^{rd} and $4/5^{th}$ graders. When transformed, the size of letter transposition advantage increased with age. However, the researchers failed to obtain any other significant interactions; all the groups performed in a statistically non-significantly different manner in all the transposition conditions. The results of Spinelli et al. (2022) indicated that significant advantages of letter transposition existed even among children across all the transposition conditions. It is also worth mentioning that Spinelli et al. (2022) found a signficant developmental pattern in terms of the size of letter transposition in relation to age.

In German, Hasenäcker and Schroeder (2022) conducted a longitudinal study from Grade 2 (the mean age of 7) to Grade 4 (the mean age of 9). They measured the same German children's performance three times at one-year intervals. Their task was a lexical decision task (mask: 500 ms, SOA: 50 ms) with 48 German words of 5 letters. However, the manipulation of letter substitution was different in Hasenäcker and Schroeder (2022); instead of two letters, they only substituted one letter (e.g. starm for STURM). Of note is that Hasenäcker and Schroeder (2022) focused on the identity (e.g. sturm for STURM) and irrelevant nonword (e.g. flinz for STURM) conditions. The results revealed that the children had significant advantages of 27 ms - 83 ms in letter transposition. There was a significant two-way interaction between age and conditions, but no statistically significant differences were reported in the comparison between the letter transposition and letter substitution conditions; nor the predicted response times in Hasenäcker and Schroeder (2022) indicated a significant difference between two conditions.

However, there are three developmental studies that observed no statistically significant advantage of letter transposition among children. Lété and Fayol (2013) investigated French children with the mean ages of 9 and 11, as well as adults. They measured the participants' responses to 2-letter-transposed, 1-letter-substituted primes (e.g. lable for TABLE) in a lexical decision with 27 French words of 5 letters (mask: 803 ms, SOA: 50 ms). Because the research was focused on the comparison of each priming condition and an irrelevant nonword priming condition, Lété and Fayol (2013) provided no statistical analysis on the difference between letter transposition and letter substitution. They reported the standardized *Z* scores of reaction times, and these Z-scores showed no evidence of advantage in letter transposition; for example, the mean *Z* score was -.10 in the transposition condition whereas the mean *Z* score was -.11 in the substitution condition among the 9-year-old children. However, the results of Lété and Fayol (2013) could not be strong evidence against the letter transposition advantage because (1) they used only 27 words and (2) all of these words were too short (5 letters). The findings of Lété and Fayol (2013) also lacked a statistical analysis on the letter transposition advantage.

Another study is Colombo, Sulpizio, and Peressotti (2019), which found no significant advantage of letter transposition in 7- and 8-year-old Italian children. Colombo et al. (2019) recruited adults and children with the mean ages of 7, 8, and 10 in a lexical decision task using 100 Italian words of 6 - 9 letters. They also adopted the sandwich priming method; the fixation point was presented for 1000 ms, followed by the initial presentation of a target (for 27 ms), a prime (for 70 ms), and the target. In addition, two letters were substituted for the letter substitution condition (e.g. vusdura for VERDURE) unlike in Hasenäcker and Schroeder (2022) or Lété and Fayol (2013). In the results, a statistically significant difference was found only among adults (55 ms - 65 ms) and 10-year-old children (86 ms - 111 ms), but not among 7- or 8-year-old children. Therefore, Colombo et al. (2019) concluded that it might be unclear whether younger learners or beginners had significant advantages of letter transposition; they suggested that an orthographically transparent language such as Italian might allow early learners to rely on phonological processes rather than orthography-based approaches, leading to a lack of significant letter transposition advantages among younger children.

The last study is one of the aforementioned studies that reported the letter transposition advantage among children: Spinelli et al. (2022). In the second experiment with 84 Italian words of 4 - 9 letters, the researchers replaced the transposition conditions with two vowel-based priming conditions: the one involving the transposition of a diphthong (e.g. camoin for CAMION), and the other involving the transposition of two vowels with a hiatus (e.g. dairio for DIARIO). The new transposition conditions were slightly more challenging to children than those in their initial experiment. The results showed that the 3rd graders and adults had a significant 23 - 119 ms advantage of letter transposition in both conditions, unlike the 2nd and 4/5th graders. However, the youngest 2nd graders demonstrated the smallest effect, presenting an inhibitory effect (i.e. disadvantage) of letter transposition (-58 ms) compared to letter substitution in the hiatus condition. On the other hand, the older 4/5th graders exhibited consistently facilitatory advantages of letter transposition over letter substitution (26 - 42 ms). Regarding the results, Spinelli et al. (2022) commented that younger learners might experience more difficulty in processing stimuli with a hiatus because they are still under the influence of phonological processing even in visual word recognition. Spinelli et al. (2022)'s comment resonates with Colombo et al. (2019)'s conclusion, implying that young and orthographically-underdeveloped brains might not show a significant advantage of letter transposition.

In summary, the empirical evidence from developmental studies suggests that children can have the letter transposition advantage when they are developmentally capable of orthographic processing. A lack of significant advantage in letter transposition may arise for young children (1) when their language is orthographically transparent (Colombo et al., 2019) or (2) when a task involves difficult phenomena (Spinelli et al., 2022). Still, older children enjoy a similar advantage of letter transposition as what adults do (Acha & Perea, 2008; Colombo et al., 2019; Comesaña et al., 2016; Kezilas et al., 2017). Therefore, it can be argued that children also possess the same type of flexibility in the processing of letter-positional information in such a way that letter identity is given more importance than letter position in lexical activation.

It should be noted that the previous research has found a developmental pattern in the letter transposition advantage among children. Because younger children often had significantly slower responses in a lexical decision task due to their underdeveloped linguistic skills, many researchers compared the reaction times among children and adults by using the standardized score (*Z*-score). When standardized, two aforementioned studies confirmed that the letter transposition advantage consistently increased as children aged (Hasenäcker & Schroeder, 2022; Ziegler et al., 2014). In particular, Ziegler et al. (2014) discovered a monotonic increase of the letter transposition advantage with age. Colombo et al. (2019) also reported a significantly increasing trend with age even when they failed to obtain significant advantages among 7- and 8-year-old children. The results of Spinelli et al. (2022) and Kezilas et al. (2017) showed no such simple or monotonous tendency of development, but the youngest children tended to have the smallest advantage of letter transposition condition. Comesaña et al. (2016) did not conduct a statistical analysis on the developmental tendencies, but the letter transposition advantage might have increased with age. For example, 10-years-old children showed an approximately 22 ms advantage of letter transposition, whereas adults had a 21 ms advantage. These children in Comesaña et al. (2016) responded almost twice as slowly as the adults. Therefore, it was likely that the letter transposition advantage among the children might have been smaller than that of the adults when the reaction times were standardized.

2.1.3. Letter Transposition Cost in L1

2.1.3.1. Letter Transposition Cost in the L1 Visual Word Recognition

Considering that letter transposed primes are not real words, it is reasonable to assume that letter transposition may accompany cost in visual word recognition. For example, letter-transposed primes (e.g. anwser for ANSWER) may result in slower responses to the target in comparison to identity primes (e.g. answer for ANSWER) because the latter provide better cues for the lexical items. Rayner et al. (2006) first addressed the issue of letter transposition cost in a reading task involving 80 sentences. This reading task did not include any primes; 30 native speakers of English were asked to read sentences with and without letter-transposed stimuli. In the sentences without any letter transposition, the speed of reading was 255 words per minute on average. On the other hand, participants slowed down to 227 words per minute (by 11%) in the sentences with word-internal letter transposition (e.g. The boy could not slove the problem so he aksed for help), 189 words per minutes (by 26%) in those with word-initial transposition, and 163 words per minute (by 36%) in those with word-final transposition. Based on the results, Rayner et al. (2006) suggested that the processing of letter transposition required the recovery of letter-positional information even though letter-transposed primes still activated relevant lexical information.

Later studies with the masked priming paradigm have discovered a significant cost of letter transposition in L1 adults. All of these later studies were discussed earlier, so the present study summarizes their findings on the letter transposition cost. First, Perea and Lupker (2004) (p. 18) (Experiment 1a) found a significant -17 ms cost of letter transposition in a Spanish lexical decision task, which included the non-adjacent transposition of letters. Second, Perea and Carreiras (2008) (p. 15) (Experiment 1) observed a -30 ms cost of letter transposition in a Spanish lexical decision. The letter transposition cost was statistically significant in primes without any illegal bigrams, but not in primes with an illegal bigram (2 ms). Third, Norris et al. (2010) (p. 14) (Experiment 1) reported a significant -22 ms cost of letter transposition in English. Lastly, Perea et al. (2012) (p. 23) confirmed a significant -30 ms cost of letter transposition in a non-Indo-European language, Thai.

Three more studies presented experimental results that hinted the existence of letter transposition cost although no statistical analysis was conducted. Again, the present discussion only notes the results concerning the letter transposition cost, as all the three studies were summarized earlier. In Yang and Lupker (2020)'s study (p. 18) on Chinese speakers, the cost of letter transposition was estimated to be -19 ms. Yang et al. (2020)'s research in Japanese (p. 16) also provided raw numbers of letter transposition costs, varying from -24 to -8 ms. Lastly, Perea and Acha (2009) (p. 15) (Experiment 3) conducted a same-different task with the masked priming paradigm in Spanish. The task presented participants with a probe word for 1000 ms, which had a mask below. The mask changed into a prime for 50 ms, and a target replaced the prime. Then, participants were requested to decide whether the target was the same as the probe word. Although the task itself did not include lexical decision, participants exhibited the letter transposition costs ranging between -32 ms and -27 ms. The observed costs of letter transposition in the three studies were in line with the results of the studies that examined the letter transposition statistically.

Recently, two studies focusing on L1 children discovered a developmental pattern in the letter transposition cost. In one of the aforementioned studies, Kezilas et al. (2017) (p. 28), the youngest 8-year-old children had a statistically non-significant difference between the letter transposition and identity conditions. At the mean age of 9, however, children began to exhibit significantly less facilitation in the letter transposed condition than in identity condition (-51 ms). Additionally, 11-year-old children demonstrated a significant -26 ms cost of letter transposition, which was similar to a significant -28 ms cost in adults. Kezilas et al. (2017) pointed out that the size of letter transposition cost increased with age, and they suggested that the larger cost of letter transposition in older children or adults indicated the development of and reliance on orthography-based processing.

Hasenäcker and Schroeder (2022) (p.30) also reported a developmental change of letter transposition cost in German. In their longitudinal study, children did not show any letter transposition cost at the mean age of 7; they even responded significantly faster (92 ms) in the letter transposition condition than in the identity condition. At the mean age of 8, the children showed no statistically difference performance between the letter-transposed and identity primes, similar the 8-year-old children in Kezilas et al. (2017) did. However, a significant -20 ms cost of letter transposition emerged when the children reached the mean age of 9. Overall, the letter transposition cost increased with age: from no cost to -39 ms (statistically non-significant) and -84 ms (significant). Regarding the results, Hasenäcker and Schroeder (2022) suggested that the increase of letter transposition cost indicated the development of precise lexical activation.

It should be noted, nonetheless, that the letter transposition cost may not be universal. In Italian, Spinelli et al. (2022) (Experiment 2) failed to detect any significant cost of letter transposition. Not only did children with the ages of 7 - 10 show statistically non-significant cost, but also fully-grown adults experienced no significant cost in processing letter-transposed primes. Considering that Italian is an orthographically transparent language, a lack of significant cost of letter transposition might suggest that even letter-transposed primes incurred strong lexical activations; a language such as Italian might not require precise orthography-based processing as Kezilas et al. (2017) noted. However, the results of Spinelli et al. (2022) require further investigation because their task (Experiment 2) was specifically designed to include a more challenging and phonology-related phenomenon: letter transposition of diphthongs (camoin for CAMION), and two vowels with a hiatus (dairio for DIARIO).

2.1.3.2. Implication of the Letter Transposition Cost in L1

A significant cost of letter transposition indicates that the information of letter position is still important in lexical activation (Hasenäcker & Schroeder, 2022; Kezilas et al., 2017; Perea & Carreiras, 2008; Perea et al., 2012). If our brains are insensitive to the information of letter position, there is no reason for any significant cost to occur in visual word recognition. For instance, a letter-transposed prime ‘uhser’ contains all the letters needed to activate a lexical item of ‘USHER’ even though it has two violations of letter position (h and s). It is expected that both the letter-transposed prime ‘uhser’ and the identity prime ‘usher’ are processed in the same manner by our position-insensitive brains. Alternatively, we can assume that the violation of letter-positional information demands a significant processing cost to activate a lexical representation. Combined with the findings of letter transposition advantage, it can be suggested that the information of letter position plays a minor but significant role compared to the information of letter identity.

It is worth mentioning that two recent developmental studies observed an important developmental transition in the investigation of letter transposition cost; from no significant cost of letter transposition to a significant adult-like cost (Hasenäcker & Schroeder, 2022; Kezilas et al., 2017). That is, younger and underdeveloped children activated lexical representations without precise integration of letter-positional information whereas older and more developed children were sensitive to violations of letter position. Kezilas et al. (2017) commented that this transition might be evidence for the development of finely-tuned system as the lexical tuning hypothesis (Castles et al., 2007) suggested. On the same transitional change, Hasenäcker and Schroeder (2022) also remarked that a developmental change was captured by the letter transposition cost, although they maintained a conservative viewpoint on the lexical tuning hypothesis. Still, both Kezilas et al. (2017) and Hasenäcker and Schroeder (2022) agreed that accumulation of vocabulary knowledge might contribute to a significant sensitivity to letter position through development; for example, children were introduced to a variety of lexical items, some of which might require precision in letter position since their orthographic forms were indistinguishable in terms of letter identity.

2.1.4. Summary of the Research on L1 Adults and Children

Concerning the advantage and cost of letter transposition, the following key findings were discovered in the previous studies using the masked priming paradigm.

(1) L1 adults possess flexibility to process stimuli in visual word recognition in such a way that the information of letter identity matters more than the information of letter position; i.e., letter transposition advantage. However, the same flexibility may not be observed in some languages that require a strict coding of letter order such as Semitic languages.

(2) L1 children can also have a similar or the same flexibility in visual word recognition unless their language is orthographically transparent, or they are underdeveloped for the requirements of a task. Furthermore, L1 children demonstrate a developmental pattern in such a way that the advantage of letter transposition over letter substitution increases with age.

(3) The flexibility in visual word recognition comes with a significant cost in L1 adults; i.e. letter transposition cost. In L1 children, a significant developmental transition is observed from a lack of cost to significant adult-like cost. Language development is likely to contribute to a heightened sensitivity to the information of letter position.

The studies on letter transposition, therefore, have suggested that a successful and adult-like lexical activation accompanies certain flexibility in the processing of letter identity and letter position. This flexibility does not imply insensitivity to violations of letter identity or letter position because flexible processing requires a small but significant cost. We can also observe that the flexible lexical activation develops over the course of language learning. L1 children even demonstrate a significant transition from a lack of precise yet flexible lexical activation to adult-like sensitivity to letter identity and letter position.

Here, one may raise a question concerning letter transposition advantage and cost, whether such flexibility in letter transposition was (1) primarily developed by language learning or (2) mainly resulted from cognitive maturation (Kezilas et al., 2017)? Younger children are less cognitively mature than older children, which indeed leads to the utilization of standardized reaction times in many previous developmental studies in letter transposition. Therefore, one may argue that a lack of advanced cognitive ability causes a bottleneck for younger children, resulting in less flexible and less precise processing; for instance, the task involving letter transposition may be demanding for younger children (Spinelli et al., 2022). Alternatively, language learning or vocabulary growth may be the leading factor in increasing flexibility in visual word recognition (Hasenäcker & Schroeder, 2022; Kezilas et al., 2017). This alternative explanation implies that even fully-matured brains can be less flexible in lexical activation if the size of vocabulary is limited. The findings of the previous research are yet to answer this question; we still don't know the exact mechanisms concerning the flexibility related to letter transposition (Yang & Lupker, 2020). As Kezilas et al. (2017) remark, it still remains unresolved which developmental factor drives the flexible (letter transposition advantage) yet precise (letter transposition cost) processing in visual word recognition.

2.2. Letter Transposition in the L2 Visual Word Recognition

The learning environments of late L2 learners may provide an interesting contrast to the developmental progress of letter transposition advantage and cost, as shown in the previous studies of L1 children because late L2 learners have fully matured cognitive abilities with underdeveloped vocabulary in L2. Late L2 learners here refer to those who were significantly exposed to their second (target) language after puberty (Jiang, 2018). Due to limited exposure, even highly successful late L2 learners may not possess the same size of vocabulary as what native speakers acquire (Hellman, 2011). These late L2 learners, however, possess fully developed cognitive abilities that they utilize in the visual word recognition of their L1. In other words, it is limited L2 abilities that differentiate late L2 learners from L1 adults, not the level or stage of cognitive development.

Furthermore, the acquisition of orthography occurs simultaneously with the acquisition of phonology and lexical representations in late L2 learners. In L1 acquisition, children with normal hearing acquire a spoken language first, which is used to decode the orthography of their L1 (Ehri, 2005, 2020). Therefore, the effect of phonology and phonological lexical representations foreshadows the development of visual word recognition. This is the reason that Colombo et al. (2019) and Spinelli et al. (2022) suspect phonology as the primary factor contributing to statistically non-significant effects of letter transposition in young children; that is, young children rely on phonology to activate lexical representations even in visual word recognition in such a way that orthography-driven effects of letter transposition are found to be non-significant. Late L2 learners, however, are often faced with a situation where they learn the phonology and orthography in L2 at the same time (Chen, Liu, Yu, & Dang, 2020; Jiang & Pae, 2020; Qu, Cui, & Damian, 2018; Veivo, Järvikivi, Porretta, & Hyönä, 2016). For instance, late L2 learners in South Korea are often simultaneously exposed to the orthographic form, pronunciation, and meaning(s) of a new L2 word, and these learners are usually tested by written materials; hence, the development of direct associations is encouraged between orthographic forms and meanings. In fact, the learning environment of late L2 learners, especially those who learn L2 as a foreign language, provides limited resources that may prioritize the development of L2 phonology over the acquisition of L2 orthography (Sicola & Darcy, 2015). If letter transposition advantage and cost are primarily orthography-driven phenomena, late L2 learners might perform differently in letter transposition than L1 children.

Therefore, the effects of letter transposition have received attention in the research of L2 word recognition. The models for L2 word recognition have acknowledged that their explanations should incorporate flexible but precise mechanisms of lexical activation which have been observed in L1. For example, one of the popular bilingual models, BIA+ model (Dijkstra & van Heuven, 2002), was originally designed to explain the non-selective access to bilingual lexical representations (see Lauro & Schwartz, 2017; Palma & Titone, 2020 for the issue of non-selectivity); the framework of this model provided no direct explanation on whether L2 learners could have either the letter transposition advantage or the cost. However, Yet, this model recognized the importance of the effects related to letter transposition in visual word recognition (Lam & Dijkstra, 2010)[7]. A more recent model, Multilink (Dijkstra et al., 2018) included the Levenshtein distance in its framework of word recognition, allowing the model to explain the processing of deviations in letter identity and position. This model was yet to fully explain the existence of letter transposition advantage and cost, but there was a recent attempt to apply this model to the issue of letter position processing in L2 (Comesaña, Haro, Macizo, & Ferré, 2021).

It is worth mentioning that the aforementioned differences between L1 speakers and late L2 learners as well as the frameworks of L2 models do not necessarily indicate that a significant difference must exist in the letter transposition advantage and cost in L2 acquisition. Late L2 learners can rely on visual information in visual word recognition in L2 as their fluency increases (Chikamatsu, 2006), which is not surprising given that these L2 learners already have profound

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[7] One of the studies based on this BIA+ model examined the facilitation from nonword (1-letter substitution) primes in L2 (Dijkstra, Hilberink-Schulpen, & Van Heuven, 2010). This study suggested that phonology-based lexical activations might occur between orthographically similar primes and targets. However, the effects of letter transposition were not an area of their research interest, and their suggestion could not fully explain the letter transposition advantage and cost.

experiences in the orthography of their L1; they are literate in L1. If a lack of significant effects from letter transposition in young L1 children is primarily caused by underdeveloped cognitive abilities, late L2 learners may have and utilize the processing ability of the same quality in L2 as L1 adults. Thus, these learners are expected to demonstrate significant advantage and cost of letter transposition as L1 adults do.

Currently, there is scant direct evidence regarding whether late L2 learners have a significant advantage and cost of letter transposition. As Comesaña et al. (2021) point out, it is still an important research topic whether L2 learners possess the same flexible but precise processing abilities to activate lexical representations in visual word recognition as the native speakers. Therefore, present study will summarize the findings of previous studies that investigated the issue of letter transposition in L2 learners.

2.2.1. Evidence for the Letter Transposition Advantage and Cost in L2

Velan and Frost (2007)'s was one of the early studies that investigated the letter transposition phenomenon in non-monolingual speakers. They requested 28 Hebrew-English bilinguals in Israel to read 20 Hebrew and 20 English sentences containing 7 - 13 words, and to identify any sentences that contained words with letter transposition. Their results showed that the participants had a significant cost of letter transposition in terms of accuracy in Hebrew; their responses were less accurate in sentences with letter transposition than those without any manipulation of letter position. On the other hand, no significant difference was observed between sentences with and without letter transposition in English. Therefore, Velan and Frost (2007) emphasized that their participants were highly sensitive to the information of letter position in Hebrew, whereas they seemed comparatively insensitive to the violation of letter position in English. Based on the results, Velan and Frost (2007) further suggested that even the same speaker might have different lexical representations such that the information of letter position was not precisely encoded in English as it was in Hebrew.

However, the results of Velan and Frost (2007) had several limitations in generalizing to late L2 learners. First, the participants were balanced bilinguals who had used both Hebrew and English at home. The same learning environment as these learners could not be expected from late L2 learners. Second, the researchers conducted a sentence reading task, which might have many different factors compared to a lexical decision task with the masked priming paradigm that was used in the previous studies on letter transposition. It was also uncertain whether the participants comprehended the sentences to the same degree in both languages because the researchers did not report the levels of comprehension; that is, a significant cost in English might only indicate the difficulty of comprehension in English sentences with letter transposition, not lexical representations of a different nature. Third, the participants were notified that the stimuli might have letter transposition; hence, they were likely to consciously look for letter-transposed forms. Thus, the results might have been related to conscious decision making processes rather than visual word recognition Lastly, the measurement was conducted on the accuracy, and the participants might have shown a significant cost in English if the researchers had measured their reaction times. Considering that a significant cost of letter transposition was observed when reaction times were measured in L1 English (Kezilas et al., 2017; Norris et al., 2010), the results of Velan and Frost (2007) provided inconclusive evidence against the letter transposition cost in non-monolingual speakers.

Meade, Grainger, and Holcomb (2022) reported a significant advantage of letter transposition in late L2 learners. Their participants were English learners of Spanish who started learning L2 much later than L1. All of these participants were less proficient in L2 than in L1 in terms of self-reported proficiency scales as well as their LexTALE vocabulary scores (Lemhöfer & Broersma, 2012). Meade et al. (2022) used 50 English and 50 Spanish words with 5 letters, all of which were presented with the masked priming paradigm (mask: 300 ms, SOA: 70 ms with a backward mask of 20 ms). The important experimental manipulations were letter transposition and 2-letter substitution. The results revealed significant advantages of letter transposition in both L1 (16 ms) and L2 (4 ms); no significant interaction was found between languages and experimental conditions. The only significant difference between L1 and L2 was observed in the participants' negative 400 measurements. Meade et al. (2022) suggested that their L2 learners might have a less flexible processing ability in L2 based on their analysis on neurological measurements. However, the interpretation of their conclusion required caution because the task was a language decision task, where participants judged whether the stimuli on the screen were Spanish or English; it was uncertain whether the observed neurological difference arose from the nature of the task, or different processing abilities. Furthermore, their evidence for less flexible lexical processing was a significant difference in neurological measurements, rather than in reaction times; the previous studies on letter transposition in L1 suggested a significantly small or non-significant advantage in reaction times for less flexible lexical processing in L1 children. A 4 ms advantage of letter transposition in L2 was smaller than that in L1 (16 ms), but Meade, Grainger, and Holcomb (2022) failed to find a significant difference between them.

There were a few studies that investigated the effects of letter transposition in L2 using a lexical decision task. The first one was Witzel, Qiao, and Forster (2011), which recruited 60 Japanese learners of English in Japan. Their lexical decision task (mask: 500 ms, SOA: 50 ms) contained 96 word with 5 letters, and four experimental conditions were considered: identity, unrelated word, letter transposition, and letter substitution. Because Japanese is often written vertically, the researchers presented the stimuli in two different letter orientations: horizontal presentation (possible in both L1 Japanese and L2 English), and vertical presentation (possible in L1, but uncommon or rare in L2). The results showed significant advantages of letter transposition, which interacted significantly with the letter orientations in such a way that the advantage in the horizontal presentation was significantly larger (35 ms) than that in the vertical presentation (15 ms from 595 ms - 581 ms). In an additional experiment with English native speakers, Witzel et al. (2011) confirmed a significantly large advantage (22 ms from 700 ms - 678 ms) of letter transposition even in the vertical orientation; L1 adults had flexible processing abilities even in an unfamiliar presentation format. Based on the results, the researchers suggested that the experience of vertical presentation in L1 might not directly translate to L2. Furthermore, Witzel et al. (2011) noted that the flexibility in L2 lexical activation might be limited in such a way that it primarily occurred in the familiar format of presentation. No statistical analysis was conducted on the letter transposition cost in Witzel et al. (2011), but the raw reaction times suggested that the L2 learners had 29 ms (horizontal) and 15 ms (vertical) costs of letter transposition.

Although Witzel et al. (2011) suggested that flexible lexical processing was limited in L2, two important issues were worth mentioning. First, the post-hoc analysis of Witzel et al. (2011) showed that the advantages in both orientations were still statistically significant. This implies that the L2 learners in Witzel et al. (2011) demonstrated a certain flexibility even in the unfamiliar vertical orientation. Second, the participants were highly-proficient students residing in an English-speaking country. All the Japanese learners of English in Witzel et al. (2011) were fluent speakers of English, and they were all studying abroad in the United States. Therefore, one might suspect that the language learning environments and language proficiency affected the lexical processing in such a way that the highly proficient L2 learners in Witzel et al. (2011) were able to develop the flexible lexical processing of L2 words in a certain situation to which they had been heavily exposed.

Secondly, Kida (2016) conducted a longitudinal study on 41 Japanese late L2 learners of English. The proficiency scores (TOEIC IPT) of the participants ranged between 330 and 735 with a mean of 565.48 and a standard deviation of 98.89, which corresponded to B2 to C1 (intermediate to advanced) in CEFR (TOEFL, 2023). Kida (2016) conducted a lexical decision task using the masked priming paradigm (mask: 800 ms, SOA: 50 ms) twice with an interval of 12 weeks, during which a reading class was held. The task included three experimental conditions: letter transposition (e.g. lpay for PLAY), letter substitution (e.g. rlay for PLAY), and irrelevant nonword (e.g. meit for PLAY). Unlike highly-proficient Japanese learners of English in Witzel et al. (2011), the participants in Kida (2016)'s showed no significant advantage of letter transposition in either the pretest (17 ms) or the posttest (-1 ms). The results only confirmed a significant improvement of reaction times from a mean of 1098 ms to a mean of 962 ms. Hence, Kida (2016) concluded that the language development of late L2 learners might not always accompany the native-like flexible lexical activation, although the overall word recognition might be expedited in L2. However, there was one caveat in Kida (2016)'s study; the manipulation of letter position was conducted on the first two letters of words (e.g. lpay for PLAY). A significant advantage of letter transposition was primarily observed in the word-internal positions. Therefore, a lack of significant letter transposition advantage in Kida (2016)'s learners only indicated the precise lexical activation in the word-final position in L2.

Lastly, a recent study by Chen, Liu, Yu, and Dang (2020) reported significant advantages of letter transposition in both low and high proficiency L2 learners. The researchers recruited 57 Chinese learners of English, 30 of whom had low proficiency (majoring in disciplines other than

English), and 27 of whom had high proficiency (majoring in English). All the participants were late L2 learners, who had learned English mainly in a foreign language environment. 60 words with 6 letters were used for a lexical decision task (mask: 500 ms, SOA: 50 ms), and three experimental conditions were included: identity, letter transposition, and letter substitution. Furthermore, Chen et al. (2020) factored in the role of word frequency: high-frequency and low-frequency stimuli. In the results, the researchers discovered that the letter transposition advantage significantly interacted with word frequency. In high-frequency words, both groups showed significant advantages of letter transposition: 34 ms and 23 ms in the low-proficiency and high-proficiency groups, respectively. In low-frequency words, no significant advantage of letter transposition was found; there was a mean difference of 0 ms in the high-proficiency group. The low-proficiency group even responded 39 ms faster to letter substitution than to letter transposition. Chen et al. (2020) did not analyze the letter transposition costs of their two groups, as they were not their main research interests, but the descriptive statistics suggested that the low-proficiency group had 67 ms (low-frequency words) and 14 ms (high-frequency words), whereas the high-proficiency showed 25 ms (low-frequency words) and 20 ms (high-frequency words) in terms of the letter transposition costs. Based on the analysis of letter transposition advantage, Chen et al. (2020) concluded that late L2 learners might have flexible lexical processing abilities if these learners were exposed to highly frequent vocabulary in L2. On the other hand, they suggested that late L2 learners might use precise mechanisms of letter-by-letter processing in dealing with low-frequency L2 words.

The results of Chen et al. (2020), however, had a few issues to consider. First, Chen et al. (2020) created nonwords for 'no' responses by substituting two letters of targets; participants were supposed to respond as 'no' to a letter-substituted target of 'erimal,' which was derived from a real word ‘animal.’ This use of letter substituted strings of letters might have significantly affected the results. For example, the participants’ brains might have developed an expectation that letter substitution must lead to ‘no’ (non-word) responses, which might have blocked potential lexical activations of letter-substituted primes. Secondly, the size of letter transposition advantage seemed bigger in the low-proficiency group (34 ms) than in the high-proficiency group (23 ms), as Chen et al. (2020) noted. The greater advantage of letter transposition in the low-proficiency group might contradict the findings of the developmental studies in L1, as the size of letter transposition advantage increased with language development. Lastly, there was a possibility that the results were confounded by familiarity, not word frequency. Chen et al. (2020) reported that the participants’ familiarity with the stimuli differed significantly between the high-frequency and low-frequency words; that is, the participants were exposed to less familiar and less frequent stimuli in the low-frequency condition. Hence, the participants might not have been well-acquainted with some of the targets words, resulting in a lack of established lexical representations to activate in a flexible manner. Therefore, the results of Chen et al. (2020)’s study require careful interpretation, even though late L2 learners might exhibit a significant advantage of letter transposition.

In summary, some of the previous studies have confirmed a significant advantage of letter transposition in late L2 learners: English learners of Spanish (Meade et al., 2022), Japanese learners of English who were studying abroad in an English-speaking country (Witzel et al., 2011), and Chinese learners of English (high-frequency words only) (Chen et al., 2020). The size of letter transposition advantage ranged between 4 ms to 35 ms in these studies. None of the studies on letter transposition in L2 analyzed the letter transposition cost statistically, but the descriptive statistics suggested that there were 14 ms to 67 ms costs of letter transposition. Not all the previous studies agreed that late L2 learners had flexible abilities of lexical activation in L2. Witzel et al. (2011) suggested that the flexibility of L2 lexical processing might be limited, and Kida (2016) reported that no significant development was observed in terms of letter transposition advantage in late L2 learners.

Yet, the findings in late L2 learners are preliminary and limited. Depending on the interpretation of each study, one can propose different assumptions on whether late L2 learners have flexible but precise processing abilities in L2 visual word recognition. Specifically, the existence of significant letter transposition cost is not statistically proven; the reported sizes of letter transposition cost also vary widely across the L2 studies. In the following sections, the present study will offer three different perspectives concerning the interpretations of the previous studies on letter transposition in L2.

2.2.2. Native-like Flexible Yet Precise Lexical Processing in L2

One of the aforementioned studies, Chen et al. (2020) suggested that late L2 learners might be able to process L2 words in a position-flexible manner if these words were highly frequent, and thus better represented. Although the authors remarked that the lexical activation of L2 learners might not be as flexible as that of L1 adults, the results of Witzel et al. (2011) presented a small but still significant advantage of letter transposition. Chen et al. (2020) further estimated that position-flexible lexical activation was developmentally more advanced than letter-by-letter precise lexical activation, particularly considering that low-frequency words lacked a significant advantage of letter transposition. Therefore, one may assume that late L2 learners can have and utilize flexible but precise lexical processing abilities in L2 in a similar way to what L1 speakers do, as precise lexical processing developmentally precedes the development of flexible lexical processing. This assumption predicts that the letter transposition cost is significant in L2 if statistical analysis is conducted on it.

Although the visual word recognition in L1 may not be always identical to that in L2, the orthographic processing may be similar or not fundamentally different between L1 and L2. For instance, Lemhöfer et al. (2008) investigated three different groups of late L2 learners: 20 French, 20 German, and 20 Dutch learners of English. They also included 20 native speakers of English as the control group. The researchers conducted a word identification task using the progressive demasking paradigm. Initially, a mask was presented for 378 ms, which was followed by the presentation of a word for 15 ms. Until participants responded, the screen continued to display the mask and the word, but the duration of the mask presentation decreased by 15 ms whereas that of the word increased by 15 ms. The participants were requested to press the designated button when they recognized the word. Additionally, these participants had to type in the word that they thought they saw on the screen. In order to incorporate various linguistic factors, the researchers used 1025 monosyllabic words with 3-5 letters. In the results, Lemhöfer et al. (2008) confirmed the presence of L2-unique factors such as a significant effect of word frequency and a facilitative effect of cognates. However, the researchers found no statistically significant differences between L1 adults and late L2 learners in terms of the effects of orthography-related factors: for example, the number of English orthographic neighbors, mean bigram frequency, and minimal bigram frequency. Furthermore, L1-specific factors failed to predict the responses from late L2 learners, except for the effect of cognates. Whereas Lemhöfer et al. (2008) emphasized that factors such as word frequency constrained L1 and L2 speakers differently, they also acknowledged a high level of similarity in orthographic processing between L1 and L2, and among L2 learners with different linguistic backgrounds.

Considering that the effects of letter transposition are highly orthography-related phenomena, it might be possible that late L2 learners have the flexible yet precise abilities in L2 visual word recognition.

2.2.3. Letter-by-letter Analytic Processing in L2

Witzel et al. (2011) remarked that the flexibility in L2 lexical processing might be limited in such a way that a robust flexibility could be found only in the situations where L2 was presented in a specific manner that was familiar to L2 learners. Furthermore, they suggested that the lexical activation in L2 might be overridden by letter-by-letter processing based on the similarity between primes and targets so that the familiarity of presentation could be a significant factor in L2. Similarly, Chen et al. (2020) acknowledged that late L2 learners might depend on letter-by-letter processing mechanisms particularly when these learners had received a low level of exposure to the words to read. These two studies suspected that letter-by-letter processing might be significantly involved in the L2 visual word recognition.

Letter-by-letter processing in visual word recognition has often been discussed in activation-based models such as the dual or multiple route theories of visual word recognition (Coltheart et al., 2001; Grainger et al., 2012; Grainger & Ziegler, 2011). These models propose two processing routes: a holistic or coarse-grained route and an analytic or fine-grained route. In the former route, flexible processing can occur in such a way that a certain degree of variance in letter position does not hinder the activation of lexical representations if the information of letter identity remains intact. All the letters show a simultaneous involvement in lexical activation (Grainger & Ziegler, 2011; Ventura et al., 2020). In the analytic or fine-grained route, however, visual stimuli are serially analyzed into fine-grained units so that each letter contributes to lexical activation sequentially. Because fine-grained units are correlated with phonemes, the analytic or fine-grained route is closely related to phonology and phonological lexical representations

(Grainger et al., 2012; Grainger & Ziegler, 2011). The dual or multiple route theories further assume that children with underdeveloped linguistic abilities primarily rely on the analytic or fine-grained route, showing a strong influence from phonology or a spoken language in visual word recognition; later in the language development, older children or adults can develop the holistic or coarse-grained route.

Indeed, there is evidence for a significant effect of phonology in the L2 visual word recognition, suggesting that the analytic or fine-grained route might be significantly involved in the L2 lexical processing. For example, Brysbaert, Van Dyck, and van de Poel (1999) conducted a word identification task with the masked priming paradigm (mask: 500 ms, SOA: 42 ms, and a 42 ms presentation of a target followed by a mask). In the task, Dutch learners of French were requested to type in what they thought they saw on the screen. There were three experimental conditions: cross-linguistic pseudo-homophone pairs (Dutch wie ‘who’ for French OUI ‘yes’), orthographic control pairs (Dutch jij ‘you’ for French OUI), and unrelated pairs (Dutch dag ‘day’ for French OUI). The error analysis found significantly faster responses in pseudo-homophone pairs compared to their orthographic control pairs. Because pseudo-homophone primes had no orthographic overlap with their target words, Brysbaert et al. (1999) concluded that L2 learners possessed phonology-based cross-linguistic mechanisms of lexical activation even in the L2 visual word recognition. A later study by Duyck, Diependaele, Drieghe, and Brysbaert (2004) replicated the findings of Brysbaert et al. (1999), and a similar finding was obtained by Nakayama, Sears, Hino, and Lupker (2012) in a lexical decision study with Japanese learners of English. These studies on cross-linguistic pseudo-homophones all suggested that L2 learners might not completely rely on orthography, or holistic lexical processing.

Significant length-related effects are additional evidence for the analytic or fine-grained processing in the L2 visual word recognition. Length-related effects have been considered to be one of the most important indicators of the analytic processing in L1 (Balota et al., 2007; Yap & Balota, 2014). These effects refer to an incremental relationship between word length (e.g. number of letters) and response latency. Several previous studies have observed significant length-related effects in the L2 visual word recognition. For instance, Chikamatsu (1996) found that late L2 learners of Japanese responded significantly faster to shorter words than to longer ones. The aforementioned study by Lemhöfer et al. (2008) also discovered a significant length-related effect in late L2 learners of English when word frequency, morphological family size, bigram frequency, and neighborhood density were factored in. A recent study by Jiang et al. (2020) investigated late L2 learners of Chinese, revealing that the number of strokes in words was significantly related to the reaction times, which was not observed among L1 speakers. Jiang and Feng (2022) reached the same conclusion as Jiang et al. (2020); late L2 learners of Chinese experienced a significant effect from the number of strokes (i.e. length) in the lexical decision of L2 words. The findings on length-related effects in L2 suggest that late L2 learners might process words rather serially in a letter-by-letter fashion through the analytic or fine-grained route.

In summary, the studies on the analytic processing have suggested that the L2 visual word recognition might be significantly affected by non-holistic letter-by-letter processing mechanisms. If so, one may assume that late L2 learners have a limited flexibility, which is in line with Chen et al. (2020) and Witzel et al. (2011). That is, no significant advantage is expected because both letter-transposed and letter-substituted primes have the same degree of orthographic overlap with their targets in terms of the letter-by-letter correspondence. The observed significant advantages of letter transposition in the previous studies may be due to either certain characteristics of the sampling group or processing mechanisms based on other factors (e.g. the familiarity in Witzel et al., 2011).

Still, we can expect a significant cost of letter transposition, which represents a processing delay incurred by letter-transposed primes.

2.2.4. Non-nativelike Flexible Processing due to Imprecise Letter Position Encoding

However, there is one interesting trend of letter transposition cost in Chen et al. (2020); the cost decreases with L2 proficiency, particularly in low-frequency words. This trend seems incompatible with the findings of the developmental studies in L1; the letter transposition cost increases with language development. Furthermore, Chen et al. (2020) report significant advantages of letter transposition only in high-frequency words, and the cost of letter transposition decreases with word frequency. Considering that high-frequency words are likely to have firmly established lexical representations, one may suspect that the acquisition of flexible processing accompanies a reduced cost of letter transposition in late L2 learners. Notably, Chen et al. (2020), Kida (2016), and Meade et al. (2022) all consider a possibility that even the lexical representations of highly proficient L2 learners may not be as precise as those of L1 adults, which leads to non-native-like processing. Thus, late L2 learners may not have the same developmental progress as L1 children and adults concerning the flexibility and precision of lexical activations.

If firmly established lexical items indeed show a smaller or even non-significant cost of letter transposition than poorly established lexical items, late L2 learners may have imprecise letter-positional information in their lexical representations. A lack of sensitivity to position-related information in L2 learners have been suggested by the studies on the form-based priming effects (Heyer & Clahsen, 2015; J. Li, Taft, & Xu, 2017; M. Li, Jiang, & Gor, 2017). For instance, J. Li and Taft (2020) discovered that a prime such as stranger (a, n, g, e, r: 4^{th} to 8^{th} letters) resulted in a significant facilitation for the target of ANGER (a, n, g, e, r: 1^{st} to 5^{th} letters) in Chinese learners of English. If these learners were highly sensitive to the information of letter position, no such significant facilitation would occur. A study by Jiang and Wu (2022) also found that Chinese learners of English demonstrated significant facilitation effects in word-internal (e.g. rubber for rub) and word-final (e.g. stage for age) overlapping pairs of primes and targets, indicating that positional information might be poorly processed or represented in L2 learners.

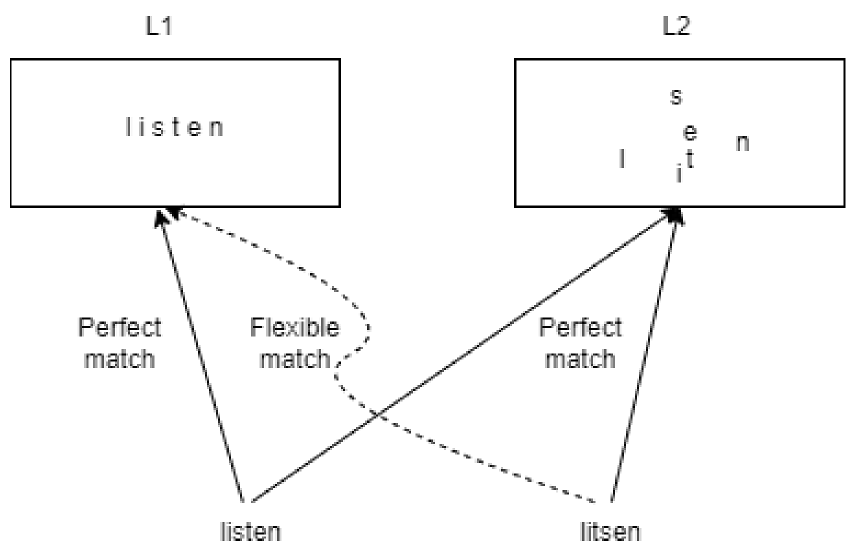
The idea that L2 lexical representations can be imprecise is not entirely new. Gor (2018) and Bordag, Gor, and Opitz (2022) hypothesized that the fuzziness in the lexical representations could cause non-nativelike characteristics in L2 learners. This hypothesis was primarily supported by evidence from L2 phonology, especially with regard to poor sound-form mapping (Cook, Pandža, Lancaster, & Gor, 2016; Cook & Gor, 2015; Gor & Cook, 2020; Gor, Cook, Bordag, Chrabaszcz, & Opitz, 2021). For instance, Ota, Hartsuiker, and Haywood (2009) conducted a visual semantic-relatedness decision task, in which participants determined whether the visually presented words were semantically related. Unlike the control group of native English speakers, Japanese L2 learners showed significantly slower reaction times and significantly higher error rates in /l/ and /r/ minimal pairs, which were likely to be poorly represented due to a lack of corresponding phonemic contrasts in Japanese. On the other hand, Arabic L2 learners responded significantly more slowly and significantly more erroneously to /p - b/ minimal pairs, which were expected to have poor lexical representations because no such phonemic distinction exists in Arabic. Ota, Hartsuiker, and Haywood (2010) reported a similar finding. They used word pairs that could be represented as homophones (e.g. fun and fan), and those which could be clearly represented in Japanese L2 learners (e.g. fun and fin). In a task where participants determined whether each visual stimulus was correctly matched with the definition, Japanese L2 learners produced significantly more errors with significantly slower reaction times in the pairs that were expected to be homophonically represented (e.g. fun: used for cooling down) compared to the clearly representable pairs. However, it should be noted that the results of Ota et al. (2009) and Ota et al. (2010) in the visual word recognition concerned the information of letter identity, not letter position.

The present study extends the notion of imprecise lexical representations in L2 by hypothesizing that letter-positional information may also be imprecise. Bordag et al. (2022) suggested that imprecise orthographic representations can exist in L2, and this imprecision may manifest as variability in letters. Furthermore, Yang, Jared, Perea, and Lupker (2021) discovered that Chinese learners of English showed a significant backward priming effect (e.g. ynam for MANY), which was absent in native speakers of English. Although Yang et al. (2021) failed to find the same backward priming effects in Spanish and Arabic learners of English, this can be attributed to Spanish learners using the same Latin script as English, and Arabic speakers possessing resilience to letter position manipulation (for Arabic, refer to Boudelaa et al., 2019; Perea et al., 2010). Considering Chen et al. (2020)'s results on letter transposition and Yang et al. (2021)'s extreme case of backward priming, a significant letter transposition advantage may accompany a lack of letter transposition cost in the L2 visual word recognition. That is, a lack of native-like sensitivity to the information of letter position in L2 may lead to imprecise lexical representations in such a way that even firmly established lexical representations are processed in a position-insensitive manner.

This hypothesis of imprecise letter position encoding is demonstrated in Figure 2 below. In native speakers (L1, on the left), a lexical representation was precisely coded with both letter identity and letter position. However, the L2 learners (on the right) have a poorly specified lexical representation of which letter identity is encoded in a primarily precise manner. Then, it is expected that both identity and letter-transposed primes activate lexical representations equally efficiently, differing only from letter-substituted primes.

Figure 2.

Hypothetical Effect of Imprecise Letter-Positional Information in Lexical Representations on the Recognition of Letter-Transposed Stimuli



2.3. Purpose of the Present Study

As reviewed above, the research on the letter transposition advantage and cost is still preliminary in the L2 visual word recognition compared to the findings in L1. Furthermore, the experimental results from late L2 learners are limited and inconclusive, making it difficult to draw a generalizable conclusion on the existence of flexible yet precise lexical processing in L2. Therefore, the aim of the present study is to investigate both the advantage and cost of letter transposition in the lexical decision performances of late L2 learners, and to further examine whether late L2 learners possess the same flexible yet precise processing abilities in their L2 as L1 adults. Specifically, the present study raises the following research question concerning late Korean L2 learners of English.

Are late Korean L2 learners of English capable of flexible yet precise lexical processing in the visual word recognition of English?

(1) Specifically, do late Korean L2 learners of English demonstrate a significant advantage of letter transposition in English? If so, is their advantage similar to native speakers of English?

(2) Additionally, do late Korean L2 learners of English experience a significant cost of letter transposition in English? If so, is the cost consistent with the findings from the previous L1 studies?

The investigation of late Korean L2 learners may provide important insights into the existence of flexible but precise lexical processing in the L2 visual word recognition. First, a confounding effect of the same or similar orthographic representations between L1 and L2 can be eliminated because the Korean language uses its own script, which shares no common orthographic traits with the Latin script. Second, another intervening effect of the previous experience in alphabetic scripts can be minimized. As the Korean script is also alphabetic, late Korean L2 learners have already acquired the knowledge concerning how alphabetic scripts can represent a word; thus, a lack of significant effect is likely to arise from the L2 visual word recognition, not from a lack of experience in alphabetic scripts. Third, the L1 transfer of orthotactic limitations is unlikely to occur. For instance, many Indo-European languages that use the Latin script share some orthotactic rules, such as the letter of "q" being followed by the vowel letter of "u," which may lead to a sensitivity to a bigram of "qu" across L1 and L2. No such transfer is expected in late Korean L2 learners. Lastly, the sensitivity to the letter-positional information is unlikely to transfer from L1 Korean to L2 English because letters are positioned not only in the left-to-right direction but also in the top-to-bottom direction in Korean. Specifically, some vowel letters must be written below the preceding consonant letter (e.g. letters for /o/ or /u/), and consonant letters in the coda position must be written below its vowel letter (e.g. /p/ in /tap/) even though the entire sequence of letters is placed in a horizontal orientation. Therefore, the results from late Korean L2 learners of English can be analyzed without significant influence from the aforementioned confounding factors, which is beneficial in determining whether the observed effects are L2-specific or not.

Table 1 below summarizes the hypotheses and expected results of the present study. In the control group of English native speakers, both significant advantages and costs of letter transposition are expected as demonstrated in the L1 studies; that is, letter-transposed primes are significantly more facilitative than letter-substituted primes, but significantly less facilitative than identity primes. If late Korean learners of English have flexible yet precise lexical processing abilities in L2, the present study presumes that the letter transposition advantage and cost are both statistically significant in English, mirroring the pattern in the control group. Alternatively, it can be assumed that late Korean L2 learners of English have no significant advantage of letter transposition, showing only a significant cost of letter transposition. This assumption implies that late Korean learners of English depend on less flexible lexical processing as suggested in the analytic or fine-grained route in the dual or multiple route models of visual word recognition. In addition, we can hypothesize that only a significant cost of letter transposition is reliably observed with no significant advantage of letter transposition. The hypothesis may suggest that the lexical representations are imprecise in terms of the letter-positional information in late Korean learners of English. Lastly, the null hypothesis can be specified that neither a significant advantage nor a cost of letter transposition exists in late L2 learners.

Table 1.

Hypotheses and Expected Results of the Present Study

Hypothesis	Letter transposition	
	Advantage	Cost
Native speakers of English		
Control	Significant	Significant
Late Korean L2 learners of English		
Native-like flexible yet precise lexical processing in L2	Significant	Significant
Letter-by-letter analytic processing in L2	Non-significant	Significant
Non-nativelike flexible processing due to imprecise letter position encoding	Significant	Non-significant
Null hypothesis	Non-significant	Non-significant

Chapter 3. Methodology

3.1. Participants

3.1.1. Native Speakers of English

A total of 60 native speakers of American English participated in the present study as the control group. They were all recruited via an online recruiting platform Prolific (prolific.com). Prospective participants were informed of the task, the requirements of participation, the estimated duration, and the compensation (USD $7). This online platform offered pre-screening data, allowing researchers to selectively display their study to those who met the requirements. While this online platform offered pre-screening data, allowing researchers to selectively display their study to those who met the requirements, pilot studies with questionnaires revealed inconsistencies. Key factors such as participants' current age and linguistic backgrounds often misaligned with the pre-screening data. To address this issue, as recommended by Prolific, the present study implemented an additional brief validation measure to ensure all participants satisfied the requirements of the present study. This validation was conducted before participants received the consent form, following the platform's procedures to save time for ineligible applicants. This validation procedure allowed the present study to collect authentic data from native speakers of English who met all the requirements. The challenges and their practical resolutions regarding online recruitment will be detailed in Appendix XII. Here, it is important to note that participation was voluntary, and participants were free to withdraw their consent.

Even with the pre-screening and validation procedures, the data from three participants were discareded due to a technical issue. A total of 57 participants used well-equipped personal computers or laptops that could display the experimental stimuli (60 Hz-compatible monitor). 3 participants faced poor conditions where the frame rates of their monitors were too low to handle with the stimuli properly. For instance, one of three participants was presented with stimuli for either 33.33 or 66.67 milliseconds (ms), which were originally supposed to be shown for 50 ms. The data from these three participants were removed[8].

The age of the remaining participants ranged from 19 to 30 with a mean of 25.74 and a standard deviation of 3.27. Gender was not matched: There were 24 men and 33 women. The age did not differ statistically significantly between two genders, p = 0.76. The descriptive statistics concerning age and gender are provided in Table 2 below. All the participants were born, and resided in the United States; they all spoke American English as their first and primary language.

Table 2.

Demographic Information of the Participants

Gender	*n*	Age			
		M	SD	Min	Max
		Native speakers of English			
Female	33	25.85	3.43	19	30
Male	24	25.58	3.11	19	30
Total	57	25.74	3.27	19	30
		Late Korean L2 learners of English			
Female	30	22.30	3.11	18	29
Male	27	24.52	3.43	18	30
Total	57	23.35	3.43	18	30

Note. n = number; M = mean; SD = standard deviation; Min = minimum; Max = maximum.

[8] Furthermore, these data did not have a high leverage; the exclusion of them resulted in statistically non-significantly different results.

3.1.2. Late Korean L2 Learners of English

The present study also recruited 60 Korean L2 learners of English as the L2 group, and the data from three participants were removed due to a frame-rate issue. All the participants were recruited at Seoul National University, the Republic of Korea, via fliers or online posts (such as on Facebook). They received the information about the task, the requirements of participation, the estimated duration, and the compensation (the amount corresponding to USD $7) in the same manner as the native speakers did, except that they were provided with the Korean translation. They all volunteered for the experiment, and they were also free to withdraw their consent. Similarly to the native speakers, the results revealed that two participants had poor devices that were incapable of presenting the experimental materials. The data from another participant indicated that one third of the stimuli were shown too briefly (less than 40 ms). The data from these three participants were excluded in the further analysis.

The remaining Korean L2 learners of English were 23.35 years old on average, with ages ranging from 18 to 30 and a standard deviation of 3.43. These late L2 learners comprised 27 men and 30 women; the former were older (mean = 24.52, standard deviation = 3.43) than the latter (mean = 22.30, standard deviation = 3.11). Considering average 1.8 years of the mandatory military service imposed on Korean men, there was no reason to assume that the male participants were exposed to English significantly more than the female participants. Korean was the first and primary language. The descriptive statistics regarding the age and gender of the Korean learners of English are included in Table 2 above.

All the Korean L2 learners of English have graduated from elementary, middle, and non-foreign-language high schools (ISCED 1, 2, and 3 according to UNESCO, 2022). The Republic of Korea has four types of high schools: general, special-purpose, specialized, and autonomous types

(National Information Center of ROK, 2010). The diplomas of these high schools are considered to hold the same level of qualification. Among them, however, there is one particular type of high schools that specializes in teaching languages: foreign language high schools. These high schools do not need to conform strictly to the teaching guidelines issued by the government of the Republic of Korea, being allowed to utilize various types of teaching and learning materials even including American textbooks. Hence, students at foreign language high schools are highly likely to be exposed to learning environments different from those of the majority of students in the Republic of Korea[9], which may ultimately lead to the vocabulary acquisition of a distinct nature[10]. Therefore, the present study screened out graduates of foreign language high schools.

The proficiency in English (L2 Proficiency) was also controlled for; the present study only recruited Korean learners of English at the advanced level (C1 to C2 in terms of the Common European Framework of Reference, or CEFR). The Korean participants were asked to submit their scores of the Test of English Proficiency by Seoul National University, or TEPS, which was one of the most accessible proficiency tests for the targeted population. As shown in Table 3 below, all of the 57 L2 learners possessed TEPS scores exceeding 390, which corresponded to 107 in TOEFL, and the Upper C1 Level of CEFR (ETS TOEFL, 2024; TEPS, 2023).

The score criterion was carefully selected so that the Korean L2 learners of English could recognize the experimental materials. Nearly half of the participants (n = 30) had a proficiency level that approximately corresponded to the Upper C1 level of the CEFR (390 to 455 in TEPS;

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[9] As in July 2024, less than 8% of the newly admitted undergraduate students were graduates of foreign language high schools (The Ministry of Education in Republic of Korea, 2024).

[10] A pilot experiment with a small sample drawn from this population discovered that graduates of foreign language high schools were highly exceptional learners. It was also found that they had been exposed to diverse curricula with various learning materials.

107 to 113 in TOEFL), whereas the remaining participants (*n* = 27) achieved higher proficiency that was close to the C2 level of the CEFR (456 to 598 in TEPS; 114 to 120 in TOEFL).

Table 3.

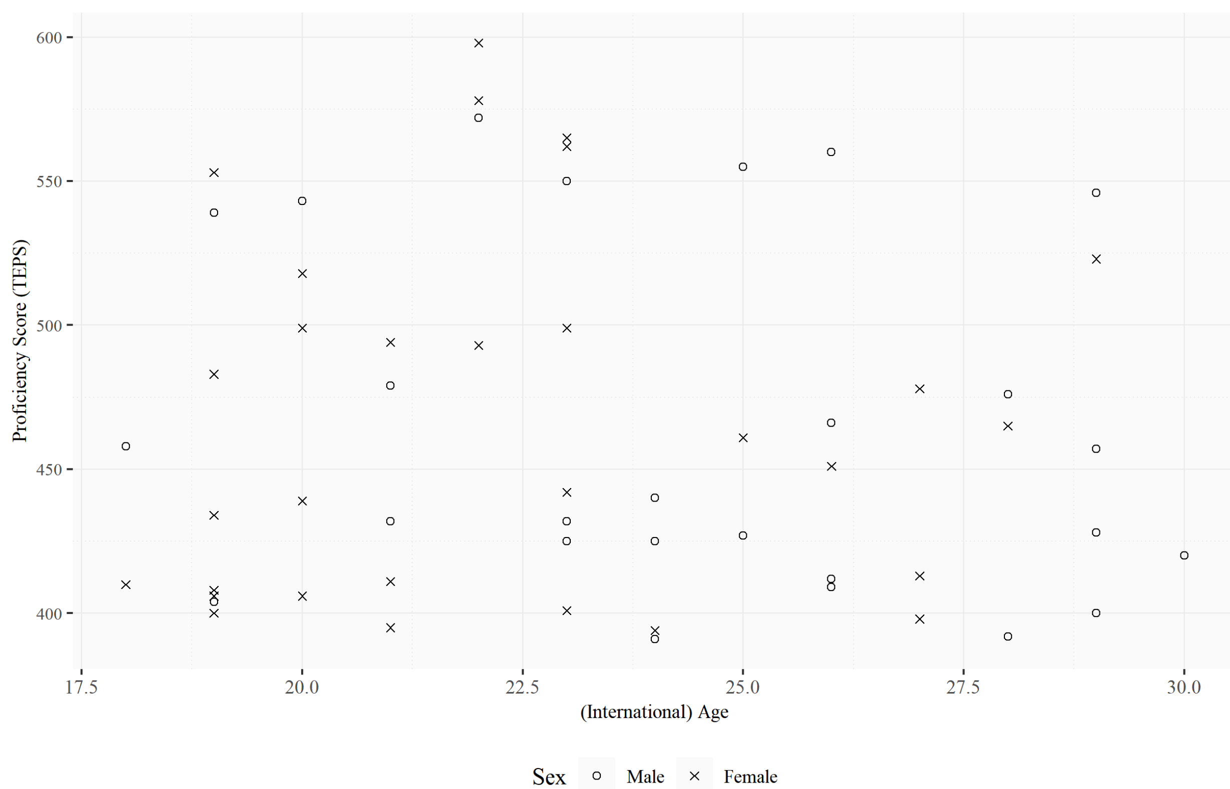
English Proficiency Scores of the Korean L2 Learners

Gender	*n*	M	SD	Min	Max
Female	30	465.90	62.19	394	598
Male	27	461.67	59.17	391	572
Total	57	463.89	60.28	391	598

Note. n = number; M = mean; SD = standard deviation; Min = minimum; Max = maximum.

Figure 3.

Biological Ages and Proficiency Scores of the Korean L2 Learners



On average, the L2 learners attained a score of 463.89 (standard deviation of 60.28). The mean score of male participants was 461.67 with a standard deviation of 59.17, while that of female participants was 465.90 with a standard deviation of 62.19. The scores did not differ statistically significantly between two genders, $p = 0.79$. No significant correlation was found between biological ages and proficiency scores, $p = 0.59$. Figure 3 below demonstrates that the L2 participants' proficiency scores were scattered across their ages without a discernible pattern.

<u>*3.2. Materials*</u>

3.2.1. Word Stimuli

The word stimuli comprised 144 English words with 5 or 6 letters. They had a mean word frequency of 127.42 per one million in the Corpus of Contemporary American English (Davies, 2008), 82.38 per one million in SUBTLEX (Brysbaert & New, 2009), and 106.13 per one million according to the Kučera and Francis (1967)'s written frequency[11]. The frequencies of the word stimuli ranged from 8.44 to 737.66 (COCA), from 10.18 to 820.86 (SUBTLEX), and from 20 to 787 (Kučera & Francis, 1967). The word frequency of the present study was relatively high, considering that the mean word frequency in the previous studies was usually under 80 per million, as shown in Figure 4 below. The choice of high frequency words was made in order to reliably capture the phenomena related to letter transposition in L2 learners, who had limited exposure to their L2.

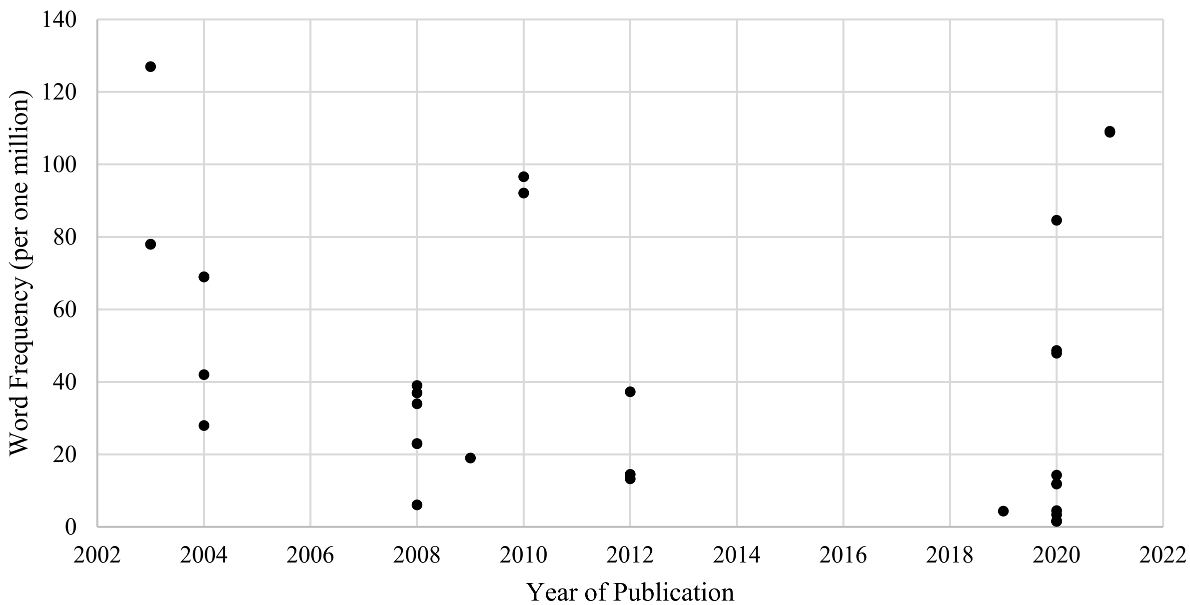
The word stimuli had 2.89 orthographic neighbors on average, ranging between 1 and 6, with a standard deviation of 1.49. The mean orthographic Levenshtein distance 20, or OLD20

[11] Many recent studies of letter transposition based the calculation of word frequency on SUBTLEX, but this database was based on spoken English. Earlier studies utilized the written word frequency data in Kučera and Francis (1967). The present study also examined the frequency values from COCA, which provided balanced coverage of written and spoken occurrences.

(Yarkoni, Balota, & Yap, 2008) was 1.81; the distance ranged from 1.55 to 2.50 with a standard deviation of 0.17. The present study selected OLD20 because it incorporated letter transposition into the neighborhood calculation, by using Damerau-Levenshtein distance (Yarkoni et al., 2008); letter transposition was considered to be a single operation, rather than two operations of substitution.

Figure 4.

Distribution of the Mean Word Frequencies of the Stimuli in the Previous L1 Studies of Letter Transposition



All the word stimuli were carefully chosen so that none of them had any extraordinary lexical characteristics in terms of word frequency, neighborhood density, or bigram measurement as shown in Table 4 below. The present study utilized the English Lexicon Project (Balota et al., 2007), and 415 out of 40,481 words were initially extracted, none of which had any values exceeding ± 3 standard deviations from the mean of each lexical property. No words were included if native speakers of English responded with high error rates (i.e. the accuracy of less than 80%) or exceptionally slow response times (more than 1,500 ms) in the lexical decision data of the

English Lexicon Project. Furthermore, this study excluded any words suffixed with *-er* or *-ed*, as these highly productive suffixes might affect the participants in such a way that the stimuli could intrigue phenomena related to a significant moderation effect from morphological decomposition.

Table 4.

Lexical Properties of Word Stimuli (Targets)

	M	SD	Min	Median	Max
Frequency (per million)					
COCA	127.42	133.96	8.44	79.92	737.66
Log(COCA)	4.42	0.92	2.13	4.38	6.60
SUB	82.38	108.06	10.18	43.22	820.86
Log(SUB)	3.89	0.97	2.32	3.77	6.71
KF	106.13	112.67	20.00	67.50	787.00
Log(KF)	4.31	0.80	3.00	4.21	6.67
Neighborhood density[a]					
Ortho. N.	2.89	1.49	1.00	3.00	6.00
OLD20	1.81	0.17	1.55	1.80	2.50
Bigram measurements[a]					
BG Sum	16,886.57	7,350.25	4,897.00	16,301.50	40,187.00
BG Mean	3,703.18	1,429.27	980.40	3,523.25	8,037.40
BG Pos.	3,064.85	1,213.67	1,042.00	2,941.00	8,216.00

Note. M = mean; SD = standard deviation; Min = minimum; Max = maximum; COCA = Davies (2008); SUB = Brysbaert and New (2009); KF = Kučera and Francis (1967); Ortho. N. = number of orthographic neighbors; OLD20 = orthographic Levenshtein distance 20; BG Sum = sums of non-positional bigram frequency; BG Mean = mean non-positional bigram frequency (averaged over the number of bigrams); BG Pos. = sums of positional bigram frequency.

[a] Based on 40,000 words in the English Lexicon Project (Balota et al., 2007).

The present study also examined (1) whether all the word stimuli were taught or exposed to the targeted population of late L2 learners, and (2) whether the targeted L2 learners were able to recognize them as words. The government of the Republic of Korea published the official handbook on the national curriculum of English, which included lists of words to be mandatorily taught to students. Among 415 items chosen from English Lexicon Project, only 342 words were found on the handbook.

After calculating the means and standard deviations of the 342 words, the present study selected 160 words, each of which had no outlying lexical properties based on the newly calculated means and standard deviations. Then, 23 undergraduate students, all sampled from the targeted population, were requested to identify any words that they did not know. Based on the judgment of these students, 144 words were further selected, all of which the majority of the students recognized (the mean accuracy rate of 98.91%).

For the experimental conditions, four types of primes were created: identity, letter-transposed, letter-substituted, and unrelated word primes. The examples of these four prime types are shown in Table 5 below. The targets were 144 words presented in uppercase (e.g. BASIC). The identity primes were the same words as the targets, but they were spelled in lowercase (e.g. basic). The letter-transposed primes were created by transposing two adjacent internal letters of identity primes (e.g. baisc). The transposed letters contained at least one consonant letter (i.e. no vowel-only transposition), considering the reported difference between vowel-only transposition and vowel-consonant or consonant-vowel transpositions (Perea & Acha, 2009; Perea & Lupker, 2004). Letter-substituted primes were a letter string containing two irrelevant letters in the places of letter manipulation in the corresponding letter-transposed primes (e.g. bauqc).

Table 5.

Examples of the Four Prime Types and Their Target (Word)

	Prime				Target
	Identity	Letter Transposition	Letter Substitution	Unrelated (Word)	
Examples	basic	baisc	bauqc	anger	BASIC
Prime Lexicality	Word	Nonword	Nonword	Word	
Target Relatedness	Yes	Yes	No	No	

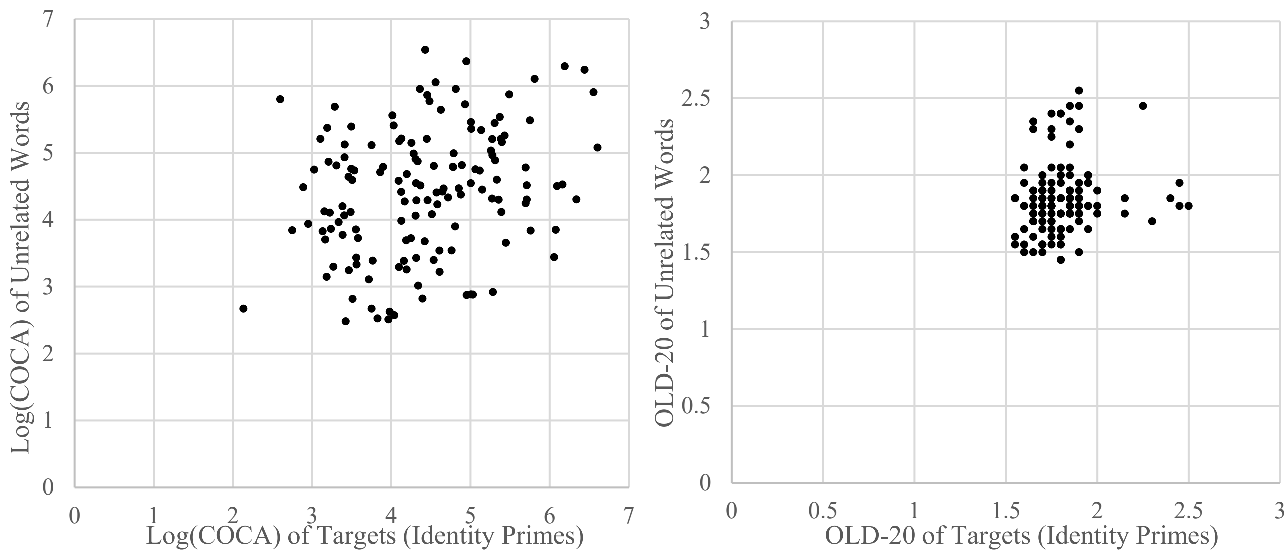
Note. Unrelated nonwords were used for the unrelated condition of the nonword targets, which will be explained in the later section.

Lastly, the present study included unrelated word primes (e.g. anger) to replicate the facilitative effect of identity priming. The inclusion of unrelated word primes enabled an equal proportion of words and nonwords in the primes; the half of the primes were words (identity and unrelated primes), while the other half were non-words (letter-transposed, and letter-substituted primes). Another set of 144 words was pooled from the aforementioned 415 words. None of 144 unrelated word primes had any extraordinary lexical properties in terms of frequency, neighborhood density, or bigram measurements. The unrelated words were paired with the targets so that the two initial letters did not overlap completely. Also, the COCA frequency, and neighborhood density measured by OLD-20 were matched within the constraints of the selected list, as shown in Figure 5 below. The unrelated words and the identity primes showed no statistically significant differences in terms of word frequency ($t(286) = -0.01$, $p > 0.90$, not assuming homogeneity of variance), and neighborhood density ($t(268) = 1.47$, $p = 0.14$, not assuming homogeneity of variance).

Figure 5.

Paired Comparison of Targets (Identity Primes) and Unrelated Words

in Terms of Word Frequency (Log(COCA)) and Neighborhood Density (OLD-20)



The letter substitution in the present study factored in the letter similarity effect (Mueller & Weidemann, 2012), ensuring that the participants were less likely to identify the substituting letters with the substituted ones. Many previous studies created letter-substituted primes by (1) using any letters other than the transposed letters, or (2) using any letters that were not present in the corresponding targets. However, these methods might not completely eliminate the possibility of misidentification; substituting letter(s) could be misidentified as the formally similar substituted letter(s). For example, a letter-substituted prime such as 'cajld,' for the target CHILD did not have any substituting letters (i.e. a, j) that were present in its target. Still, one of the substituting letters, 'j,' was visually and perceptually similar to the substituted letter (i). To control the confounding effect of letter similarity, the present study devised a systematic substitution table based on the results of Mueller and Weidemann (2012)'s experiment on the letter similarity effect. The substitution table assigned each letter to one of the visually and perceptually dissimilar letters in such a way that there was a one-to-one correspondence between the substituted and substituting letters.

The four types of stimuli — identity, letter-transposed, letter-substituted, and unrelated word primes — were counterbalanced by using a 4 × 4 Latin square design as in Table 6 below. A total of 36 unique pairs of primes and targets were prepared for each of the four priming conditions to ensure that each priming condition occurred equally often across the participants. The present study randomly assigned each participant to one of the four counterbalanced lists so that they received 36 stimuli of each type; thus, a total of 144 were presented to each participant. Each target was displayed to each participant only once per list, as well. A parallel counterbalancing procedure was applied to the nonword items, the details of which will be elaborated in the subsequent section.

Table 6.

Composition of the Four Counterbalanced Lists

	Primes				Total
	Identity Primes	Letter Transposition	Letter Substitution	Unrelated Word	
Prime Lexicality	Word	Nonword	Nonword	Word	
Target Relatedness	Yes	Yes	No	No	
Examples	basic	baisc	bauqc	anger	BASIC
List 1	36	36	36	36	144
List 2	36	36	36	36	144
List 3	36	36	36	36	144
List 4	36	36	36	36	144
Total	144	144	144	144	

3.2.2. Nonwords

Nonword stimuli were selected from English Lexicon Project (Balota et al., 2007). They were all 5- or 6-letter strings with legal bigrams, and they had 1.69 orthographic neighbors on average, ranging between 1 and 5, with a standard deviation of 0.95. The orthographic neighborhood density of the nonwords was lower than that of the word stimuli, but this lower density was a result of stimulus selection; the present study chose the nonwords with high rejection accuracies in order to reduce the false positive rate of lexical decision. It should be also noted that no previous studies of the letter transposition reported that the number of orthographic neighbors in nonwords had any significant impacts on the experimental results. Furthermore, no nonwords ended with a string of characters that could be analyzed as a legal morpheme: such as *-ant, -ate, -ble, -ed, -ee, -ent, -er, -es, -est, -ic, -ish, -ive, post-, pre-, -s*, or *-y*.

Of greater importance was whether native speakers of English were indeed able to reject the nonwords of the present study. According to the lexical decision data from English Lexicon Project (Balota et al., 2007), the nonwords of the present study had a mean accuracy of 98.12% with a standard deviation of 1.44%. No nonword stimuli showed an accuracy of less than 96.70%. Four types of primes were created for the nonwords in the same manner as those for the words: identity, letter-transposed, letter-substituted, and unrelated nonword primes. All the nonwords were also counterbalanced.

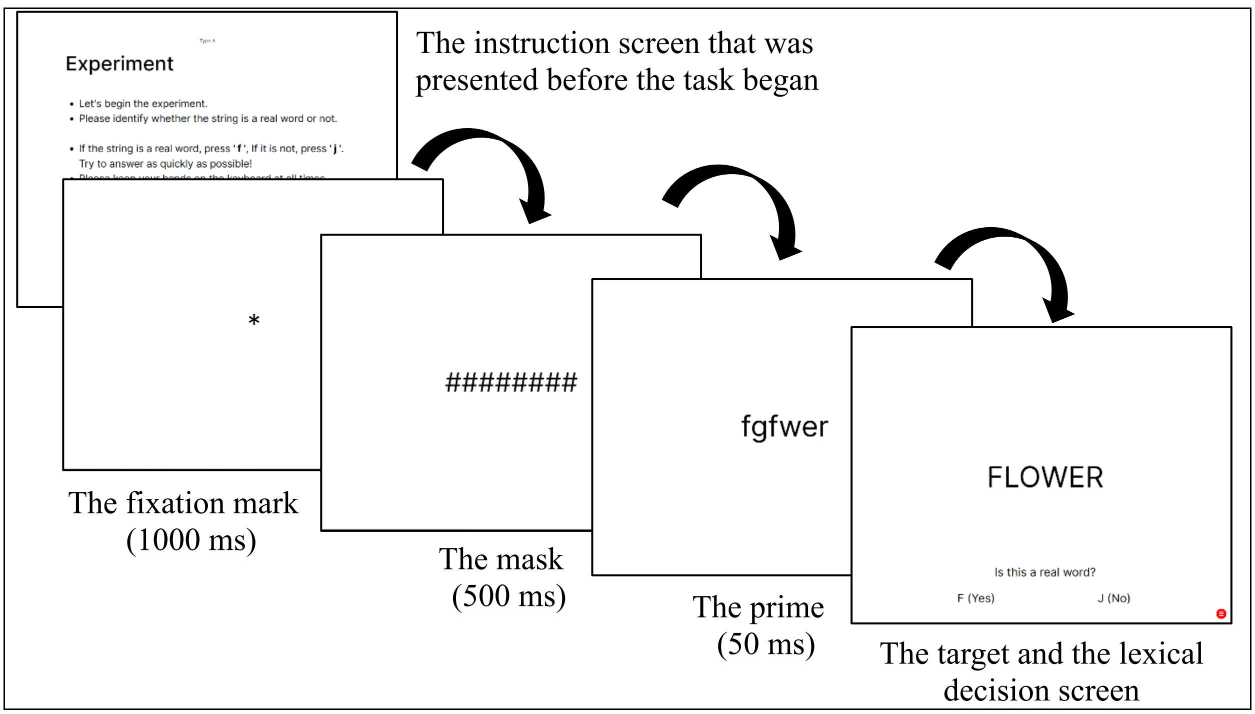
3.3. Task and Procedure

A lexical decision task with the masked priming paradigm was conducted to measure the participants' reaction times and accuracies. The procedures are presented in Figure 6 below.

Three short training sessions were provided before the actual task began. First, the participants were informed that they should decide whether a string on the screen was a real English word or not. They were also instructed on how to respond "yes" (by using the 'f' key), and "no" (by using the "j" key). Second, all the participants received a very brief practice session with only 5 word and 5 nonword stimuli. The goal of the second session was to familiarize the participants with the keys. A pilot experiment revealed that this second session greatly reduced errors, particularly those caused by pressing the wrong button. Third, a training session with 10 word and 10 nonword stimuli was conducted in such a way that the participants were encouraged to respond as quickly as possible, rather than to contemplate the stimuli on the screen. In order to minimize the fatigue, only three practice sessions were conducted, all of which took about 5 minutes on average.

Figure 6.

Procedures of Lexical Decision Task



The lexical decision task began with an instruction screen, where the participants were reminded of (1) the task that they should do (i.e. lexical decision), and (2) the keys which they should use for their responses, as well as (3) the instruction that they should press the key as quickly as possible. Each participant was randomly presented with 144 word stimuli for the “yes” responses and 144 nonword stimuli for the “no” responses. Before each target was shown, a fixation mark of a single asterisk (*) appeared on the screen for 1,000 ms. This fixation mark preceded a forward mask of hash marks (########), which remained on the screen for 500 ms. The hash marks were followed by a brief presentation of a prime (for 50 ms), which was replaced by the target[12]. Then, the participants determined whether a string of letters on the screen (i.e. the target) was a real English word as quickly as possible. For each response, the present study provided feedback by using a green check mark (✓) for correct answers, and a red X mark (X) for incorrect answers. A break screen appeared after half of the stimuli (n = 144) to reduce fatigue and maintain cognitive acuity. The participants were allowed to proceed when they were ready.

The entire experiment was conducted online by using Gorilla (gorilla.sc). They were all created, maintained, and conducted by Task Builder version 2.0 of Gorilla. The participants used their own personal computers, and no serious technical issues occurred concerning the display of experimental stimuli. Only one participant among the Korean L2 learners of English encountered a technical error at the very last question due to an abrupt malfunction of the device. The participant confirmed that this issue was not caused by the experimental program. As a result, one datapoint was lost; the remaining data were successfully transmitted to the server. The integrity of the data from this participant was carefully examined, and the transmitted data was safely compiled without any data corruption. Hence, the present study included the responses from this participant.

The participants spent 20.06 minutes on average in completing the experiment. This figure excluded the time during which the participants paused to request clarification on the consent form. In the lexical decision task, the native speakers required an average of 14.52 minutes with a

[12] That is, the SOA was 50 ms. In one of the pilot experiments, the SOA was set to 67 ms in order to provide learners of English with more exposure to primes. Many participants, however, reported that they noticed the primes, especially in the transposition condition. Therefore, the SOA was readjusted to 50 ms, and no participants reported that they could identify the primes.

standard deviation of 4.00, whereas the Korean L2 learners spent an average of 13.36 minutes with a standard deviation of 1.86. However, the difference of task duration did not indicate that the native speakers were slower in lexical decision than the Korean L2 learners, as each participant enjoyed as much break time as they needed.

3.4. Data Processing

3.4.1. Data treatment

A total of 32,832 datapoints were obtained from 57 native speakers and 57 Korean L2 learners of English. The data from 6 participants (n = 1,728) were excluded because their devices failed to display the stimuli with high precision, as described in the participants section above. A single datapoint from a Korean L2 learner was removed due to an unexpected technical issue (i.e. 32,832 - 1 = 32,831). All of the remaining 32,831 datapoints were used in the error analysis.

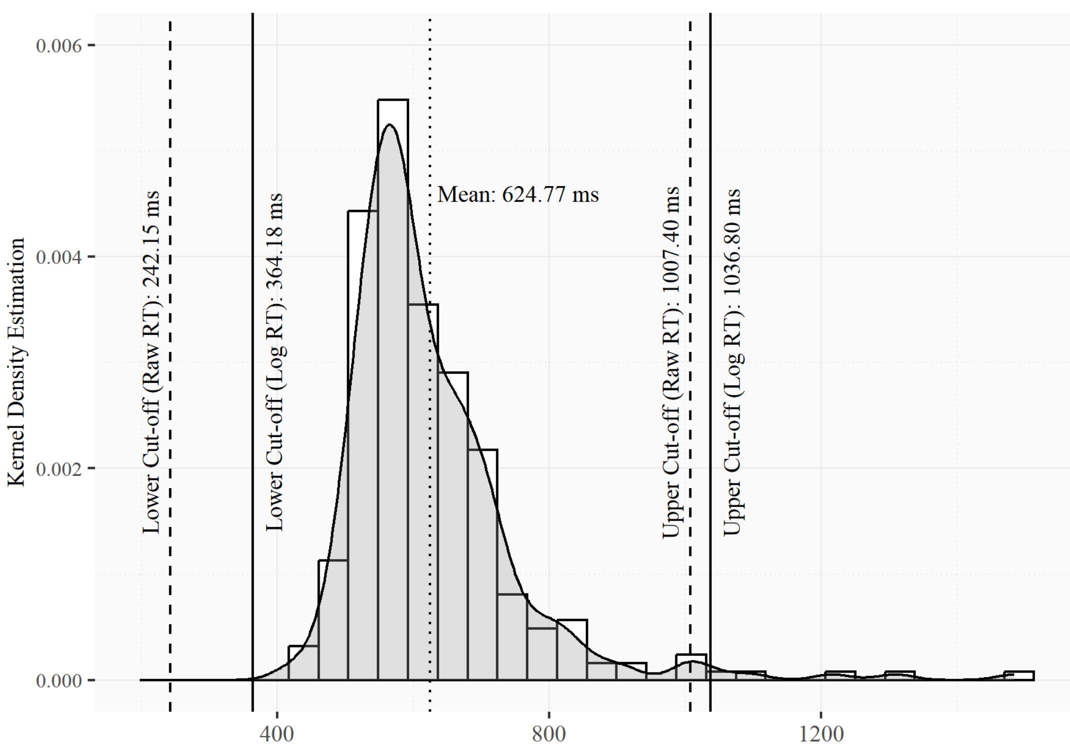
The latency analysis excluded any responses exceeding 5,000 ms or 5 seconds (70 out of 32,831, 0.21%), and inaccurate responses (844 out of 32,831, 2.57%); the responses over 5,000 ms might have involved a highly conscious judgment on the stimuli, or they might have been obtained when participants were interrupted. The inaccurate responses were also removed because neither the false alarm nor the miss was the primary focus of the investigation.

Outliers were estimated based on each participant's mean and standard deviation of their log-transformed reaction times (480 out of 32,831, 1.46%). The present study eliminated any responses of which reaction times fell outside the range of ±3 standard deviations from each participant's mean. Log-transformation was used because the measured reaction times were significantly right-skewed; the Pearson's median coefficient of skewness was 0.36 for the 32,831 datapoints.

Figure 7 below demonstrates an example of a bias in the outlier detection based on raw reaction times. This figure illustrates the distribution of the reaction times from a single participant. When the raw reaction times were used, as shown in the dotted lines, the cut-off values for this participant were 242.15 ms (mean - 3 standard deviations) and 1007.40 ms (mean + 3 standard deviations). These cut-off values penalized the right tail (i.e. longer reaction times), whereas they were lenient on the left tail (i.e. shorter reaction times). On the other hand, the log-transformation of reaction produced the cut-off values of 364.18 ms and 1036.80 ms for the same participant (shown in the solid lines), which addressed the issue of the right-skewness in a proper manner.

Figure 7.

Example of Two Types of Cut-off Values for Participant A



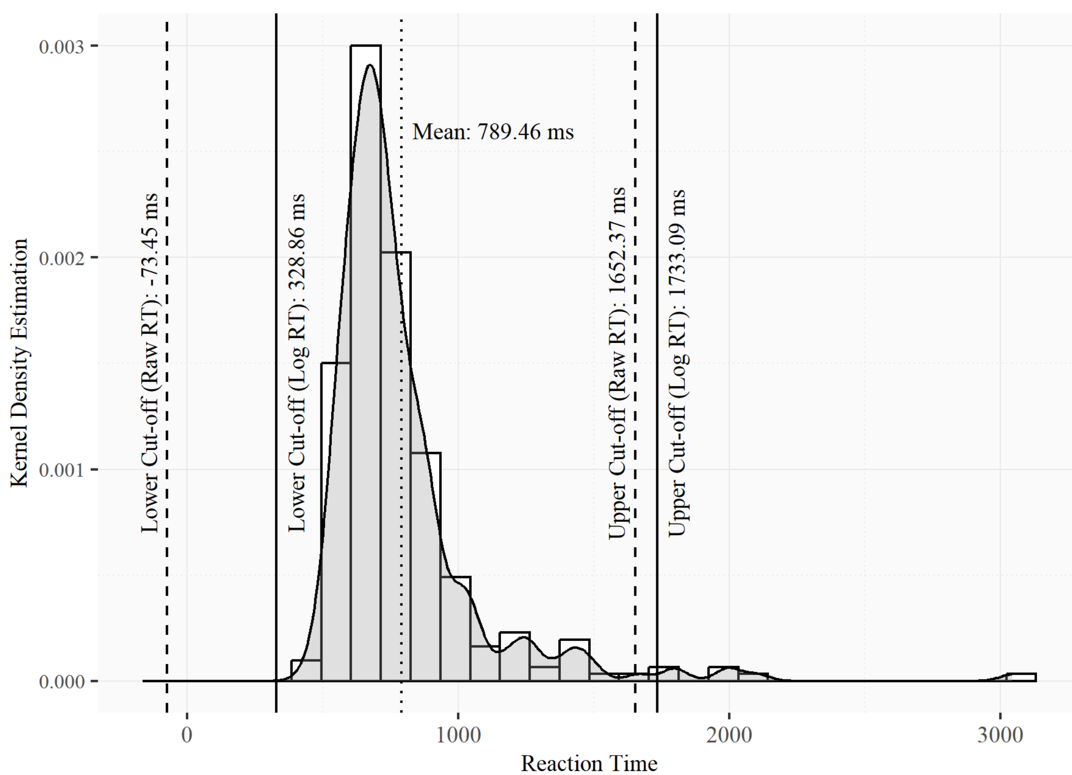
Note. Raw RT = based on raw reaction times; Log RT = based on log-transformed reaction times (the numbers were back-transformed for comparison).

Figure 8 below shows another issue of the outlier detection based on raw reaction times;

an unreasonably low cut-off value can arise when raw reaction times are used as in Figure 8. For this particular participant, the cut-off values were estimated to be -73.45 ms and 1652.37 ms when the mean and the standard deviation were calculated based on the raw reaction times. The lower cut-off value of -73.45 ms was unrealistic because none of the participants were capable of providing any answers before any stimuli appeared on the screen. As demonstrated by the solid lines, the cut-off values based on log transformation were safe from this problem, yielding 328.86 ms and 1733.09 ms for the same participant.

Figure 8.

Example of Two Types of Cut-off Values for Participant B



Note. Raw RT = based on raw reaction times; Log RT = based on log-transformed reaction times (the numbers were back-transformed for comparison).

Finally, the present study did not examine any responses shorter than 300 ms (9 out of 32,831, 0.03%) or longer than 1,500 ms (507 out of 32,831, 1.54%) in the analysis of reaction times. The first value of 300 ms was chosen to remove the extremely fast responses, which might have been generated before participants could adequately read the stimuli on the screen. This value was determined through a pilot test, where a small sample of participants were instructed to ignore the stimuli on the screen and provide random answers; the most reaction times fell between 200 ms and 300 ms. The second value of 1,500 ms might be too restrictive for the data from late L2 learners. However, this value was one of the most common cut-off values in notable studies of letter transposition (e.g. Lupker et al., 2012, 2008; Perea & Acha, 2009; Perea & Carreiras, 2008; Perea et al., 2008; Perea & Lupker, 2004; Perea & Pérez, 2009; Yang & Lupker, 2020). Therefore, the present study selected the cut-off values of 300 ms and 1,500 ms by considering the replicability of the results found in the previous L1 studies.

As a result, the latency analysis investigated only 30,921 datapoints (94.18% of 32,831). A total of 1,910 datapoints (5.82%) were removed, and the latency analysis examined 94.18% of the datapoints (n = 30,921) that the error analysis investigated (n = 32,831).

3.4.2. Statistical Methods

The reliability of the experimental items was measured by (1) the internal consistency of responses, and (2) the sensitivity to correct answers. The internal consistency was estimated by using a bootstrapping split-half method; a random subset of the experimental data was compared to the other subset in order to examine the measurement consistency or inter-item correlations of the test stimuli. Furthermore, the present study investigated the sensitivity to correct answers because the participants, especially the late L2 learners, might have a bias toward either 'yes' or 'no' in lexical decision. Statistical analyses on the sensitivity were performed by using the *d* prime and *c* index. The estimation of the internal consistency and the sensitivity was based on *R* packages of *splithalf* (Parsons, 2021) and *psycho* (Makowski, 2018).

The present study also examined the actual presentation duration of primes. Because the present study conducted an online experiment, each participant used different sets of devices in various computing environments. Therefore, it was worthwhile to investigate whether the actual presentation duration of primes might have differed from the set value of 50 ms. Statistical analysis was conducted by using bootstrapping to calculate the confidence interval of the actual presentation duration of primes.

For the latency and error analyses, generalized linear mixed-effects models (GLMMs) were constructed. Mixed-effect models were chosen in order to control for the item-unique and participant-unique variances in a statistically appropriate manner; therefore, random variables of item and participant were included in the models. For instance, each participant might have an individual difference of physically feasible minimum reaction time; that is, a person could be physically slow across all the conditions. A random variable of participant took each participant's unique variances into consideration in such a way that the statistical analyses of the results addressed the differences among the experimental conditions, independent of each participant's unique speed of response. Likewise, a random effect of item allowed the statistical analyses to estimate the item-unique variances that were not explained by the factors to be included.

The present study analyzed the responses to the word stimuli separately from those to the nonword stimuli since the responses to the words involved a decision process of a different nature than those to the nonwords. In the present study, the participants were expected to press the 'yes' key when they deemed that a real English word appeared on the screen. Therefore, each response to a word stimulus required a successful mental search for a lexical item. Conversely, the participants were instructed to press the 'no' key if they regarded the stimulus on the screen as a nonword. Thus, a nonword response resulted from mental rejection; a successful mental search was impossible since nonwords were absent in the mental lexicon. Consequently, the present study constructed separate statistical models for the words and the nonwords, as in many previous studies of letter transposition (Boudelaa et al., 2019; Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014; Lupker et al., 2012; Perea & Acha, 2009; Perea & Carreiras, 2008; Perea et al., 2012, 2008, 2010; Perea & Lupker, 2003, 2004; Perea & Pérez, 2009; Yang et al., 2019).

In the latency analysis, the GLMMs were built on the raw reaction times by implementing the Gamma distribution with the identity link function. No transformation of data was required, as the assumption of the Gamma distribution could provide a statistically reliable explanation of reaction times (Lo & Andrews, 2015). Furthermore, there were two important benefits of the GLMMs over traditional linear mixed-effects models with the transformation. (1) First, additive effects were assessed in a statistically better manner (Lo & Andrews, 2015). For example, the difference of 100 ms between 500 ms and 600 ms was statistically non-significantly different from the difference of 120 ms between 600 ms and 720 ms if these reaction times were log-transformed (a simplified example based on the explanation by Lo & Andrews, 2015). However, the increase of 20 ms in the differences might be a significant additive effect, which could be a phenomenon worth examining. (2) Second, the results of the statistical analysis were easier to interpret. In the Gamma GLMMs with the identity link, the regression coefficients were directly comparable since no transformation was conducted. For example, a regression coefficient of 20 referred to a difference of 20 ms, which could be straightforwardly compared to a regression coefficient of 100 without any back-transformations. The present study used an R package of *glmmtmb* (Brooks et al., 2017) to construct the Gamma GLMMs with the identity link for the latency analysis.

In the error analysis, the GLMMs assumed a Binomial distribution with a logit link function. A logit link is the most canonical link function for the Binomial responses: i.e. correct or incorrect

(Hardin & Hilbe, 2007). The error analysis incorporated a bias adjustment based on the second order of Taylor approximation, which factored in the standard deviation of the models (Lenth, 2024b). An R package of *lme4* (Bates, Mächler, Bolker, & Walker, 2015) was used to fit the GLMMs for the error analysis.

The global analysis of the datapoints included fixed effects of group (i.e. Native and L2) and prime type (i.e. Identity, Transposition, Substitution, and Unrelated). In the latency analysis of the word stimuli, a covariate of log-transformed word frequency was factored into the model, due to the word frequency effect (Keuleers, Lacey, Rastle, & Brysbaert, 2012; Mandera, Keuleers, & Brysbaert, 2019). In particular, the present study modeled an interaction between the covariate of frequency and the group factor because L2 learners had been known to exhibit a significantly stronger effect of word frequency than native speakers (Diependaele, Lemhöfer, & Brysbaert, 2013; Duyck, Vanderelst, Desmet, & Hartsuiker, 2008). The covariate of frequency was mean-centered in order to obtain interpretable results; statistical analysis investigated the effect when the covariate of frequency equaled to its mean, not when the effect of word frequency amounted to zero.

In order to investigate the effect of L2 proficiency, the present study further analyzed the data from Korean L2 learners of English by dividing them into two groups: higher proficiency (C2 level of CEFR), and lower proficiency (Upper C1 level of CEFR). The fixed effects for the L2-only GLMMs were proficiency group (i.e. Higher and Lower) and prime type (Identity, Transposition, Substitution, and Unrelated). Both latency and error analyses were conducted on the L2 data.

In addition, a follow-up post-hoc analysis was performed by including one more fixed effect: the sums of non-positional bigram frequency of the targets. This fixed effect will be explained in the later sections.

The GLMMs in the present study incorporated all the fixed factors and their interactions; thus, the full models were analyzed. No terms were dropped based on the *p*-values. Furthermore, stepwise regression was not applied in the models since (1) the purpose of the present study was to examine the effects of letter transposition using well-designed sets of items, rather than to identify the most important factors in random observations, and (2) stepwise regression based on *p*-values might produce misleading results with biased estimates or issues of data dredging (Brambor, Clark, & Golder, 2006; Whittingham, Stephens, Bradbury, & Freckleton, 2006). For example, a certain interaction term might fail to reach the significance level, only because the sample size was insufficient to statistically support the significance of the interaction. Therefore, the present study examined marginal effects without dropping any terms when a full model had no statistically significant interaction. An interaction term was analyzed only if it reached the significance level.

Lastly, two different types of contrast coding were applied for categorical variables: sum-to-zero coding and dummy coding. Sum-to-zero coding was one of the statistical requirements for the appropriate estimation of marginal effects. However, dummy coding was also used to obtain easily interpretable regression coefficients since dummy-coded coefficients were calculated based on the reference level. For instance, the sum-to-zero-coded regressors for the factor of prime type represented each condition's deviance from the mathematically average point of four prime types; this deviance was neither focal nor interpretable in the present study[13]. On the other hand, the

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[13] For instance, a regression coefficient for the letter-transposed prime indicates a departure from a hypothetical scenario where primes lack specific characteristics of identity, letter substitution, or unrelated word, instead possessing a blend of all prime attributes.

dummy-coded regressors for the factor of prime type demonstrated each condition's deviance from the reference level such as the identity condition. Hence, two coding schemes were utilized depending on the type of statistical analysis to be conducted.

All the statistical analyses were conducted using the statistical software *R* (R Core Team, 2024). An *R* package of *emmeans* (Lenth, 2024a) was used for the post-hoc tests and the calculation of the marginal effects. The post-hoc analyses adopted the Tukey adjustment for multiple comparison correction in pairwise comparisons.

Chapter 4. Results

4.1. Reliability

4.1.1. Internal Consistency of Responses

The indices of split-half reliability were calculated separately for each participant group because the data were collected from two heterogeneous populations. The present study conducted a permutation-based bootstrapping for 50,000 random split-half samples. In the accuracy data of native speakers, the Spearman-Brown corrected reliability estimate was 0.84 with the 95% confidence interval of 0.75 and 0.90. The Korean L2 learners of English showed a Spearman-Brown corrected reliability of 0.77 with the 95% confidence interval of 0.66 and 0.86. The data from both groups had adequate reliability scores (de Vet, Mokkink, Mosmuller, & Terwee, 2017). Therefore, it was concluded that the data were internally consistent.

4.1.2. Accuracy and Sensitivity to Correct Answers

Both the native speakers and the Korean L2 learners of English showed high accuracy as shown in Table 7. All the participants recorded accuracies above 90.00%, with the exception of a single participant (88.19%).

Table 7.

Response Accuracy

Group	M	SD	SEM	M-SEM	M+SEM
Native Speakers of English	98.14%	0.14	0.11%	98.03%	98.25%
Korean L2 Learners of English	96.69%	0.18	0.14%	96.55%	96.83%

Note. M = mean; SD = standard deviation; SEM = standard error of mean.

Additionally, the *d*-prime estimates indicated that both groups were sensitive to the correct answers. The native speakers of English had a mean *d* prime of 4.32 with a standard deviation of 0.67. The Korean L2 learners of English showed a mean *d* prime of 3.77 with a standard deviation of 0.55. Furthermore, the *c*-indices suggested that both groups provided unbiased answers. The native speakers of English had a mean *c* index of -0.03 with a standard deviation of 0.19. On the other hand, the Korean L2 learners of English demonstrated a mean *c* index of 0.01 with a standard deviation of 0.19. Appendix X and Appendix XI provides a detailed explanation of the *d*-prime and *c*-index measurements.

To summarize, both groups highly accurately identified the correct answers, demonstrating sensitive and unbiased "yes" and "no" responses.

4.2. Actual Presentation Durations of Primes

The present study examined the actual presentation durations of primes, based on the timestamps provided by Gorilla. The experimental program recorded each participant's system clock when they pressed a button to proceed to the presentation of a prime (*performance.now()* function). This program also measured the system clock when the prime was removed from the screen. The differences between two timestamps of the system clock were estimated to be the actual presentation durations of primes.

The actual presentation duration of primes was 50.85 ms on average with a standard deviation of 1.89, as shown in Table 8. Approximately 90% of the prime presentations were performed for the durations of 48.90 to 53.20 ms, while 95% were for the durations of 48.60 to 54.30 ms. There were a few exceptional datapoints in which the primes disappeared in less than 40 ms (n = 13) or the primes remained on the screen for more than 70 ms (n = 33). However, these exceptional cases were randomly distributed across the participants, providing no evidence that certain participants experienced consistently or systematically exceptional presentations of primes. Thus, random errors of measurement were likely to intrigue these few exceptional numbers. Therefore, the present study decided to include the exceptional datapoints in the analysis.

Table 8.

Actual Presentation Durations of Primes

	M	SD	SEM	M-SEM	M+SEM
Native Speakers of English	50.94	1.97	0.015	50.92	50.96
Korean L2 Learners of English	50.75	1.79	0.014	50.74	50.76
Total	50.85	1.89	0.010	50.84	50.86

Note. M = mean; SD = standard deviation; SEM = standard error of the mean.

The native speakers and Korean L2 learners of English were exposed to the primes for 50.94 ms and 50.75 ms on average, respectively. The present study concluded that the difference of 0.19 ms between the two groups was insignificant because (1) the difference was less than 1 ms, (2) there had been no reports that such a small difference in prime presentation might have a significant impact on visual word recognition, and (3) there had been no reasonable psychological or neurological findings or theories that such a difference could alter the patterns of recognition between two groups.

One remaining question was whether the mean actual presentation duration of 50.85 ms might had a significantly different effect on the results than the intended 50 ms. Considering the magnitude of difference (0.85 ms), the mean lag was likely to have occurred due to the practical limitations of online testing environments. The present study assumed that the lag had a negligible effect on the results, as there had been no theoretical or research-based evidence that a lag of less than 1 ms produced significant differences in the results.

4.3. Analyses of Experimental Results

4.3.1. Global Analysis Between the Native Speakers and L2 Learners

This section focuses on the group comparison between the native speakers of English and the Korean L2 learners of English.

4.3.1.1. Word Targets

The responses to the word targets will be analyzed first because they differ in nature (i.e. lexical retrieval) compared to the responses to the nonword targets.

4.3.1.1.1. Latency Analysis

The reaction times in the word targets were summarized in Table 9 below.

Table 9.

Reaction Times in the Word Targets

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
Native Speakers of English						
ID	634.17	1,974	180.37	4.06	630.11	638.23
TR	651.49	1,954	167.29	3.78	647.70	655.27
SB	676.67	1,938	168.88	3.84	672.83	680.50
UN	664.03	1,953	168.15	3.80	660.22	667.83
Total	656.49	7,819	171.97	1.94	654.55	658.43
Korean L2 Learners of English						
ID	634.32	1,956	166.21	3.76	630.56	638.08
TR	656.75	1,936	170.50	3.88	652.87	660.62
SB	685.66	1,942	171.01	3.88	681.78	689.54
UN	692.79	1,907	177.45	4.06	688.72	696.85
Total	667.21	7,741	172.86	1.96	665.25	669.17

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

The reaction times were regressed on the fixed effects of group and prime type. The covariate of log-transformed frequency was included in such a way that this covariate had different intercepts depending on the group factor. Two random effects were included: item and participant. The GLMM was created as follows: glmmTMB (Reaction_Time ~ 1 + Group * Prime_Type + Group * MeanCentered_LogFrequency + (1 | Item) + (1 | Participant), family = Gamma (link = "identity")).

A summary of the regression results, presented as a Type III analysis-of-variance table, is shown in Table 10 below. The regression discovered a significant main effect of prime type, $\chi^2(3) = 372.89$, $p < 0.001$. The main effect of Group was not statistically significant, $p > 0.50$. The covariate of log-transformed frequency was statistically significant, $\chi^2(1) = 17.97$, $p < 0.001$. This covariate interacted significantly with the group factor, $\chi^2(1) = 5.86$, $p < 0.05$.

Table 10.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Reaction Times in the Word Targets

	χ^2	df	p	
(Intercept)	6,194.11	1.00	<.001	***
Group	0.37	1.00	0.541	
Prime Type	372.89	3.00	<.001	***
Mean-centered Log(Frequency)	17.97	1.00	<.001	***
Group : Log(Frequency)	5.86	1.00	0.015	*
Group : Prime Type	22.92	3.00	<.001	***

The regression coefficients, shown in Table 11 below, revealed the differences in the covariates between the two groups. By an increase of a single unit of log-transformed frequency, the native speakers of English showed a significant decrease of 9.15 ms, $z = -3.06$, $p < 0.01$. The

Korean L2 learners of English exhibited a decrease of 14.46 ms, which was significantly larger by 5.31 ms than the native speakers, $z = -2.42$, $p < 0.05$. Hence, the influence of word frequency was significantly stronger for the L2 learners compared to the native speakers.

Table 11.

Coefficients of the Regression (Dummy-coded Contrast) on Reaction Times in the Word Targets

	b	SE(b)	*z*	*p*	
(Intercept)	635.41	11.92	53.30	<.001	***
Mean-centered Log(Frequency)	-9.15	2.99	-3.06	0.002	**
Prime Type (TR)	19.39	3.88	4.99	<.001	***
Prime Type (SB)	43.80	3.97	11.03	<.001	***
Prime Type (UN)	32.75	3.93	8.34	<.001	***
Group (L2)	0.58	16.53	0.03	0.972	
Group (L2) : Mean-centered Log(Frequency)	-5.31	2.19	-2.42	0.015	*
Group (L2) : Prime Type (TR) [a]	4.41	5.53	0.80	0.425	
Group (L2) : Prime Type (SB) [a]	5.57	5.65	0.99	0.324	
Group (L2) : Prime Type (UN) [a]	25.38	5.65	4.49	<.001	***

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

[a] The interaction terms were referenced to the base level of ID due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

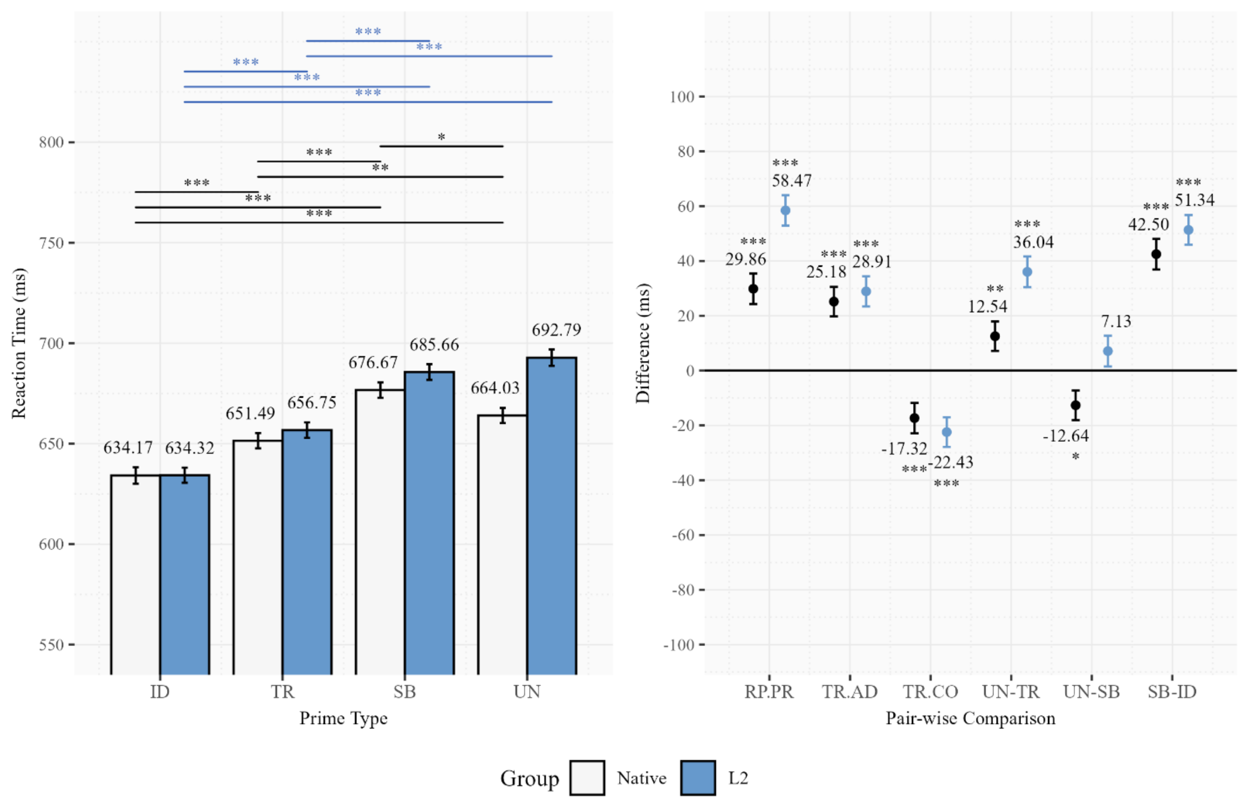
Importantly, a significant two-way interaction was identified between the factors of group and prime type, $\chi^2(3) = 22.92$, $p < 0.001$. A pair-wise post-hoc analysis of the two-way interaction with the Tukey adjustment discovered that the native speakers had a significant difference of 29.85 ms between the identity (M = 634.17 ms, SD = 180.37) and unrelated conditions (M = 664.03 ms, SD = 168.15) and, $z = 8.34$, $p < 0.001$. The L2 learners also exhibited a significant difference of 58.47 ms between the identity (M = 634.32 ms, SD = 166.21) and unrelated conditions (M = 692.79

ms, *SD* = 177.45), $z = 14.29$, $p < 0.001$. The repetition priming effects, shown as RP.PR in Figure 9 below, were calculated based on these differences (Unrelated – Identity).

Letter transposition advantages were also significant in both groups, which were , presented as TR.AD in Figure 9 (Substitution - Transposition).

Figure 9.

Global Latency Analysis of the Word Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

In the native speakers, the difference of 25.18 ms was significant between the letter-transposed (*M* = 651.49 ms, *SD* = 167.29) and letter-substituted primes (*M* = 676.67 ms, *SD* = 168.88), $z = 6.04$, $p < 0.001$. Likewise, the L2 learners had a significant difference of 28.91 ms between the letter-transposed (*M* = 656.75 ms, *SD* = 170.50) and letter-substituted primes (*M* = 685.66 ms, *SD* = 171.01), *z* = 6.23, *p* < 0.001. These differences were then used to calculate the letter transposition advantages

Significant costs of letter transposition were confirmed both in the native speakers and in the L2 learners. The data from the native speakers indicated a significant difference of -17.31 ms between the identity (*M* = 634.17 ms, *SD* = 180.37) and letter transposition conditions (*M* = 651.49 ms, *SD* = 167.29), *z* = -4.99, *p* < 0.001. The L2 learners had a significant difference of -22.43 ms between the identity (*M* = 634.32 ms, *SD* = 166.21) and letter transposition conditions (*M* = 656.75 ms, *SD* = 170.50), *z* = -6.05, *p* < 0.001. These differences are represented as TR.CO in Figure 9 (Identity - Transposition).

Significant differences were found between the letter transposition and unrelated in both groups. The native speakers had a significant difference of 12.54 ms between the letter transposition (*M* = 651.49 ms, *SD* = 167.29) and unrelated conditions (*M* = 664.03 ms, *SD* = 168.15), *z* = 3.34, *p* < 0.01. The L2 learners also exhibited a significant difference of 36.04 ms between the letter transposition (*M* = 656.75 ms, *SD* = 170.50) and unrelated conditions (*M* = 692.79 ms, *SD* = 177.45) and, *z* = 8.27, *p* < 0.001. Figure 9 shows these differences as UN-TR (Unrelated - Transposition).

Likewise, the differences between the letter-substituted and identity primes were significant in the two groups. In the native speakers, the identity primes (*M* = 634.17 ms, *SD* = 180.37) produced significantly faster responses by 42.49 ms than the letter-substituted primes (*M* = 676.67 ms, *SD* = 168.88), *z* = 11.03, *p* < 0.001. Also, the L2 learners were significantly faster by 51.34 ms in the identity condition (*M* = 634.32 ms, *SD* = 166.21) than in the letter substitution condition (*M* = 685.66 ms, *SD* = 171.01), *z* = 12.27, *p* < 0.001. In Figure 9, these differences are designated as SB-ID (Substitution - Identity).

However, the pairwise comparisons highlighted the contrasting differences between the letter substitution and unrelated conditions in the two groups. The native speakers showed a significant inhibitory effect of letter substitution by -12.64 ms between the letter substitution (M = 676.67 ms, SD = 168.88) and unrelated conditions (M = 664.03 ms, SD = 168.15), $z = -2.71$, $p < 0.05$. On the other hand, the L2 learners exhibited a 7.13 ms facilitatory effect of letter substitution between the letter substitution (M = 685.66 ms, SD = 171.01) unrelated conditions (M = 692.79 ms, SD = 177.45). This facilitatory effect, however, failed to reach a significance level, $z = 2.07$, $p = 0.163$. These differences are referred to UN-SB in Figure 9 (Unrelated - Substitution).

The difference between the two groups was not statistically significant in each condition. In the identity condition, the native speakers (M = 634.17 ms, SD = 180.37) were faster by 0.15 ms than the L2 learners (M = 634.32 ms, SD = 166.21). In the letter transposition condition, the native speakers (M = 651.49 ms, SD = 167.29) provided faster responses by 5.26 ms than the L2 learners (M = 656.75 ms, SD = 170.50). The letter substitution condition also found that the native speakers (M = 676.67 ms, SD = 168.88) were faster by 8.99 ms than the L2 learners (M = 685.66 ms, SD = 171.01). In the unrelated condition, the native speakers (M = 664.03 ms, SD = 168.15) responded faster by 28.76 ms than the L2 learners (M = 692.79 ms, SD = 177.45). None of the pairwise comparisons, however, were statistically significant, $p > 0.10$.

The present study employed a custom contrast to investigate whether the observed differences in prime type varied between the two groups, as detailed in Table 12 below. To control the family-wise error rate in multiple comparisons, the present study used the multivariate t (mvt) adjustment available in the *emmeans* package (Lenth, 2024a), which accounted for the dependencies among the observed differences[14]. The results suggested that the native speakers had a significantly smaller effect of repetition priming (29.85 ms) than the L2 learners (58.47 ms), $z = 4.49$, $p < 0.001$. The sizes of letter transposition advantage and cost did not vary significantly between the two groups, $p > 0.50$. However, the two groups showed different magnitudes in the differences (1) between the letter transposition and unrelated conditions ($z = 3.64$, $p < 0.01$), and (2) between the letter substitution and unrelated conditions ($z = 3.37$. $p < 0.01$). The remaining difference was not statistically significant.

Table 12.

Custom Contrast Comparisons of the Latency-related Effects between the Two Groups (with the Multivariate Adjustment)

	z	*Unadj. p*	*Adj. p*	
RP.PR (Repetition Priming)	4.49	<.001	<.001	***
TR.AD (Transposition Advantage)	0.20	0.841	0.997	
TR.CO (Transposition Cost)	0.80	0.425	0.856	
UN-TR	3.64	<.001	0.002	**
UN-SB	3.37	0.001	0.004	**
SB-ID	0.99	0.324	0.758	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

Therefore, the latency analysis confirmed significant advantages and costs of letter transposition in both the native speakers and Korean L2 learners of English; the two groups had

[14] That is, each contrast was not independent from each other. For instance, the identity condition was correlated to the contrasts of RP.PR (the difference between the identity and unrelated conditions), TR.CO (the difference between the identity and letter transposition), and SB-ID.

advantages of 25.18 ms and 28.92 ms and costs of -17.31 ms and -22.43 ms, respectively. These advantages and costs were statistically non-significantly different between the two groups. However, a significant difference emerged from the repetition priming: the L2 learners exhibited significantly larger effect (58.47 ms) than the native speakers (29.85 ms). The custom contrast analysis also revealed significant divergences between the two groups; the native speakers showed a significantly smaller difference (12.54 ms) between the letter transposition and unrelated conditions than the L2 learners (36.04 ms). Additionally, the native speakers performed significantly worse in the letter substitution condition compared to the unrelated condition (-12.64 ms), the pattern of which was significantly different from that of the L2 learners, who showed a better performance in the letter substitution condition (7.13 ms).

4.3.1.1.2. Error Analysis

The descriptive statistics for the error analysis are presented in Table 13. The accuracies were regressed on the fixed effects of group and prime type with two random effects of item and participant: glmer (Accuracy ~ 1 + Group * Prime_Type + (1 | Item) + (1 | Participant), family = binomial, control = glmerControl (optimizer = "bobyqa")). Table 14 and Table 15 present a Type III analysis-of-variance table and a regression coefficient table, respectively.

The results of the regression confirmed significant main effects of group ($\chi^2(1) = 19.38$, $p < 0.001$) and prime type ($\chi^2(3) = 19.72$, $p < 0.001$). There was also a significant two-way interaction between group and prime type ($\chi^2(3) = 11.04$, $p < 0.05$). A pair-wise post-hoc analysis of the interaction discovered that the native speakers of English showed a significant difference of 1.22% between the identity (M = 99.03%, SD = 9.83) and letter transposition conditions (M = 97.81%, SD = 14.65), $z = -3.09$, $p < 0.05$. This difference is shown as TR.CO (Identity - Transposition) in Figure 10.

Table 13.

Accuracies in the Word Targets

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
Native Speakers of English						
ID	99.03%	2,052	0.10	0.22%	98.81%	99.24%
TR	97.81%	2,052	0.15	0.32%	97.48%	98.13%
SB	97.51%	2,052	0.16	0.34%	97.17%	97.86%
UN	98.44%	2,052	0.12	0.27%	98.17%	98.71%
Total	98.20%	8,208	0.13	0.15%	98.05%	98.35%
Korean L2 Learners of English						
ID	97.76%	2,052	0.15	0.33%	97.43%	98.09%
TR	96.83%	2,052	0.18	0.39%	96.45%	97.22%
SB	96.69%	2,052	0.18	0.40%	96.29%	97.08%
UN	95.37%	2,051	0.21	0.46%	94.90%	95.83%
Total	96.66%	8,207	0.18	0.20%	96.46%	96.86%

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 14.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Accuracies in the Word Targets

	χ^2	df	*p*	
(Intercept)	1,114.16	1.00	<.001	***
Group	19.38	1.00	<.001	***
Prime Type	19.72	3.00	<.001	***
Group : Prime Type	11.04	3.00	0.012	*

Table 15.

Coefficients of the Regression (Dummy-coded Contrast) on Accuracies in the Word Targets

	b	SE(b)	*z*	*p*	
(Intercept)	5.30	0.27	19.44	<.001	***
Prime Type (TR)	-0.86	0.28	-3.09	0.002	**
Prime Type (SB)	-0.99	0.27	-3.64	0.000	***
Prime Type (UN)	-0.53	0.29	-1.79	0.073	.
Group (L2)	-1.03	0.31	-3.28	0.001	**
Group (L2) : Prime Type (TR) [a]	0.50	0.34	1.47	0.141	
Group (L2) : Prime Type (SB) [a]	0.58	0.34	1.72	0.085	.
Group (L2) : Prime Type (UN) [a]	-0.26	0.35	-0.74	0.457	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

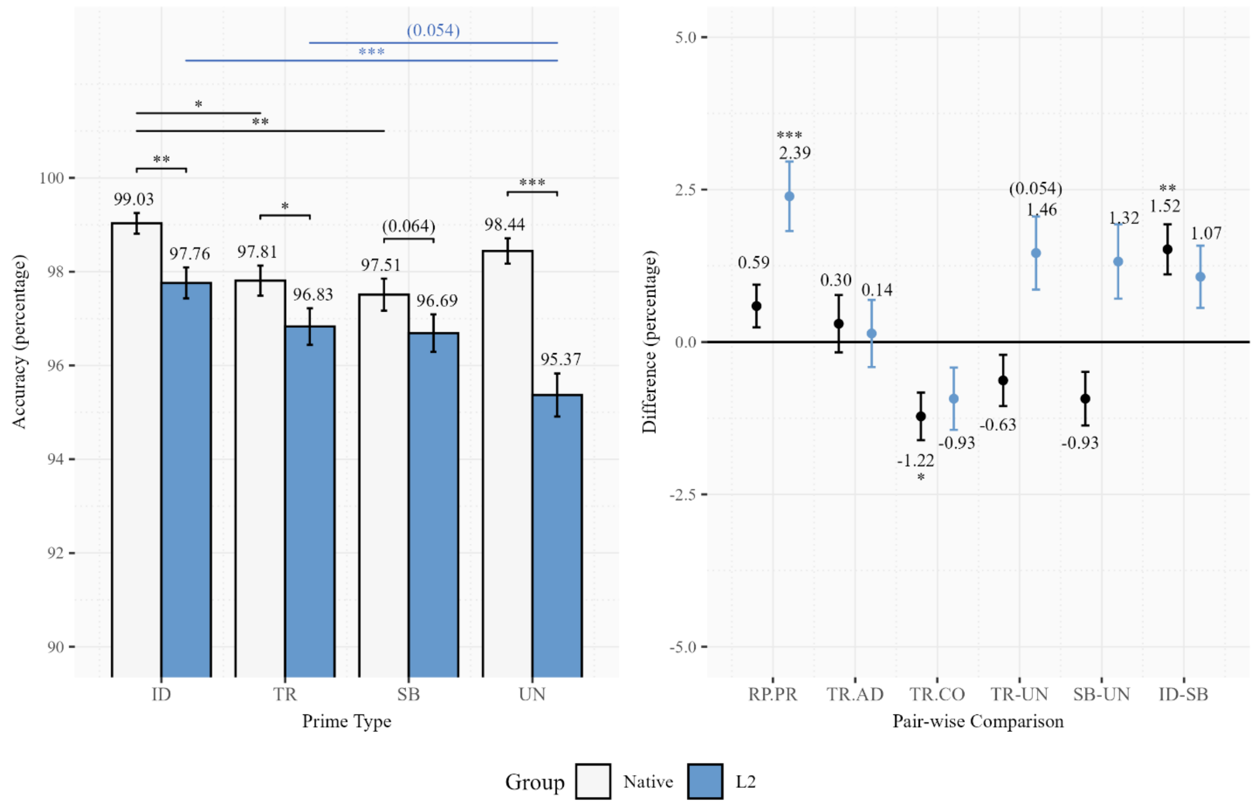
[a] The interaction terms were referenced to the base level of ID due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast, refer to the section of 3.4.2. Statistical Methods..

Additionally, the difference between the identity (M = 99.03%, SD = 9.83) and letter substitution conditions (M = 97.51%, SD = 15.57) was significant by 1.51% in the native speakers, $z = 3.64$, $p < 0.01$. In Figure 10, this difference is presented as ID-SB (Identity - Substitution).

In contrast, the Korean L2 learners of English had a significant difference of 2.39% between the identity (M = 97.76%, SD = 14.81) and unrelated conditions (M = 95.37%, SD = 21.02), $z = 4.20$, $p < 0.001$. A marginally significant difference of 1.46% was also found between the letter transposition (M = 96.83%, SD = 17.52) and unrelated conditions (M = 95.37%, SD = 21.02), $z = 2.54$, $p = 0.054$. These differences are presented as RP.PR (Identity - Unrelated) and TR-UN (Transposition - Unrelated) in Figure 10, respectively.

Figure 10.

Global Error Analysis of the Word Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

The accuracies of two groups differed significantly from each other in the identity (Native: M = 99.03%, SD = 9.83; L2: M = 97.76%, SD = 14.81, z = 3.28, $p < 0.01$), letter transposition (Native: M = 97.81%, SD = 14.65; L2: M = 96.83%, SD = 17.52, z = 2.10, $p < 0.05$), and unrelated conditions (Native: M = 98.44%, SD = 12.39; L2: M = 95.37%, SD = 21.02, z = 4.97, $p < 0.001$). The native speakers performed significantly better than the L2 learners in all three conditions. The difference between the two groups was marginally significant in the letter substitution condition, z = 1.85, p = 0.064; still, the native speakers had higher accuracies (M = 97.51%, SD = 15.57) than the L2 learners (M = 96.69%, SD = 17.90).

As detailed in Table 16, another custom contrast was developed to explore whether the observed differences of prime type varied between the two groups. The results found that the native speakers showed a significantly different deviance in terms of the difference between the letter transposition and unrelated conditions (-0.63%) compared to the L2 learners (1.46%), $z = 2.60$, $p < 0.05$. In a similar vein, the difference between the substitution and unrelated condition varied significantly in its direction when comparing the native speakers (-0.93%) to the L2 learners (1.32%), $z = -2.92$, $p < 0.05$. None of the other differences reached statistical significance.

Table 16.

Custom Contrast Comparisons of the Error-related Effects between the Two Groups (with the Multivariate Adjustment)

	z	*Unadj. p*	*Adj. p*	
RP.PR (Repetition Priming)	-0.74	0.457	0.878	
TR.AD (Transposition Advantage)	0.27	0.786	0.993	
TR.CO (Transposition Cost)	1.47	0.141	0.452	
TR-UN	-2.60	0.009	0.046	*
SB-UN	-2.92	0.004	0.018	*
ID-SB	1.72	0.085	0.310	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

The error analysis discovered that only the native speakers of English had a significant cost of letter transposition by -1.22% with a significant difference between the identity and letter substitution conditions (1.52%). In contrast, the L2 learners only showed a significant difference between the identity and unrelated conditions (2.39%). Furthermore, the two groups diverged significantly in the direction of differences between (1) the letter transposition and unrelated conditions (Native: -0.63%, L2: 1.46%), and (2) the letter substitution and unrelated conditions (Native: -0.93%, L2: 1.32%).

4.3.1.2. Nonword Targets

Given that letter-transposed primes were inherently nonwords, a comprehensive analysis of the nonword targets was essential. This investigation aimed to examine whether the effects of letter transposition observed in the word targets were lexical in origin. If a comparable effect emerged with the nonword targets, especially in the L2 learners, it would suggest that the findings in the word targets might be due to an artifact of sublexical processing. Consequently, a thorough examination of the nonword target performance was deemed necessary.

4.3.1.2.1. Latency Analysis

Table 17 shows the descriptive statistics for the latency analysis in the nonword targets.

The reaction times to the nonwords were regressed only on the fixed effects of group and prime type without any covariate of word frequency modelled in, because nonwords had no lexical frequency. The present study used the following formula with two random effects of item and participant: glmmTMB (Reaction_Time ~ 1 + Group * Prime_Type + (1 | Item) + (1 | Participant), family=Gamma (link = "identity")). The results of the regression were summarized in Table 18, presented as a Type III analysis-of-variance table.

The results of the regression found a significant main effect of prime type, $\chi^2(3) = 11.26$, $p < 0.05$. The main effect of group was marginally significant, $\chi^2(1) = 2.94$, $p = 0.087$. The two-way interaction between group and prime type was not statistically significant, $p > 0.50$. The present study decided to focus primarily on the significant main effect of prime type since the main effect of group was only marginally significant. Table 19 presents the regression coefficient table.

Table 17.

Reaction Times in the Nonword Targets

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Native Speakers of English			
ID	691.01	1,932	173.61	3.95	687.06	694.96
TR	695.27	1,933	181.06	4.12	691.16	699.39
SB	694.03	1,935	172.46	3.92	690.11	697.95
UN	696.81	1,926	164.42	3.75	693.06	700.55
Total	694.28	7,726	172.97	1.97	692.31	696.25
			Korean L2 Learners of English			
ID	720.30	1,914	178.19	4.07	716.23	724.38
TR	725.15	1,912	188.01	4.30	720.85	729.45
SB	732.41	1,916	185.71	4.24	728.17	736.66
UN	732.00	1,893	185.35	4.26	727.74	736.26
Total	727.46	7,635	184.38	2.11	725.35	729.57

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 18.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Reaction Times in the Nonword Targets

	χ^2	df	p	
(Intercept)	5,112.38	1.00	<.001	***
Group	2.94	1.00	0.087	.
Prime Type	11.26	3.00	0.010	*
Group : Prime Type	2.20	3.00	0.532	

Table 19.

Coefficients of the Regression (Dummy-coded Contrast) on Reaction Times in the Nonword Targets

	b	SE(b)	*z*	*p*	
(Intercept)	697.00	14.06	49.58	<.001	***
Prime Type (TR)	1.43	3.97	0.36	0.719	
Prime Type (SB)	2.02	3.96	0.51	0.610	
Prime Type (UN)	6.63	3.98	1.67	0.096	.
Group (L2)	29.01	19.47	1.49	0.136	
Group (L2) : Prime Type (TR) [a]	1.31	5.74	0.23	0.819	
Group (L2) : Prime Type (SB) [a]	7.81	5.75	1.36	0.174	
Group (L2) : Prime Type (UN) [a]	4.49	5.77	0.78	0.437	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

[a] The interaction terms were referenced to the base level of ID due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

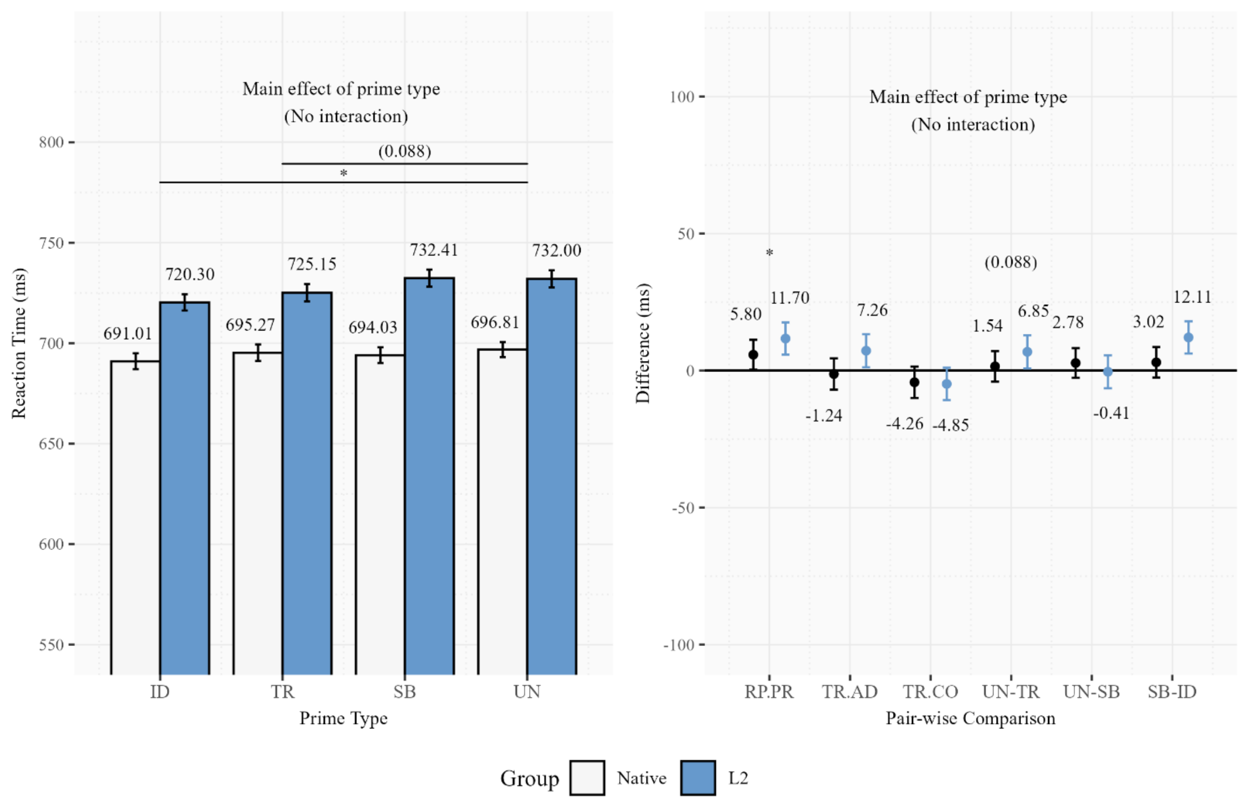
A pair-wise post-hoc analysis of the main effect of prime type discovered a significant difference of 8.67 ms between the identity (M = 705.59 ms, SD = 176.49) and unrelated conditions (M = 714.25 ms, SD = 175.97) , $z = 3.08$, $p < 0.05$. The difference between the letter transposition (M = 710.13 ms, SD = 185.13) and unrelated conditions (M = 714.25 ms, SD = 175.97) was marginally significant, $z = 2.35$, $p = 0.088$. Figure 11 below shows these differences as RP.PR (Unrelated - Identity) and UN-TR (Unrelated - Transposition), respectively. The pairwise comparisons between other conditions failed to reach statistical significance, $ps > 0.10$.

There was a difference of 33.18 ms between the native speakers (M = 694.28 ms, SD = 172.97) and Korean L2 learners of English (M = 727.46 ms, SD = 184.38), but this group difference was marginally significant as mentioned earlier, $\chi^2(1) = 2.94$, $p = 0.087$.

Figure 11 below summarizes the results. No evidence was found regarding the presence of either the letter transposition advantage or cost in the nonwords. The only statistically significant effect observed in either the native speakers or the L2 learners was that of identity priming. Consequently, the findings of the latency analysis of the nonword targets indicate that the effects of letter transposition in the word targets were lexical in origin, not attributable to sublexical processing. Instead, the results of the nonword targets suggest that the effect of repetition priming might be susceptible to sublexical processing.

Figure 11.

Global Latency Analysis of the Nonword Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

4.3.1.2.2. Error Analysis

The descriptive statistics for the error analysis are presented in Table 20.

The accuracies in the nonwords were regressed on the fixed effects of group and prime type with two random effects of item and participant. The model was built as follows: glmer(Accuracy ~ 1 + Group * Prime_Type + (1 | Item) + (1 | Participant), family = binomial, control = glmerControl (optimizer = "bobyqa")). The results of the regression are summarized in Table 21 and Table 22, as a Type III analysis-of-variance table and a regression coefficient table, respectively.

Table 20.

Accuracies in the Nonword Targets

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Native Speakers of English			
ID	98.15%	2,052	0.13	0.30%	97.85%	98.45%
TR	98.10%	2,052	0.14	0.30%	97.80%	98.40%
SB	98.10%	2,052	0.14	0.30%	97.80%	98.40%
UN	98.00%	2,052	0.14	0.31%	97.69%	98.31%
Total	98.09%	8,208	0.14	0.15%	97.94%	98.24%
			Korean L2 Learners of English			
ID	96.88%	2,052	0.17	0.38%	96.50%	97.26%
TR	96.78%	2,052	0.18	0.39%	96.39%	97.17%
SB	96.88%	2,052	0.17	0.38%	96.50%	97.26%
UN	96.30%	2,052	0.19	0.42%	95.88%	96.71%
UN	96.71%	8,208	0.18	0.20%	96.51%	96.91%

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 21.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Accuracies in the Nonword Targets

	χ^2	df	*p*	
(Intercept)	1,112.28	1.00	<.001	***
Group	10.71	1.00	0.001	**
Prime Type	1.08	3.00	0.782	
Group : Prime Type	0.24	3.00	0.970	

Table 22.

Coefficients of the Regression (Dummy-coded Contrast) on Accuracies in the Nonword Targets

	b	SE(b)	*z*	*p*	
(Intercept)	4.56	0.22	20.90	<.001	***
Prime Type (TR)	-0.03	0.23	-0.12	0.904	
Prime Type (SB)	-0.03	0.23	-0.13	0.900	
Prime Type (UN)	-0.08	0.23	-0.36	0.720	
Group (L2)	-0.58	0.26	-2.22	0.026	*
Group (L2) : Prime Type (TR) [a]	-0.01	0.30	-0.03	0.979	
Group (L2) : Prime Type (SB) [a]	0.03	0.30	0.11	0.915	
Group (L2) : Prime Type (UN) [a]	-0.10	0.29	-0.35	0.724	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

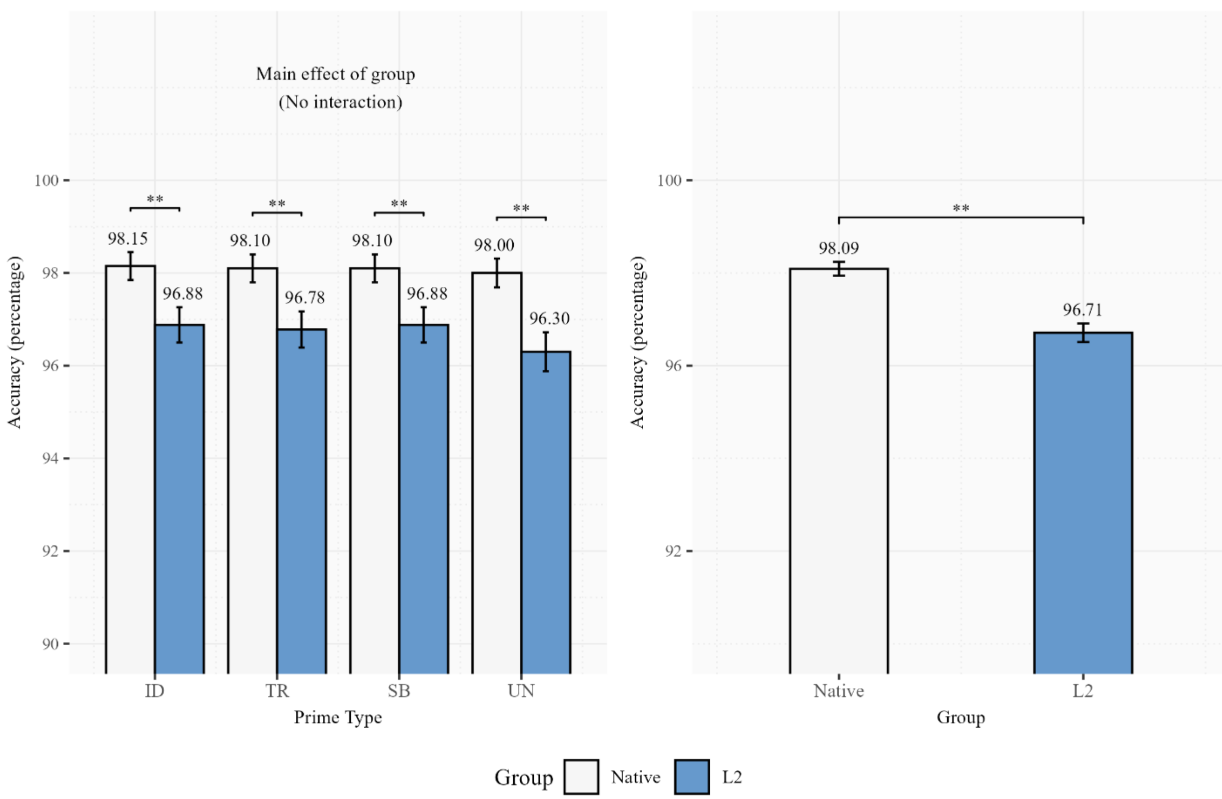
[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

Only the main effect of group was statistically significant, $\chi^2(1) = 10.71$, $p < 0.01$. The main effect of prime type failed to reach statistical significance, $p > 0.70$. Additionally, the interaction between group and prime type was not statistically significant, $p > 0.90$. A post-hoc analysis of the main effect of group discovered that the native speakers made more accurate decisions ($M = 98.09\%$, $SD = 13.70$) by 1.38% than the L2 learners ($M = 96.71\%$, $SD = 17.84$).

As summarized in Figure 12, there were no significant effects of prime type; the error analysis of the nonwords provided no strong evidence of either letter transposition advantage or cost in the two groups. However, as with the error analysis of the words, the native speakers demonstrated significantly greater accuracy than the Korean L2 learners of English.

Figure 12.

Global Error Analysis of the Nonword Stimuli



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

4.3.2. L2 Subset Analysis Between Two Proficiency Groups

The present study further examined the data from the Korean L2 learners of English, as their proficiency could have impacted the observed effects. As mentioned in the methodology section, 27 participants possessed higher proficiency scores which matched the C2 level of CEFR, whereas 30 participants of the L2 learners had a lower proficiency corresponding to the Upper C1 level of CEFR. Therefore, the present study introduced a new fixed factor of proficiency group, which consisted of higher proficiency (n = 27) and lower proficiency groups (n = 30). The following subset analyses were performed with the same fixed and random effects as the global analyses were, except for the group factor (native vs. L2), which was replaced by proficiency group (higher proficiency vs. lower proficiency).

4.3.2.1. Word Targets

Consistent with the global analysis, the responses to the word targets are analyzed separately from those to the nonword targets.

4.3.2.1.1. Latency Analysis

Table 23 provides the descriptive statistics for the reaction times used in the L2 subset analysis of the word targets.

A GLMM was constructed with the fixed effects of proficiency group and prime type as well as a covariate of mean-centered log-transformed frequency. The model also included two random effects of item and participant. The following formula was used: glmmTMB (Reaction_Time ~ 1 + Proficiency * Prime_Type + MeanCentered_LogFrequency + (1 | Item) + (1 | Participant), family = Gamma (link = "identity")). Table 24 shows the Type III analysis-of-variance table for the regression, whereas Table 25 displays the coefficient table of the regression.

Table 23.

Reaction Times in the Word Targets (L2 Subset)

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Higher Proficiency			
ID	607.05	941	157.79	5.14	601.91	612.20
TR	630.99	935	156.33	5.11	625.88	636.10
SB	651.91	927	151.22	4.97	646.94	656.87
UN	660.46	921	157.14	5.18	655.29	665.64
Total	637.44	3,724	156.95	2.57	634.87	640.01
			Lower Proficiency			
ID	659.60	1,015	169.86	5.33	654.27	664.93
TR	680.80	1,001	179.52	5.67	675.13	686.48
SB	716.49	1,015	181.94	5.71	710.78	722.20
UN	722.98	986	189.68	6.04	716.94	729.02
Total	694.81	4,017	182.12	2.87	691.94	697.68

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 24.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Reaction Times to the Word Targets (Subset)

	χ^2	df	*p*	
(Intercept)	3,982.77	1.00	<.001	***
Proficiency Group	8.11	1.00	0.004	**
Prime Type	254.31	3.00	<.001	***
Mean-centered Log(Frequency)	16.32	1.00	<.001	***
Proficiency Group : Prime Type	2.90	3.00	0.407	

Table 25.

Coefficients of the Regression (Dummy-coded Contrast) on Reaction Times in the Word Targets (Subset)

	b	SE(b)	*z*	*p*	
(Intercept)	663.16	14.71	45.09	<.001	***
Mean-centered Log(Frequency)	-14.51	3.59	-4.04	<.001	***
Prime Type (TR)	20.97	5.74	3.66	<.001	***
Prime Type (SB)	52.99	5.88	9.02	<.001	***
Prime Type (UN)	61.26	5.95	10.29	<.001	***
Proficiency Group (Higher)	-56.05	20.85	-2.69	0.007	**
Proficiency Group (Higher) : Prime Type (TR) [a]	5.75	7.94	0.72	0.469	
Proficiency Group (Higher) : Prime Type (SB) [a]	-6.58	8.15	-0.81	0.419	
Proficiency Group (Higher) : Prime Type (UN) [a]	-5.94	8.21	-0.72	0.469	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

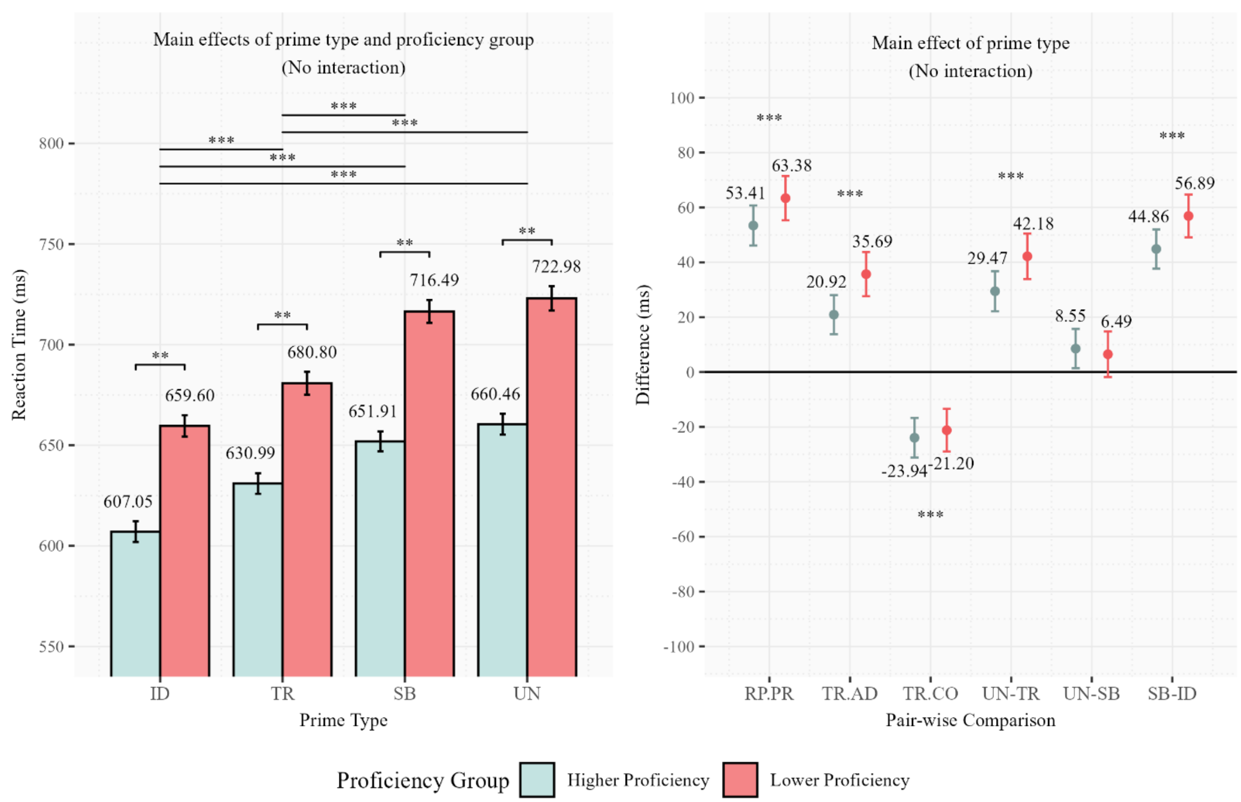
[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

The results of the regression revealed significant main effects of proficiency group ($\chi^2(1) = 8.11$, $p < 0.01$) and prime type ($\chi^2(3) = 254.31$, $p < 0.001$). The higher proficiency group (M = 637.44, SD = 156.95) was significantly faster by 57.37 ms than the lower proficiency group (M = 694.81, SD = 182.12), $z = 3.27$, $p < 0.01$. The covariate of log-transformed frequency was statistically significant as well, $\chi^2(1) = 16.32$, $p < 0.001$. However, the interaction between proficiency group and prime type was not statistically significant, $p > 0.40$.

A pair-wise post-hoc analysis of the main effect of prime type replicated the findings in the global analysis concerning the Korean L2 learners of English. All the learners showed a significant difference of 58.47 ms between the identity (M = 634.32 ms, SD = 166.21) and unrelated conditions (M = 692.79 ms, SD = 177.45), z = 14.25, p < 0.001 (RP.PR in Figure 13). Additionally, a significant difference of 36.04 ms was confirmed between the letter transposition (M = 656.75 ms, SD = 170.50) and letter substitution conditions (M = 685.66 ms, SD = 171.01), z = 6.27, p < 0.001 (TR.AD in Figure 13). The difference between the identity (M = 634.32 ms, SD = 166.21) and letter transposition conditions (M = 656.75 ms, SD = 170.50) was also statistically significant, z = -6.02, p < 0.001 (TR.CO in Figure 13).

Figure 13.

L2 Subset Latency Analysis of the Word Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

Furthermore, the letter transposition condition (M = 656.75 ms, SD = 170.50) differed significantly by 36.04 ms from the unrelated condition (M = 692.79 ms, SD = 177.45) , z = 8.25, p < 0.001 (UN-TR in Figure 13). A significant difference of 51.34 ms emerged between the identity (M = 634.32 ms, SD = 166.21) and letter substitution conditions (M = 685.66 ms, SD = 171.01), z = 12.27, p < 0.001 (SB-ID in Figure 13). However, no significant difference was found between the letter substitution (M = 685.66 ms, SD = 171.01) and unrelated conditions (M = 692.79 ms, SD = 177.45), p > 0.10 (UN-SB in Figure 13).

The L2 subset latency analysis replicated the findings of the L2 learners in the global latency analysis. The L2 learners demonstrated a significant repetition priming effect, a significant letter transposition advantage and a significant transposition cost as well as significant differences between the letter transposition and unrelated conditions, and between the identity and letter substitution conditions. In particular, the two proficiency groups showed no significant variation in the observed effects. Both groups revealed comparably significant effects of repetition priming, letter transposition advantage, and letter transposition cost. Therefore, proficiency did not alter the patterns of L2 learners observed in the global analysis, except that the higher proficiency group responded more quickly than the lower proficiency group.

4.3.2.1.2. Error Analysis

The accuracies in the word targets for the L2 subset analysis are summarized in Table 26.

The error analysis examined the fixed effects of proficiency group and prime type as well as two random effects of item and participant by using the following formula: glmer (Accuracy ~ 1 + Proficiency * Prime_Type + (1 | Item) + (1 | Participant), family = binomial, control = glmerControl (optimizer = "bobyqa")). Table 27 and Table 28 show the Type III analysis-of-variance table and coefficient table of the regression, respectively.

Table 26.

Accuracies in the Word Targets (Subset)

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Higher Proficiency			
ID	98.87%	972	0.11	0.34%	98.53%	99.21%
TR	97.94%	972	0.14	0.46%	97.49%	98.40%
SB	96.50%	972	0.18	0.59%	95.91%	97.09%
UN	96.40%	971	0.19	0.60%	95.80%	96.99%
Total	97.43%	3,887	0.16	0.25%	97.18%	97.68%
			Lower Proficiency			
ID	96.76%	1,080	0.18	0.54%	96.22%	97.30%
TR	95.83%	1,080	0.20	0.61%	95.22%	96.44%
SB	96.85%	1,080	0.17	0.53%	96.32%	97.38%
UN	94.44%	1,080	0.23	0.70%	93.75%	95.14%
Total	95.97%	4,320	0.20	0.30%	95.67%	96.27%

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 27.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Accuracies to the Word Stimuli (Subset)

	χ^2	df	*p*	
(Intercept)	837.81	1.00	<.001	***
Proficiency Group	8.67	1.00	0.003	**
Prime Type	20.24	3.00	<.001	***
Proficiency Group : Prime Type	8.46	3.00	0.037	*

Table 28.

Coefficients of the Regression (Dummy-coded Contrast) on Accuracies in the Word Targets (Subset)

	b	SE(b)	*z*	*p*	
(Intercept)	3.80	0.22	17.46	<.001	***
Prime Type (TR)	-0.28	0.23	-1.18	0.236	
Prime Type (SB)	0.00	0.25	-0.01	0.995	
Prime Type (UN)	-0.59	0.22	-2.66	0.008	**
Proficiency Group (Higher)	1.08	0.38	2.86	0.004	**
Proficiency Group (Higher) : Prime Type (TR) [a]	-0.30	0.45	-0.67	0.501	
Proficiency Group (Higher) : Prime Type (SB) [a]	-1.13	0.43	-2.61	0.009	**
Proficiency Group (Higher) : Prime Type (UN) [a]	-0.61	0.42	-1.47	0.142	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

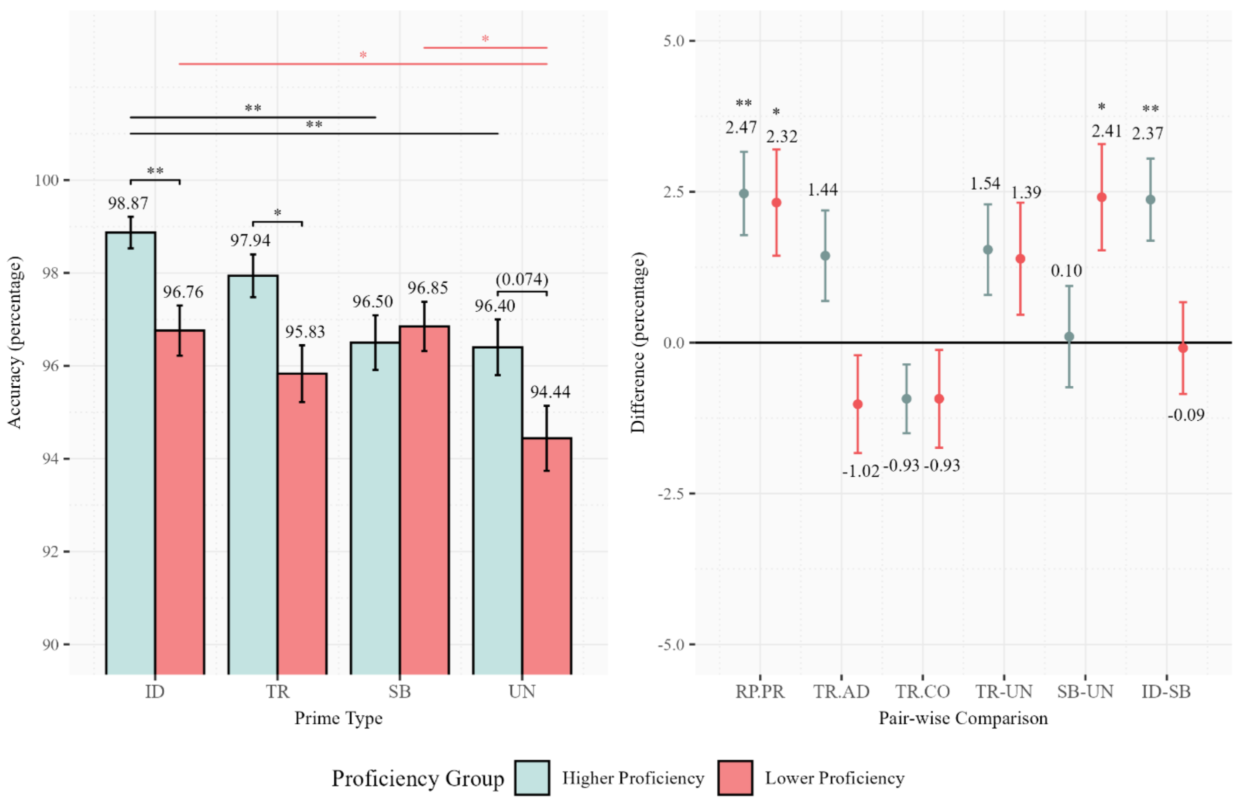
The results of the regression found significant main effects of proficiency group ($\chi^2(1)$ = 8.67, $p < 0.01$) and prime type ($\chi^2(3)$ = 20.24, $p < 0.001$). Additionally, a two-way interaction between group and prime type was also proven to be statistically significant, $\chi^2(3) = 8.46$, $p < 0.05$.

A pair-wise post-hoc analysis of the interaction suggested that both the higher and lower proficiency groups responded more accurately in the identity condition (Higher: *M* = 98.87%, *SD* = 10.58; Lower: *M* = 96.76%, *SD* = 17.72) than in the unrelated condition (Higher: *M* = 96.40%, *SD* = 18.65; Lower: *M* = 94.44%, *SD* = 22.95), Higher: $z = 3.42$, $p < 0.01$; Lower: $z = 2.66$, $p < 0.05$. RP.PR in Figure 14 shows two proficiency groups' differences.

Additionally, the higher proficiency group also showed a significant difference of 2.17% between the identity (*M* = 98.87%, *SD* = 10.58) and letter substitution conditions (*M* = 96.50%, *SD* = 18.38), *z* = 3.20, *p* < 0.01. On the other hand, the lower proficiency group failed to show such a significant difference between the identity (*M* = 96.76%, *SD* = 17.72) and letter substitution conditions (*M* = 96.85%, *SD* = 17.47), *p* = 1.00. These differences are presented as ID-SB in Figure 14.

Figure 14.

L2 Subset Error Analysis in the Word Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

Lastly, the L2 learners with lower proficiency performed significantly differently by 2.41% between the letter substitution (*M* = 96.85%, *SD* = 17.47) and unrelated conditions (*M* = 94.44%, *SD* = 22.95), *z* = 2.57, *p* < 0.05 (SB-UN in Figure 14). The other pair-wise comparisons failed to be statistically significant.

The two groups differed significantly from each other in the identity (Higher: M = 98.87%, SD = 10.58; Lower: M = 96.76%, SD = 17.72, z = -2.86, $p < 0.01$), and letter transposition conditions (Higher: M = 97.94%, SD = 14.20; Lower: M = 95.83%, SD = 19.99, z = -2.52, $p < 0.5$). A marginally significant difference was found between the two groups in the unrelated condition (Higher: M = 96.40%, SD = 18.65; Lower: M = 94.44%, SD = 22.95, z = -1.79, p = 0.074). In these three conditions, the higher proficiency group recorded higher accuracies by 2.11%, 2.11% and 1.96%, respectively. The difference between the two groups was not statistically significant in the letter substitution condition, $p > 0.80$.

As in the previous post-hoc analyses of interaction, a custom contrast was created to examine if the observed differences of prime type significantly differed between the two groups, as shown in Table 29.

Table 29.

Custom Contrast Comparisons of the Error-related Effects between the Two Groups (with the Multivariate Adjustment)

	z	*Unadj. p*	*Adj. p*	
RP.PR (Repetition Priming)	-1.47	0.142	0.453	
TR.AD (Transposition Advantage)	-2.21	0.027	0.119	
TR.CO (Transposition Cost)	-0.67	0.501	0.906	
TR-UN	-0.87	0.386	0.820	
SB-UN	1.54	0.124	0.412	
ID-SB	-2.61	0.009	0.044	*

Note. Unadj. = unadjusted; Adj = adjusted; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

A significant difference was only discovered in the difference between the identity and letter substitution conditions, $z = -2.61$, $p < 0.05$. This suggests that the difference of 2.37% in the lower proficiency was significantly larger than that of -0.09% in the higher proficiency. None of the other comparisons reached statistical significance.

Hence, the L2 subset error analysis confirmed a significant effect of repetition priming in both groups, but it failed to find neither significant advantage nor cost of letter transposition. Furthermore, the higher proficiency group demonstrated a significant difference between the identity and letter substitution conditions, while the lower proficiency group had a significant difference between the letter substitution and unrelated conditions. The observed differences of the two groups only differed significantly in the comparison of the identity and letter substitution conditions. As a final point, the higher proficiency group responded more accurately than the lower proficiency group except for in the letter substitution condition.

4.3.2.2. Nonword Targets

As with the global analysis, the present study also investigated the performance on the nonword targets to confirm the observed patterns in the word targets were lexical in origin.

4.3.2.2.1. Latency Analysis

Table 30 presents the descriptive statistics for the reaction times in the nonword targets.

The L2 subset latency analysis of the nonword stimuli examined two fixed effects of proficiency group and prime type with two random effects of item and participant as follows: glmmTMB (Reaction_Time ~ 1 + Proficiency * Prime_Type + (1 | Item) + (1 | Participant), family = Gamma (link = "identity")). The results of the regression were presented in Table 31 and Table 32, shown as a Type III analysis-of-variance table and a coefficient table, respectively.

Table 30.

Reaction Times in the Nonword Targets (Subset)

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Higher Proficiency			
ID	691.91	921	172.54	5.69	686.22	697.59
TR	692.23	912	179.86	5.96	686.27	698.18
SB	704.09	922	180.53	5.95	698.14	710.03
UN	708.63	907	178.19	5.92	702.72	714.55
Total	699.20	3,662	177.88	2.94	696.26	702.14
			Lower Proficiency			
ID	746.64	993	179.38	5.69	740.95	752.33
TR	755.18	1,000	190.33	6.02	749.16	761.20
SB	758.69	994	186.67	5.92	752.77	764.61
UN	753.50	986	189.26	6.03	747.47	759.53
Total	753.51	3,973	186.44	2.96	750.55	756.47

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

Table 31.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Reaction Times to the Nonword Stimuli (Subset)

	χ^2	df	*p*	
(Intercept)	2,882.19	1.00	<.001	***
Proficiency	4.90	1.00	0.027	*
Prime Type	9.30	3.00	0.026	*
Proficiency Group : Prime Type	4.64	3.00	0.200	

Table 32.

Coefficients of the Regression (Dummy-coded Contrast) on Reaction Times in the Nonword Targets (Subset)

	b	SE(b)	*z*	*p*	
(Intercept)	755.58	18.87	40.05	<.001	***
Prime Type (TR)	5.54	6.11	0.91	0.365	
Prime Type (SB)	8.82	6.13	1.44	0.150	
Prime Type (UN)	4.60	6.12	0.75	0.452	
Proficiency Group (Higher)	-60.82	26.93	-2.26	0.024	*
Proficiency Group (Higher) : Prime Type (TR) [a]	-5.49	8.46	-0.65	0.516	
Proficiency Group (Higher) : Prime Type (SB) [a]	1.83	8.52	0.21	0.830	
Proficiency Group (Higher) : Prime Type (UN) [a]	12.50	8.52	1.47	0.142	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

The results confirmed a significant main effect of prime type, $\chi^2(3) = 9.30$, $p < 0.05$. The main effect of proficiency group was also significant, $\chi^2(1) = 4.90$, $p < 0.05$. The two-way interaction between two factors, however, failed to reach a significance level, $p > 0.20$.

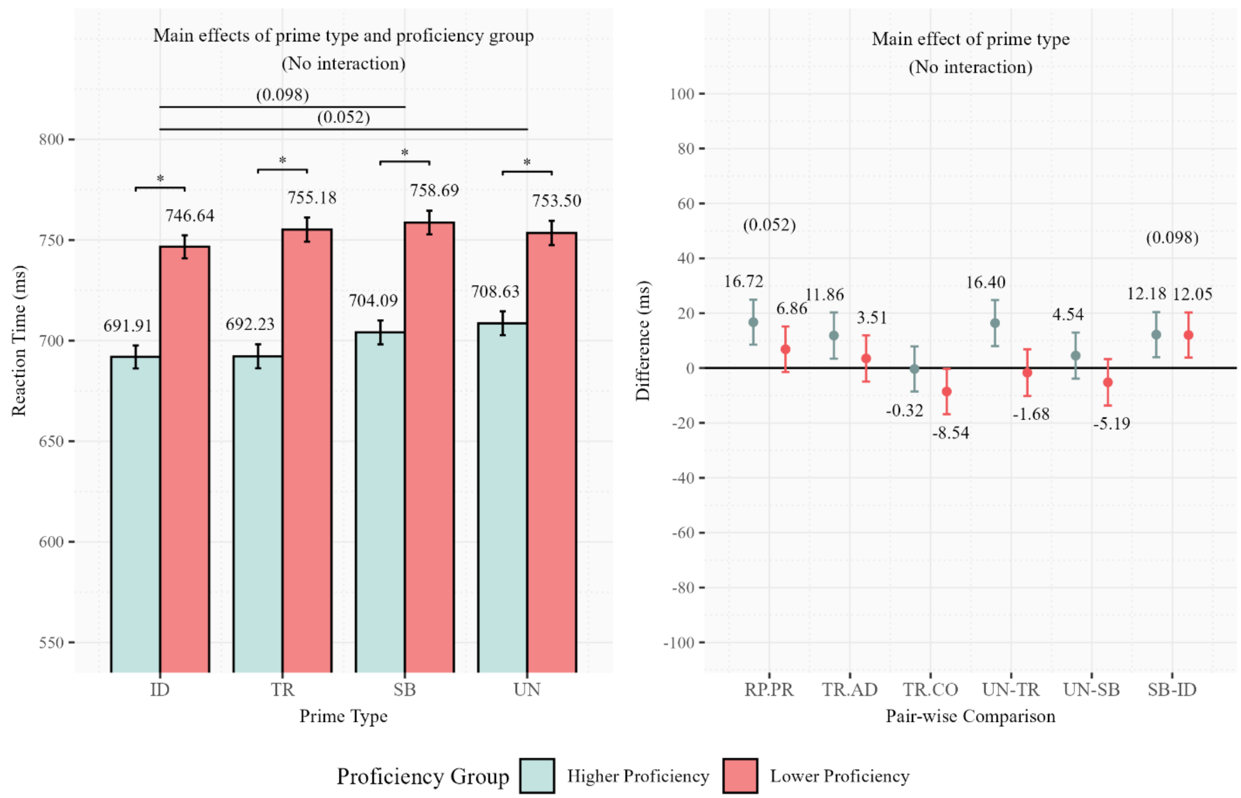
A pairwise post-hoc analysis of the main effect of prime type indicated that the L2 learners were marginally significantly faster in the identity condition (M = 720.30 ms, SD = 178.19) than in the unrelated condition (M = 732.00 ms, SD = 185.35), $z = 2.56$, $p = 0.052$. The differences in the two proficiency groups are presented as RP.PR in Figure 15.

The difference between the letter substitution (M = 732.41 ms, SD = 185.71) and identity conditions (M = 720.30 ms, SD = 178.19) was also marginally significant, $z = 2.30$, $p = 0.098$.

Figure 15 shows the differences in the two proficiency groups as SB-ID in Figure 15. No significant difference was found in the other pair-wise comparisons across the priming conditions.

Figure 15.

L2 Subset Latency Analysis of the Nonword Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

Also noted was that the higher proficiency group (M = 699.20 ms, SD = 177.88) made a significantly faster judgement by 54.31 ms than the lower proficiency group (M = 753.51 ms, SD = 186.44), $z = 2.22$, $p < 0.05$.

The L2 subset analysis further supports that the observed effects in the word targets were primarily lexical in origin; in particular, no significant evidence was found for a letter transposition advantage or cost in the nonword targets. The only statistically significant finding was a difference of 54.31 ms between the two proficiency groups.

4.3.2.2.2. Error Analysis

Table 33 summarizes the descriptive statistics of the accuracies in the nonword targets.

As in the L2 subset error analysis of the words, the accuracy data were regressed on the fixed effects of proficiency group and prime type as well as the random effects of item and participant as follows: glmer (Accuracy ~ 1 + Proficiency * Prime_Type + (1 | Item) + (1 | Participant), family = binomial, control = glmerControl (optimizer = "bobyqa")).

Table 33.

Accuracies in the Nonword Targets (Nonword)

Prime Type	M	Datapoints	SD	SEM	M-SEM	M+SEM
			Higher Proficiency			
ID	97.22%	972	0.16	0.53%	96.69%	97.75%
TR	96.60%	972	0.18	0.58%	96.02%	97.19%
SB	97.22%	972	0.16	0.53%	96.69%	97.75%
UN	96.91%	972	0.17	0.56%	96.36%	97.47%
Total	96.99%	3,888	0.17	0.27%	96.72%	97.26%
			Lower Proficiency			
ID	96.57%	1,080	0.18	0.55%	96.02%	97.13%
TR	96.94%	1,080	0.17	0.52%	96.42%	97.47%
SB	96.57%	1,080	0.18	0.55%	96.02%	97.13%
UN	95.74%	1,080	0.20	0.61%	95.13%	96.36%
Total	96.46%	4,320	0.18	0.28%	96.18%	96.74%

Note. M = mean; SD = standard deviation; SEM = standard error of the mean; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

The regression results are summarized in Table 34 and Table 35.

Table 34.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Accuracies in the Nonword Targets (Subset)

	χ^2	df	*p*	
(Intercept)	649.48	1.00	<.001	***
Proficiency	0.39	1.00	0.531	
Prime Type	1.25	3.00	0.741	
Proficiency Group : Prime Type	2.40	3.00	0.493	

Table 35.

Coefficients of the Regression (Dummy-coded Contrast) on Accuracies in the Nonword Targets (Subset)

	b	SE(b)	*z*	*p*	
(Intercept)	3.92	0.24	16.21	<.001	***
Prime Type (TR)	0.13	0.25	0.54	0.591	
Prime Type (SB)	-0.01	0.24	-0.03	0.977	
Prime Type (UN)	-0.26	0.23	-1.11	0.265	
Proficiency Group (Higher)	0.19	0.33	0.56	0.575	
Proficiency Group (Higher) : Prime Type (TR) [a]	-0.36	0.37	-0.97	0.330	
Proficiency Group (Higher) : Prime Type (SB) [a]	0.03	0.38	0.07	0.942	
Proficiency Group (Higher) : Prime Type (UN) [a]	0.18	0.36	0.50	0.620	

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

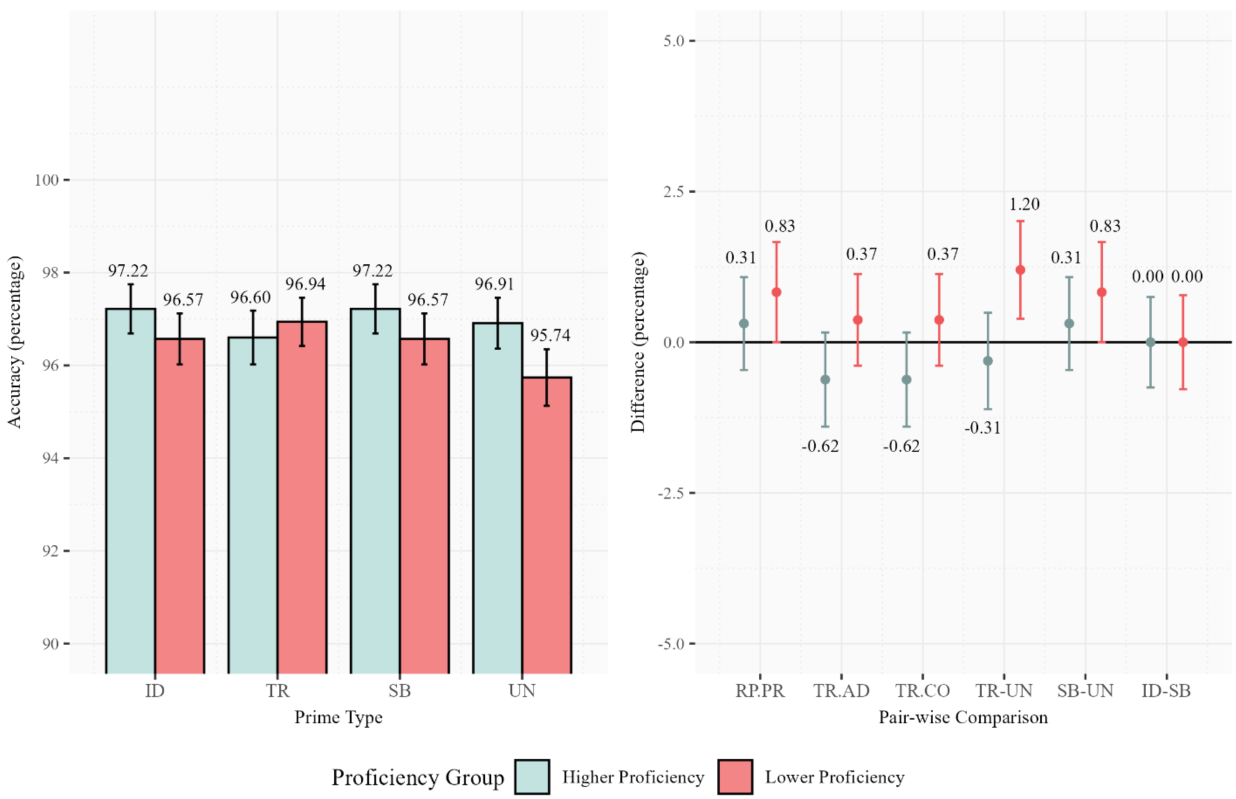
[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

The regression, however, detected no significant main effects or any significant interaction. The main effects of proficiency group and prime type were statistically non-significant, *ps* > 0.50. The interaction between the two factors were also statistically non-significant, $p > 0.40$. Only the intercept was statistically significant, $\chi^2(1) = 649.48$, $p < 0.001$.

Figure 16 further illustrated the results in the nonword targets. While the higher proficiency group ($M = 96.99\%$, $SD = 17.09$) showed a tendency to outperform the lower proficiency group ($M = 95.46\%$, $SD = 18.49$), the difference between the two groups was non-significant.

Figure 16.

L2 Subset Error Analysis of the Nonword Targets



Note. The error bars were based on the standard errors of the mean (SEM); ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; RP = repetition; PR = priming; AD = advantage; CO = cost.

Consequently, the findings of the nonword target suggest that the observed effects in the word targets among these learners primarily stemmed from differences in lexical retrieval, as opposed to sublexical processing. It should be further noted that the identity primes yielded a significant advantage of accuracy over the unrelated primes in the word targets but not in the nonword targets.

4.3.3. Summary of the Analyses

The global latency analysis of the word targets, as presented in Table 36, discovered significant similarities between the native speakers of English and the Korean L2 learners of English. First, a significant repetition priming effect in reaction time was observed in both groups. Additionally, the two groups showed significant advantage and cost of letter transposition in terms of speed of response. Finally, a significant difference emerged between the identity and letter substitution conditions in the latency analysis.

However, some distinctions distinguished the two groups. First, the repetition priming effect in reaction time was significantly larger for the L2 learners than the native speakers. Second, a significant effect of repetition priming in accuracies was uniquely observed in the L2 learners, not in the native speakers. Third, the native speakers demonstrated a significant cost of letter transposition in accuracies, the pattern of which was not seen in the L2 learners. Fourth, the native speakers exhibited a significant difference in reaction time between the letter substitution and unrelated conditions, indicating an inhibitory effect of letter-substituted primes compared to the unrelated word primes. Lastly, both the latency and error analyses revealed a shared significant pattern; the differences between the letter transposition and unrelated conditions, and between the letter substitution and unrelated conditions, varied significantly between the two groups.

Table 36.

Summary of the Results (Percentage Accuracies in Parentheses)

Group	Repetition Priming	Letter transposition		UN vs. TR	UN vs. SB	SB vs. ID
		Advantage	Cost			
Global Analysis						
Word Targets						
Native	29.86 $^{***\,a}$	25.18 ***	-17.31 ***	12.54 $^{**\,b}$	-12.64 $^{*\,b}$	42.50 ***
	(0.59)	(0.30)	(-1.22 *)	(-0.63 ^{c})	(-0.93 ^{c})	(1.52 **)
L2	58.47 $^{***\,a}$	28.92 ***	-22.43 ***	36.04 $^{***\,b}$	7.13 ^{b}	51.34 ***
	(2.39 ***)	(0.14)	(-0.93)	(1.46 ^{c})	(1.32 ^{c})	(1.07)
Nonword Targets						
Native	5.80 *	-1.24	-4.26	1.54	2.78	3.02
	(0.15)	(0.00)	(-0.05)	(0.10)	(0.10)	(0.05)
L2	11.70 *	7.26	-4.85	6.85	-0.41	12.11
	(0.58)	(-0.10)	(-0.10)	(0.48)	(0.58)	(0.00)
L2 Subset Analysis						
Word Targets						
Higher Proficiency	53.41 ***	20.92 ***	-23.94 ***	29.47 ***	8.55	44.86 ***
	(2.47 **)	(1.44)	(-0.93)	(1.54)	(0.10)	(2.37 $^{**\,c}$)
Lower Proficiency	63.38 ***	35.69 ***	-21.20 ***	42.18 ***	6.49	56.89 ***
	(2.32 *)	(-1.02)	(-0.93)	(1.39)	(2.41 *)	(-0.09 ^{c})
Nonword Targets						
Higher Proficiency	16.72	11.86	-0.32	16.40	4.54	12.18
	(0.31)	(-0.62)	(-0.62)	(-0.31)	(0.31)	(0.00)
Lower Proficiency	6.86	3.51	-8.54	-1.68	-5.19	12.05
	(0.83)	(0.37)	(0.37)	(1.20)	(0.83)	(0.00)

Note. * $p < .05$; ** $p < .01$; *** $p < .001$.

^{a} The effects (differences) differing between the two groups at $p < 0.001$.

^{b} differing between the two groups at $p < 0.01$. ^{c} differing between the two groups at $p < 0.05$.

The global analysis of the nonword targets further indicated that lexical retrieval primarily drove the observed effects. Aside from the repetition priming effect in reaction time, no other significant effects observed in the words appeared in the nonwords.

The L2 subset analysis generally replicated the findings of the global analysis for the L2 learners, even across the two proficiency groups. Both groups exhibited a significant effect of repetition priming in reaction time and accuracies. Furthermore, significant advantage and cost of letter transposition were observed in both proficiency groups. Additionally, the differences between the letter transposition and unrelated conditions, and between the identity and letter substitution conditions, were also significant in the two groups.

However, the error analysis of the L2 subset revealed additional findings. The higher proficiency group, but not the lower proficiency group, showed a significant difference in accuracies between the identity and letter substitution conditions, which mirrored the performance of the native speakers. Conversely, the lower proficiency group exhibited a significant difference between the letter substitution and unrelated conditions.

As with the global analysis, the L2 subset analysis of the nonword targets demonstrated that the patterns observed among the L2 learners were lexically driven, as these effects were absent in the nonword targets.

4.4. Post-hoc Latency Analysis with Bigram Frequency of Primes

4.4.1. Motivation

The previous global latency analysis of words found a significant two-way interaction between the factors of group and prime type. The native speakers and Korean L2 learners showed significant advantage and cost of letter transposition, and the significant interaction was driven by the difference between the unrelated and letter substitution conditions; the native speakers exhibited a significant inhibitory effect of letter substitution by -12.64 ms while the L2 learners had a statistically non-significant facilitatory effect by 7.13 ms. This suggested that the letter-substituted primes might have actually affected on the two groups in different manners. the processing of the letter-substituted primes was significantly inhibitory compared to the exposure to the unrelated word primes in the native speakers, while the effect of letter-substituted primes was not more detrimental to the target recognition than the exposure to the unrelated word primes.

Since the size of letter transposition advantage depended on the responses to letter substitution, it was worth investigating a potentially confounding factor that contributed to the different responses to letter substitution in two groups. For instance, one might suspect that the letter substituting method of the present study could be strongly detrimental to visual word recognition in the native speakers because the letter-substituted primes contained highly infrequent sequences of letters in English. It might be reasonably expected that the native speakers showed a strong inhibitory effect of letter substitution compared to the unrelated condition because the unrelated primes contained no such extremely unusual sequences of letters in the present study. On the other hand, the L2 learners might have suffered less from such unusual sequences of letters than the native speakers since these learners were less sensitive to the orthographic patterns in their L2. Hence, one might alternatively suggest that the bigram frequency of primes could have been a compounding factor in the previous global latency analysis.

Therefore, the present study further examined the non-positional bigram frequency of primes; the position-flexible measurements were chosen since the experiment involved letter transposition. The present study utilized the CELEX2 database (Baayen, Piepenbrock, & Gulikers, 1995) in an *R* package *vwr* (Keuleers, 2013) for the calculation of bigram frequency, as this database provided the necessary lexical information required for the letter-transposed and letter-substituted forms in the present study. An *R* package *strngram* (van Heuven, 2020) was used to extract and summarize the bigram-related information from the CELEX2 database. Table 37 provides the descriptive statistics of the non-positional bigram frequency of primes.

Table 37.

Sums of Non-positional Bigram Frequency of Primes (based on 66,330 forms)

Prime Type	M	SD	Min	Max
ID	14,423.56	6,449.32	4,031	35,202
TR	13,307.56	6,725.87	1,355	33,496
SB	7,427.30	4,544.75	877	21,731
UN	14,853.69	6,507.98	3,178	36,911

Note. M = mean; SD = standard deviation; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated.

The mean non-positional bigram frequency was almost twice as low in the letter substitution condition (*M* = 7,427.30, *SD* = 4,544.75) than in either the identity (*M* = 14,423.56, *SD* = 6,449.32) or unrelated conditions (*M* = 14,853.69, *SD* = 6,507.98). Thus, one might suggest that a new set of primes was needed, of which bigram frequency was matched and controlled.

However, bigram-matched primes with letter substitution might be susceptible to the letter similarity effect (c.f. Mueller & Weidemann, 2012) due to the limitations of English orthography. Specifically, there are only five pure vowel letters, three of which share visual similarities to each other (i.e. a, e, o). This lack of vowel letters with diverse shapes greatly limits the number of letter substitution combinations that are highly frequent in English and perceptually different from the substituted letters. For example, a letter string of “er”, which is highly frequent in English, does not have any matching combinations of letter substitution; a letter string of “in” (12,900 in

CELEX2) has similar non-positional bigram frequency to a letter string of “er” (11,033 in CELEX2), but the letter ‘n’ of the former has perceptual similarities to the letter ‘r’ of the latter.

Rather, the present study decided to conduct an additional post-hoc regression analysis with a new covariate of non-positional bigram frequency of primes. It was deemed best to re-examine the data with a new covariate, as the letter similarity effect had already been minimized in the data, and the inclusion of a covariate could account for the effect related to the bigram frequency of primes without introducing another confounding effect.

4.4.2. Results

The descriptive statistics remained consistent with Table 9 in the global latency analysis of the word targets, as this new post-hoc regression only introduced a new covariate, not a fixed factor.

A new regression model included all the factors of the previous global latency analysis: the fixed effects of group and prime type as well as a covariate of mean-centered log-transformed word frequency. The new model introduced a new covariate: mean-centered non-positional bigram frequency of a prime. Since this new covariate was on a numerically large scale, they were divided by 1,000 in order to obtain easily interpretable regression coefficients. Centering was performed instead of standardization to enhance the interpretability of the regression coefficients, especially given that the covariates were constructed to interact with the group variable (Afshartous & Preston, 2011). Specifically, the following formula was used: glmmTMB (Reaction_Time ~ 1 + Group * Prime_Type + Group * MeanCentered_LogFrequency + Group * MeanCentered_NonPositional_BigramFrequency + (1 | Item) + (1 | Participant), family = Gamma (link = "identity")). Table 38 presents the Type III analysis-of-variance table for the post-hoc regression.

Table 38.

Type III Analysis-of-Variance Table of the Regression (Sum-to-zero Contrast) on Reaction Times in the Word Targets (with Non-Positional Bigram Frequency of Primes Factored In)

	χ^2	df	p	
(Intercept)	6,228.68	1.00	<.001	***
Group	0.45	1.00	0.501	
Prime Type	369.51	3.00	<.001	***
Mean-centered Log(Frequency)	19.42	1.00	0.000	***
Mean-centered Bigram-Freq-of-Prime	5.29	1.00	0.021	*
Group : Prime Type	21.35	3.00	0.000	***
Group : Log(Frequency)	6.70	1.00	0.010	*
Group : Mean-centered Bigram-Freq-of-Prime	8.64	1.00	0.003	**

Note. Bigram-Freq-of-Primes = non-positional bigram frequency of a prime

The new regression model confirmed a significant main effect of prime type, $\chi^2(3) = 369.51$, $p < 0.001$. However, the main effect of group was statistically non-significant, $p > 0.50$. The factor of prime type interacted significantly with the factor of group, $\chi^2(3) = 21.35$, $p < 0.001$). Table 39 presents the coefficient table for this new regression.

The covariate of log-transformed word frequency was also statistically significant, $\chi^2(1) = 19.42$, $p < 0.001$. This covariate interacted significant with the factor of group, as well, $\chi^2(1) = 6.70$, $p < 0.05$. By an increase of a single unit of log-transformed word frequency, the native speakers showed a significant decrease of 9.14 ms, $z = -3.12$, $p < 0.01$, and the performance of the L2 learners decreased further by 5.68 ms compared to that of the native speakers, $z = -2.59$, $p < 0.05$. These regression coefficients are numerically similar to those in the global analysis (L1: 9.15 ms; L2: 5.31 ms), although a statistical comparison would be needed to confirm if there is a statistically significant difference.

Table 39.

Coefficients of the Regression (Dummy-coded Contrast) on Reaction Times in the Word Targets (with Non-Positional Bigram Frequency of Primes Factored In)

	b	SE(b)	*z*	*p*	
(Intercept)	635.15	11.91	53.33	<.001	***
Mean-centered Log(Frequency)	-9.14	2.93	-3.12	0.002	**
Mean-centered Bigram-Freq-of-Prime	0.01	0.27	0.05	0.961	
Prime Type (TR)	19.41	3.89	4.99	<.001	***
Prime Type (SB)	43.89	4.38	10.01	<.001	***
Prime Type (UN)	32.74	3.93	8.33	<.001	***
Group (L2)	0.25	16.53	0.02	0.988	
Group (L2) : Mean-centered Log(Frequency)	-5.68	2.19	-2.59	0.010	*
Group (L2) : Mean-centered Bigram-Freq-of-Prime	0.98	0.33	2.94	0.003	**
Group (L2) : Prime Type (TR) [a]	5.33	5.53	0.96	0.335	
Group (L2) : Prime Type (SB) [a]	12.31	6.09	2.02	0.043	*
Group (L2) : Prime Type (UN) [a]	24.88	5.66	4.40	0.000	***

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; Bigram-Freq-of-Primes = non-positional bigram frequency of a prime

[a] The interaction terms were referenced to the ID's base level due to the use of a dummy-coded contrast. For an explanation of using a dummy-coded contrast in coefficient estimation, refer to the section of 3.4.2. Statistical Methods.

Notably, the covariate of non-positional bigram frequency of primes was statistically significant, $\chi^2(1) = 5.29$, $p < 0.05$. Additionally, this new covariate had a significant interaction with the factor of group, $\chi^2(1) = 8.64$, $p < 0.01$. A post-hoc analysis of the interaction revealed that only the L2 learners were significantly affected by the non-positional bigram frequency of primes. By an increase of 1,000 in the non-positional bigram frequency of primes, the native speakers were slowed down only by 0.01 ms, which was statistically non-significant, $z = 0.05$, $p > 0.90$. However, the L2 learners showed a significant increase of 0.98 ms by an increase of 1,000 in the non-positional bigram frequency of primes, $z = 2.94$, $p < 0.01$.

A pair-wise post-hoc analysis of the two-way interaction between group and prime type replicated the previous findings in the global latency analysis of words. In the native speakers of English, a 29.85 ms facilitative effect of repetition priming was still significant, measured by the difference between the unrelated (M = 664.03 ms, SD = 168.15), and identity conditions (M = 634.17 ms, SD = 180.37), $z = 8.33$, $p < 0.001$. In the Korean L2 learners of English, a significant facilitative effect of 58.47 ms was also proven to be significant between the unrelated (M = 692.79 ms, SD = 177.45), and identity conditions (M = 634.32 ms, SD = 166.21), $z = 14.17$, $p < 0.001$.

Even with a new covariate being considered, both groups presented significant letter transposition advantages. The native speakers had a significant advantage of 25.18 ms between the letter substitution (M = 676.67 ms, SD = 168.88) and letter transposition conditions (M = 651.49, SD = 167.29), $z = 5.65$, $p < 0.001$. Likewise, the L2 learners had a significant advantage of 28.92 ms between the letter substitution (M = 685.66 ms, SD = 171.01) and letter transposition conditions (M = 656.75 ms, SD = 170.50), $z = 7.12$, $p < 0.001$.

The letter transposition costs were also significant in the native speakers and L2 learners. The results found that the native speakers' cost of -17.31 ms was significant between the identity (M = 634.17 ms, SD = 180.37) and letter transposition conditions (M = 651.49 ms, SD = 167.29), $z = -4.99$, $p < 0.001$. The L2 learners' cost of -22.43 ms was still significant between the identity (M = 634.32 ms, SD = 166.21) and letter transposition conditions (M = 656.75 ms, SD = 170.50), $z = -6.28$, $p < 0.001$.

Significant facilitative effects of letter transposition priming were confirmed in the new regression model. The native speakers had a significant effect of 12.54 ms between the unrelated (M = 664.03 ms, SD = 168.15) and letter transposition conditions (M = 651.49 ms, SD = 167.29), $z = 3.31$, $p < 0.01$. The L2 learners revealed a significant effect of 36.04 ms between the unrelated (M = 692.79 ms, SD = 177.45) and letter transposition conditions (M = 656.75 ms, SD = 170.50), $z = 7.89$, $p < 0.001$.

The native speakers were significantly slower in the letter substitution condition (M = 676.67 ms, SD = 168.88) by 42.49 ms than in the identity condition (M = 634.17 ms, SD = 180.37), $z = 10.01$, $p < 0.001$. A significant decrease of 51.34 ms was also confirmed in the L2 learners between the letter substitution (M = 685.66 ms, SD = 171.01) and identity condition (M = 634.32 ms, SD = 166.21), $z = 12.61$, $p < 0.001$.

Notably, the -12.64 ms inhibitory effect of letter substitution in the native speakers was marginally significant between the unrelated (M = 664.03 ms, SD = 168.15) and letter substitution conditions (M = 676.67 ms, SD = 168.88), $z = -2.44$, $p = 0.070$. The 7.13 ms facilitatory effect of letter substitution in the L2 learners failed to reach a significance level between the unrelated (M = 692.79, SD = 177.45) and letter substitution conditions (M = 685.66, SD = 171.01), $z = 0.30$, $p = 0.990$.

The results replicated the findings of the previous global latency analysis; the same significant effects were present in both groups, except for the native speaker's marginally significant difference between the letter substitution and unrelated conditions. Importantly, a covariate of bigram frequency was non-significant in the native speakers, and the inhibitory effect of letter substitution did not entirely disappear in the native speakers; if the data of the native speakers were only analyzed, it was unlikely that the covariate of bigram frequency would be necessary, as it merely reduced the effect size. The reaction times of the native speakers were not primarily reduced by the low non-positional bigram frequency of primes.

Rather, it was plausible that the prime lexicality was the primary cause of the native speakers' slower responses to the letter substitution condition compared to the unrelated condition. Table 40 rearranges the native speakers' data by prime lexicality and target-relatedness of primes.

Table 40.

Native Speakers' Reaction Times in the Word Targets: Prime Type Recategorized by Prime Lexicality and Target-Relatedness [a]

Target-Relatedness [a]	Prime Lexicality		
	Word	Nonword	
Related	Identity 634.17	Letter Transposition 651.49	ID-TR -17.32 ***
Unrelated	Unrelated 664.03	Letter Substitution 676.67	UN-SB -12.64 [b]
	UN-ID 29.86 ***	SB-TR 25.18 ***	

Note. *** $p < 0.001$; ID = identity; TR = letter transposition; UN = unrelated; SB = letter substitution.

[a] Relatedness in terms of whether the primes facilitate the lexical retrieval of the targets.

[b] Significant at $p < 0.05$ in the global analysis.

In Table 40, each condition of word primes resulted faster responses than the corresponding condition of nonword primes. That is, target-related word primes (the identity condition) were significantly faster than the target-related nonword primes (letter transposition condition). Likewise, the target-unrelated word primes (unrelated condition) demonstrated faster responses than the target-unrelated nonword primes (letter substitution condition). Although the post-hoc regression showed a marginally significant difference between the letter substitution and unrelated conditions, the data of the native speaker, as previously noted, did not necessitate an additional covariate of bigram frequency. Therefore, it is probable that the difference between letter substitution and unrelated conditions was indeed significant, as indicated by the earlier global analysis.

Thus, the inhibitory effect of letter substitution observed in the native speakers, relative to the unrelated condition, was primarily due to prime lexicality, rather than the low non-positional bigram frequency of the letter-substituted primes. It should also be noted that the inclusion of a bigram frequency covariate of primes did not drastically change the observed effects.

Chapter 5. Discussion

5.1. Priming Effects in the Native Speakers of English

5.1.1. Replication of the Previous Findings in L1 Studies

The present study investigated the behavioral responses in the native speakers of English for two purposes. First, the experiment was designed to replicate the traditional findings in the L1 studies. Second, the aim of the experiment was to obtain a control data set for the analysis of the Korean L2 learners of English. To these ends, four priming conditions were created: identity, letter transposition, letter substitution, and unrelated.

The identity condition used the same stimuli as the targets, but in lowercase. The unrelated condition used stimuli different from the targets; the word targets were primed by unrelated words, and the nonword targets by unrelated nonwords. In the word targets, the primes in both the identity and unrelated conditions were consistently word primes. For the remaining two conditions, primes consisted of non-lexical letter sequences that included two word-internal letters designed to disturb the lexical activation of targets. In the letter transposition condition, two internal letters of the targets were switched, violating the information of letter position. Conversely, the letter substitution condition involved two internal letters that disrupted the information of letter identity. The findings from the native speakers will be discussed in the following order: (1) repetition priming effect, (2) letter transposition advantage, (3) letter transposition cost, (4) the difference between the letter transposition and unrelated conditions, and (5) the difference between the identity and letter substitution, as well as the difference between the letter substitution and unrelated condition in the next section.

First, the native speakers demonstrated a significant facilitation of 29.86 ms between the identity and unrelated conditions, consistent with the well-established effect of repetition priming. This facilitation did not emerge from the latency analysis of the word targets. Additionally, the latency analysis of the nonword targets discovered a significant repetition priming effect of 5.80 ms.

Second, the present study successfully replicated the letter transposition advantage in the previous L1 studies. The native speakers showed a significant advantage of letter transposition by 25.18 ms over letter substitution.

The size of letter transposition advantage in the present study lies within the range of the findings of previous literature in L1. In English, the letter transposition advantage has been estimated to be around 20-30 ms: 20 ms in Colombo et al. (2020), 23-28 ms in Lupker et al. (2012), 25-33 ms in Meade et al. (2021), 21 ms in Norris et al. (2010), and 11-44 ms in Perea and Lupker (2003). Notably, this study found a comparable advantage of letter transposition, even in a highly frequent range of word frequency, consistent with previous research.

The presence of a significant and comparable letter transposition advantage indicates that successful preparation of experimental conditions, where the selected word stimuli are adequate for inducing the native speakers to demonstrate their position-flexible processing abilities in visual word recognition. Furthermore, the advantage of letter transposition is observed in the latency analysis of the word targets, not in the analysis of the nonword targets. This clearly indicates the lexical origin of the observed letter transposition advantage.

Third, there were significant letter transposition cost of -17.31 ms in the native speakers. The size of this cost is also comparable to the previous findings. In L1 studies, the letter transposition cost ranges between -8 ms and -32 ms: -22 ms in Norris et al. (2010), -32 to -27 ms in Perea and Acha (2009), -17 ms in Perea and Lupker (2004), -30 ms in Perea and Carreiras (2008), -30 ms in Perea et al. (2012), -19 ms in Yang and Lupker (2020), and -24 to -8 ms in Yang et al. (2020).

Once more, the significant and comparable cost of letter transposition confirms that the experimental conditions are well-organized to reveal the native speakers' sensitivity to the correct letter position. It is also worth noting that the native speakers show a significant cost of -1.22% in the error analysis of the word targets, but no such cost in the analyses of the nonword targets. This further suggests that the observed sensitivity to letter position (precision) is lexical in origin.

Fourth, the present study discovered a significant facilitative effect of letter-transposed primes compared to unrelated word primes.

The average size of this effect is estimated to be 29.85 ms in the present study, which is within the range of 14-35 ms in Perea and Lupker (2003). However, the effect of the present study seems relatively smaller than 62-63 ms reported by Forster et al. (1987). These sizes may not be directly comparable due to the use of different stimuli, but it can be suggested that the presentation duration of primes might be relevant: 51 ms in the present study, 40 ms in Perea and Lupker (2003), and 60 ms in Forster et al. (1987).

One might point out that the effect in Forster et al. (1987) is still large, and the difference of 10-20 ms seemed negligible given the presentation duration of primes. Here, it is worth mentioning that the present study chose a presentation duration of 50 ms (and the actual presentation of 51 ms) because many participants noticed the letter-transposed primes at the SOA of 67 ms; in other words, the presentation duration of 60 ms, which Forster et al. (1987) employed, might have been the possibly longest duration for letter-transposed primes, which most benefited the participants. Still, it remains open to what caused the longer facilitative effect in Forster et al.

(1987).

Significantly, the difference between the letter transposition and unrelated conditions manifested primarily in the latency analysis of the word targets; the corresponding difference in the nonword targets were small (1.54 ms) and marginal. This finding, paralleling the advantage and cost of letter transposition, points to a lexical origin for the significant facilitative effect of letter transposition relative to the unrelated condition.

Fifth, significant differences of 42.50 ms (reaction time) and 1.52% (accuracies) existed between the identity and letter substitution conditions. No such differences were observed in the nonword targets. The difference in latency appears smaller than 59 - 63 ms in Perea and Lupker (2003). While this may require further investigation in future research, it is worth noting that this difference has not been the primary focus of research in the L1 visual word recognition; for this difference by itself has little impact on understanding the flexible yet precise processing abilities of native speakers.

Thus, the data from the native speakers prove sufficient as the control data, demonstrating the flexible yet precise processing abilities of the native speakers, especially given the comparable advantage and cost of letter transposition. Importantly, the present study contributes to existing L1 research by demonstrating comparable advantage and cost of letter transposition even within highly frequent words. As explained in the materials section, many previous studies have used words with a word frequency of less than 80 per million for the investigation of letter transposition. The present study selects highly frequent words, which are appropriate for L2 learners with limited experience in L2. Yet, the native speakers demonstrate robust effects of letter transposition even in the highly frequent words. This is a noticeable replication, especially in light of the fac that that high-frequency words produce significantly faster responses than low-frequency words (c.f.

Keuleers et al., 2012; New, Ferrand, Pallier, & Brysbaert, 2006); the expected size of effect can be statistically small to detect due to fast reaction times.

5.1.2. Slower Responses to Letter Substitution than Unrelated Words

One of the interesting findings in the present study is a significantly delayed response in the letter substitution condition compared to the unrelated condition. In the previous research, letter-substituted primes have served as the baseline items for letter transposition advantage, as they share the same lexical status of nonword, and they have the same degree of orthographic overlaps at word-initial and word-final positions as letter-transposed primes. Furthermore, earlier research presumed that letter-substituted primes do not effectively facilitate the recognition of target words.

Then, one may wonder how the letter substitution condition in the present study is significantly slower than the unrelated condition, given that both provide irrelevant information for the lexical activation of targets. Here, a question can be raised regarding the letter manipulation method of the present study, specifically whether the unusual letter sequences in the letter substituted primes played a significant role in the observed difference between the letter substitution and unrelated conditions.

Therefore, the present study conducted a post-hoc regression analysis with a covariate of non-positional bigram frequency of a prime. The regression results revealed that the low bigram frequency of primes was not the primary cause of slow reaction times in the native speakers. Even if a statistically non-significant covariate of bigram frequency was included, a marginally significant difference ($p = 0.070$) was still found between the unrelated and letter substitution conditions.

As suggested earlier, the prime lexicality likely contributed to slower reaction times in the letter substitution condition compared to the unrelated condition. As shown Table 40 above, the native speakers exhibited a strong effect of prime lexicality; the target-related word primes (the identity condition) lead to significantly faster responses than the target-related nonword primes (letter transposition condition) while the target-unrelated word primes (unrelated condition) had faster responses than the target-unrelated nonword primes (letter substitution condition).

Indeed, the present study is not entirely novel in reporting delayed reaction times in the letter substitution condition relative to the unrelated condition. One of the pioneering studies by Perea and Lupker (2003) included unrelated word primes as in Table 41.

Table 41.

Comparison of Native Speakers' Results Between the Present Study and Perea and Lupker (2003)

Word Primes		Nonword Primes		UN-SB
ID (target-related[a])	UN (target-unrelated[a])	TR (target-related[a])	SB (target-unrelated[a])	
		Present Study		
634.17	664.03	651.49	676.67	-12.64 *
		Perea and Lupker (2003): Experiment 1		
523	570	556	586	-16 [b]
		Perea and Lupker (2003): Experiment 3		
527	577	542	586	-9 [b]

Note. * $p < 0.05$; ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated. The present study included only relevant excerpts from Perea and Lupker (2003)'s data; the two experiments were independently conducted, and they were not identical.

[a] Relatedness in terms of whether the primes facilitate the lexical retrieval of the targets.

[b] Not examined in the statistical analyses

In Perea and Lupker (2003)'s, the prime lexicality appears to have an impact on the results;

target-related word primes produced faster responses than target-related nonword primes while target-related nonword primes resulted in faster reaction times than target-unrelated nonword primes. While Perea and Lupker (2003) did not statistically analyze these differences due to being outside their primary interest, it is noticeable that the effect of prime lexicality appears to persist across their two different sets of tests. Furthermore, the -12.64 ms difference in the present study, between the letter substitution and unrelated conditions, aligns well with the -9 ms to -16 ms range in Perea and Lupker (2003).

Additionally, Perea and Lupker (2003) intentionally selected the substituting letters that were visually similar to the original (substituted) letters. Therefore, their manipulation was even more challenging than the present study's; thus, a high level of precision in letter identification was required. Perea and Lupker (2003)'s results were still consistent with those of the present study, particularly in terms of the difference between the letter substitution and unrelated conditions. This indicates that a specific letter manipulation method was not the primary cause of significantly delayed responses in the letter substitution condition relative to the unrelated condition.

Therefore, it is plausible to conclude that for the native speakers, the letter-substituted primes demanded more processing time than unrelated word primes, not simply due to their inefficient relation to the targets, but also because prime lexicality affected the lexical processing.

5.2. Priming Effects in Korean L2 Learners of English

5.2.1 Observed Effects

As in the previous section, the findings from the L2 learners will be discussed in the following order: (1) repetition priming effect, (2) letter transposition advantage, (3) letter transposition cost, (4) the difference between the letter transposition and unrelated conditions, and

(5) the difference between the identity and letter substitution, and (6) the difference between the letter substitution and unrelated condition. Additionally, this section will discuss the similarities and differences between the native speakers and the L2 learners.

5.2.1.1. Significant Repetition Priming Effect

The effect of repetition priming provides one of the key examinations of experimental priming conditions, particularly concerning whether a brief presentation of primes can actually facilitate the target recognition in participants (Forster & Davis, 1984; Forster et al., 1987). The Korean L2 learners of English in the present study exhibited significant effects of repetition priming, indicating that they processed briefly-presented stimuli in such a way that their lexical decisions could be expedited.

In the global latency analysis, a significant effect of 58.47 ms was observed in the word targets. This effect was statistically significantly larger compared to the corresponding effect observed in the native speakers (29.86 ms, 1.96 times larger). In the nonword targets, the L2 learners also exhibited a significant effect of 11.70 ms, which did not differ significantly that of the native speakers (5.80 ms). Additionally, the global error analysis of the word targets discovered a significant effect of 2.39%, a pattern absent in the native speakers. The accuracy data of the nonword targets showed no significant effect of repetition priming.

The L2 subset latency analysis of the word targets discovered significant effects of 53.41 ms and 63.38 ms in the higher and lower proficiency groups, respectively; these effects were not statistically different. The error analysis of the word targets also confirmed significant effects of 2.47% and 2.32% in the two groups, respectively, with no statistical difference between them. A significant effect of repetition priming in the nonword targets. The significant effect of repetition priming in the nonword targets, initially observed in the global latency analysis, was reduced to a marginally significant effect in the subset analysis.

Therefore, it can be concluded that the L2 learners, across both proficiency groups, showed a significantly larger effect of repetition priming in the reaction times to the word targets compared to the native speakers. Notably, this difference between the native speakers and the L2 learners extended to the accuracies in the word targets. Only the significant repetition priming effects in the latency analysis of the nonword targets were indistinguishable between the two groups.

5.2.1.2. Significant Letter Transposition Advantage

The present study discovered a significant advantage of letter transposition in the Korean L2 learners of English. In the global analysis of the word targets, the advantage was estimated to be 28.92 ms, which was statistically non-significantly different from the native speakers' advantage of 25.18 ms. The size of the L2 learners' letter transposition advantage fell in the range of 20-30 ms in the previous L1 studies.

The L2 subset analysis of the word targets found a significant advantage of 35.69 ms in the lower proficiency group and a significant advantage of 20.92 ms in the higher proficiency group. These differences did not statistically significantly differ from each other, as no two-way interaction was found between proficiency group and prime type. Despite the lack of statistical significance, the lower proficiency group (35.69 ms) had a numerically larger advantage than the higher proficiency group (20.92 ms). This observed pattern is in contrast to the previous L1 literature, which generally predicts learners with lower proficiency to have a smaller advantage of letter transposition than those with higher proficiency.

No significant advantage of letter transposition was observed in the error analysis of the word targets, nor in the latency or error analysis of the nonword targets. The absence of a comparable significant effect in the nonword targets suggests a lexical origin for the letter transposition advantage observed in the L2 learners' responses to the word targets.

5.2.1.3. Significant Letter Transposition Cost

A significant cost of letter transposition was confirmed in the Korean L2 learners of English, particularly in the latency analyses. The global analysis of the word targets revealed a significant cost of -22.43 ms. The L2 subset analysis further identified a significant cost of -21.20 ms in the lower proficiency group, and -23.94 ms in the higher proficiency group. The observed costs of letter transposition were consistent with the -8 ms to -32 ms range reported in the prior L1 studies. Importantly, the cost of -22.43 ms did not statistically differ from the cost of -17.31 ms observed in the native speakers.

However, the L2 learners showed several important differences when compared to the native speakers in the present study, and the L1 children in the previous developmental studies. First, the native speakers displayed a significant letter transposition cost (-1.22%) in the accuracy data of the word targets, while the L2 learners did not. Second, more developed children in the previous literature showed a larger cost compared to less developed children; a cost increased with language development.

Still, the significant cost of letter transposition was found only in the word targets, which implies that this phenomenon, too, has a lexical origin even in the L2 learners.

5.2.1.4. Faster Responses to Letter Transposition Compared to the Unrelated Condition

The Korean L2 learners of English showed significantly faster responses in the letter transposition condition than in the unrelated condition. In the global latency analysis of the word targets, these learners were significantly faster by 36.04 ms in the letter transposition condition. The size of this effect falls near the range of 14 ms - 35 ms documented in Perea and Lupker (2003).

However, a custom contrast analysis confirmed that the L2 learners' effect of 36.04 ms was statistically significantly greater than the native speakers' effect of 12.54 ms (2.87 times).

The L2 subset analysis of the word targets revealed that the higher proficiency group had an effect of 29.47 ms, while the lower proficiency group showed an effect of 42.18 ms. However, it is inconclusive whether these effects in the two proficiency groups were statistically significantly different, as no significant interaction was found between prime type and proficiency group.

It is likely that a lexical origin might have resulted in the L2 learners' faster response to letter transposition compared to the unrelated condition; the corresponding differences of 6.85 ms in the nonword targets were only marginally significant.

5.2.1.5 Faster Responses to Identity Compared to Letter Substitution

Significantly faster responses to the identity condition were observed in the Korean L2 learners of English, compared to their responses to letter substitution. These learners demonstrated a significant processing advantage of 51.34 ms for the identity primes over the letter-substituted primes in their responses to the word targets. However, this effect did not statistically differ from that of the native speakers (42.50 ms).

Nevertheless, the performances of the native speakers and the L2 learners were not entirely identical for this effect. The error analysis of the word targets revealed that no significant difference emerged between the identity and letter substitution conditions for the L2 learners, whereas the native speakers did.

In the L2 subset latency analysis of the word targets, the higher proficiency group demonstrated a significant difference of 44.86 ms, while the lower proficiency group had a significant difference of 56.89 ms between the identity and letter substitution conditions. These differences in reaction time were not statistically different between the two proficiency groups.

An interesting pattern emerged from the L2 subset error analysis of the word targets. The higher proficiency group displayed a significant difference of 2.37% between the identity and letter substitution condition, parallelling the native speakers' performance (1.52%). Conversely, the lower proficiency group failed to exhibit such a significant difference.

As with the previously discussed effects, a significant difference between identity and letter transposition was observed exclusively in the analysis of the word targets, suggesting its lexical origin. No significant difference was shown in the analyses of the nonword targets.

5.2.1.6. Faster Responses to Letter Substitution Compared to the Unrelated Condition

The most noticeable difference between the native speakers and Korean L2 learners of English was found in the comparison between the letter substitution and unrelated conditions. In the global latency analysis of the word targets, the L2 learners showed faster responses in the letter substitution condition (7.13 ms) than in the unrelated condition although this difference failed to reach statistical significance. Conversely, the native speakers responded significantly slower in the letter substitution condition (-12.64 ms) than in the unrelated condition. Notably, a custom contrast analysis revealed that the 7.13 ms difference in the L2 learners differed significantly from the -12.64 ms difference in the native speakers.

Another interesting pattern emerged from the global error analysis of the word targets. Although both the native speakers and the L2 learners did not demonstrate a significant difference between the letter substitution and unrelated conditions, the 1.32% difference in the L2 learners was statistically significantly different from the -0.93% difference in the native speakers.

Additionally, the L2 subset error analysis of the word targets discovered that the lower proficiency group, not the higher proficiency group, performed significantly better (2.41%) in the letter substitution condition compared to the unrelated condition. This pattern was not observed in the native speakers.

Furthermore, determining whether the observed patterns in the L2 learners had a lexical origin remains undecisive given that the global analysis of both word and nonword targets found no statistically significant differences between the letter substitution and unrelated conditions.

5.2.1.7. Summary of Primary Factors and Nativelikeness in the Observed Effects

Table 42 summarizes the primary factors for the observed effects that are discussed earlier, with key comparisons between the native speakers and Korean L2 learners of English. The specific size of each effect and its statistical inference are omitted in this table, as they were provided in the aforementioned Table 36.

Table 42.

Primary Factors (Lexical / Sublexical) for the Observed Effects and the Comparison between the Native Speakers and the L2 Learners

Effect	Group		Comparison
	Native	L2	
Repetition Priming	Lexical and sublexical	Lexical and sublexical	Native < L2
Letter Transposition Advantage	Lexical	Lexical	Similar
Letter Transposition Cost	Lexical	Lexical	Similar
UN vs. TR	Lexical	Lexical	Native < L2
SB vs. ID	Lexical	Lexical	Similar
UN vs. SB	Lexical	? [a]	Native < L2

Note. UN = unrelated; TR = letter transposition; SB = letter substitution; ID = identity.

[a] No significant difference was observed in both word targets and nonword targets

In the native speakers, all the observed effects are lexical in origin, except for the repetition priming, as significant effects only appear in the word targets. In the L2 learners, four effects are estimated to be primarily driven by lexical retrieval: (1) letter transposition advantage, (2) letter transposition cost, (3) the difference between the letter transposition and unrelated conditions, and (4) the difference between the identity and letter substitution conditions. Similar to the native speakers, the repetition priming effect in the L2 learners has both lexical and sublexical origins, supported by significant effects in both word and nonword targets. However, in the comparison between the letter substitution and unrelated conditions, the L2 learners exhibit no statistically significant differences in both word and nonword targets, contrasting with the native speakers' performance.

The L2 learners yield statistically non-significant differences in (1) letter transposition advantage, (2) letter transposition cost, and (3) the difference between identity and letter substitution compared to the native speakers. On the other hand, the effects in the L2 learners are significantly larger than the native speakers in (1) repetition priming, (2) the difference between letter transposition and unrelated conditions, and (3) the difference between letter substitution and unrelated conditions. Specifically, the letter substitution condition demonstrates statistically non-significant facilitation compared to the unrelated condition, which contrasts with a statistically significant inhibition observed in the native speakers.

Table 43 below provides a key summary of the nativelikeness of the observed effects across the two proficiency groups. As indicated in Table 42, the letter transposition advantages are nativelike in both groups. Regarding the letter transposition cost, the L2 learners are nearly nativelike, except that the native speakers, not the L2 learners, show a significant cost in the error analysis of the word targets. In contrast, repetition priming, the difference between the letter transposition and unrelated conditions, and the difference between the letter substitution and unrelated conditions are all non-nativelike in both proficiency groups.

The difference between two proficiency group exists in the difference between the identity and letter substitution conditions. The higher proficiency group, like the native speakers, showed a significant difference between the two conditions in both the latency and error analyses of the word targets. However, the lower proficiency group showed a significant difference only in the latency analysis of the word targets.

Table 43.

Nativelikeness of the Observed Effects across the Two Proficiency Groups

Effect	Proficiency		Note
	Higher	Lower	
Repetition Priming	Non-nativelike	Non-nativelike	Larger effect [a]
Letter Transposition Advantage	Nativelike	Nativelike	
Letter Transposition Cost	Nearly Nativelike	Nearly Nativelike	
UN vs. TR	Non-nativelike	Non-nativelike	Larger effect [a]
SB vs. ID	Nativelike	Nearly Nativelike	Differences in Error
UN vs. SB	Non-nativelike	Non-nativelike	Larger effect [a]

Note. UN = unrelated; TR = letter transposition; SB = letter substitution; ID = identity.

[a] Larger than the native speakers' effect (see Table 42)

5.3. Nuanced Performance of the L2 Learners

5.3.1. Confounding Nativelike and Non-Nativelike Patterns

The finding of the present study reveals a nuanced picture, as the Korean L2 learners of English show both nativelike and non-nativelike patterns.

Significant similarities exist between the native speakers and the L2 learners in terms of letter transposition advantage and cost. The measured advantages of letter transposition in the word targets are statistically non-significant between the native speakers and the L2 learners.

Additionally, statistically comparable costs of letter transposition in the word targets exist in the reaction times of both groups. In the comparison between the identity and letter substitution conditions, the high proficiency group has the same pattern as the native speakers: significant differences in both latency and error analysis of the word targets.

These similarities strongly support one of the hypotheses proposed earlier in the present study: native-like flexible yet precise lexical processing in L2. Not only did the Korean L2 learners of English demonstrate a significant advantage of letter transposition in English, but also their advantage was statistically comparable to that of the native speakers. Furthermore, a significant cost of letter transposition in reaction time was observed in these learners, which was statistically comparable to the cost observed in the native speakers. All of the observed advantage and cost in the L2 learners is consistent with the findings in the previous literature in L1.

However, such similarities do not indicate that the performances of the L2 learners were identical to those of the native speakers. Rather, non-nativelike patterns were observed in (1) repetition priming, (2) the difference between the letter transposition and unrelated conditions, and (3) the difference between the letter substitution and unrelated conditions. These non-nativelike patterns cannot be easily dismissed due to three reasons. First, the identity condition, used in the measurement of repetition priming, was also utilized to estimate the letter transposition cost. Second, the letter transposition condition itself led to significantly different responses compared to the unrelated condition across the two groups. Third, the letter substitution condition served as the baseline for the letter transposition advantage.

Hence, a more detailed and nuanced explanation is needed before asserting that the L2 learners in the present study possess the same flexible yet precise lexical processing abilities in their L2 as the native speakers.

5.3.2. Possible Explanations on the Observed Effects

5.3.2.1. Possibility of L1 Transfer

Since the performances of the native speakers are not entirely identical to that of the L2 learners, one may suspect that the L2 learners' performances in certain effects are merely superficial, resembling the native speakers because these effects are readily transferable from L1. Put otherwise, one may raise question of whether letter transposition advantage and cost are indeed nativelike. If these learners' L1 has orthographic traits that demand both high precision in letter identity and high flexibility in letter position simultaneously, then the abilities related to letter transposition might transfer from L1 to L2, contributing to nativelike performances in letter transposition advantage and cost.

Indeed, the orthography of Korean, the L1 of the L2 learners in the present study, uses a more complex system for letter encoding compared to English or the Latin script. The identification of letters in Korean requires high precision particularly for vowels, as phonemes can be differentiated by variations in the horizontal or vertical alignments of a few straight lines[15]. Furthermore, the Korean script both left-to-right and top-to-bottom (or top-left-to-bottom) orientations, which requires a more flexibility in letter position. For instance, even the leftmost letter can be interpreted as the coda following a vowel, or the last consonant of a syllable if it occupies the bottom position. Therefore, it might be possible that the Korean learners of English had well-developed processing abilities characterized by both high precision in letter identity and high flexibility in letter position.

However, the L1 transfer cannot explain why the L2 learners showed the different patterns

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[15] For instance, each letter in ㅏㅓㅗㅜ represents [a, ʌ, o, u], respectively. Line lengths are not the primary factor for identification; the horizontal line, for example, can be elongated.

compared to the native speakers in other effects such as repetition priming, the difference between the letter transposition and unrelated conditions, and the difference between the letter substitution and unrelated conditions. Furthermore, there is counter-evidence against this account. Witzel et al. (2011) discovered that Japanese L2 learners of English showed nearly the same advantage of letter transposition (52 ms and 53 ms) in L1 Japanese across all the orientation conditions. This result was expected considering Japanese is often written in the vertical direction, which requires the flexibility even in the vertical position. However, the same learners demonstrated a smaller advantage of letter transposition in the vertical presentation condition than in horizontal presentation condition when the stimuli were English words. Based on the results, Witzel et al. (2011) concluded that the processing abilities of letter position were language-independent. Furthermore, Lee and Taft (2009) discovered that Korean speakers exhibited higher precision in letter positions when processing Korean stimuli compared to English speakers processing English words, indicating that the interplay of left-to-right and top-to-bottom in Korean rather led to position-specific activation of letters. Then, the L2 flexibility observed in the present study. The studies of Witzel et al. (2011) and Lee and Taft (2009), therefore, suggest that the L2 learners' flexibility observed in the present study is a characteristic developed within L2..

Considering the observed patterns in the present study, it is unlikely that the L2 learners achieved nativelike performances in the effects related to letter transposition mainly due to L1 transfer. This, however, does not rule out the possibility of L1 transfer; further research is needed to clearly identify how L1 transfer is involved, especially regarding the effects of letter transposition.

5.3.2.2. Lexical Tuning Hypothesis

One of the influential theories regarding the development of visual word recognition, the lexical tuning hypothesis by Castles et al. (2007), may provide explanations regarding a larger repetition priming effect and the non-nativelike patterns observed when comparing the letter transposition condition to the unrelated condition and the letter substitution condition to the unrelated condition in the L2 learners.

This hypothesis assumes that (1) lexical processing is fundamentally flexible, and (2) a formal overlap, especially for developing learners, can be sufficient to provide a significant facilitation at the the verification stage of lexical access (i.e. only the word targets show facilitation), but (3) formal overlap has a limited role in lexical activation, which depends on the size of vocabulary.

In this hypothesis, the vocabulary of developing learners is sparsely represented in such a way that a strong verification process may not be always required to correctly activate lexical items. For instance, these learners may not know words like 'plait,' or 'plaid,' while they have acquired the word 'plain.' Therefore, the lexical activation process of these learners might not be fine-tuned to activate words with no orthographic competitors in the mental lexicon; even a sequence of letters like 'pla' or 'plai' is sufficient to facilitate the lexical activation of 'plain.'

Hence, letter-substituted primes may have a processing advantage over unrelated primes in developing learners. Additionally, letter-transposed primes are processed even faster than letter-substituted ones due to the perfect match of information regarding letter identity. Identity primes are, of course, processed the fastest due to their perfect visual match with their targets.

As vocabulary size increases with language development, developing learners cannot rely mainly on formal overlap to activate the correct words because orthographically similar lexical items are present in the mental lexicon. Therefore, the facilitation based on formal overlap becomes less pronounced. This transition enables developing learners, especially L1 children, to develop adult-like lexical processing based on the densely represented vocabulary. Finally, adult native speakers no longer process letter-substituted primes faster than unrelated primes due to their precision in lexical retrieval.

This hypothesis may generally account for the results from the L2 learners in the present study by assuming that they are developing learners with limited vocabulary. Thus, these learners may still depend on formal overlap in such a way that a strong (larger than adult native speaker) repetition priming effect occurs as well as a significant advantage of letter transposition. A significant cost of letter transposition is also expected given that identity primes offer a better formal match than letter-transposed primes. It is predicted that the difference between letter transposition and unrelated conditions larger in these learners when compared to the native speakers, as the letter transposition results in significant formal overlap. Finally, unlike adult native speakers, the L2 learners are still susceptible to the formal overlap of letter-substituted primes, resulting in the opposing responses compared to the native speakers.

However, there remains one crucial question. This hypothesis assumes that the size of vocabulary is the decisive factor for the lexical processing abilities. Therefore, a developmental pattern of the same nature is anticipated in both L1 children and L2 learners, as they all have limited vocabulary compared to the adult native speakers. However, the letter transposition advantage in the L2 learners of the present study is not consistent with the developmental trends in L1 studies; the size of letter transposition advantage does non-significantly differ between two proficiency groups. Additionally, no significant developmental trends are observable in the present study in terms of repetition priming, letter transposition cost, or the difference between letter transposition and unrelated conditions.

5.3.2.3. Account Based on the Multiple-Route Model

The results of the present study may seem compatible with the multiple route model (Coltheart et al., 2001; Grainger et al., 2012; Grainger & Ziegler, 2011). This model assumes that lexical activation develops from highly serial processing with phonology-dependent encoding to highly flexible processing with coarse encoding. In this model, underdeveloped learners rely on serial processing of visual stimuli (i.e. the fine-grained sublexical route) as if they are exposed to a spoken language; the identification of letters occurs sequentially, which leads to phonological decoding, and ultimately to the activation of phonological representations. Skilled readers, possessing the serial processing mechanism, can develop additional processing mechanisms based on whole-word representations (i.e. the coarse-grained lexical route). This processing enables them to reduce interference from irrelevant letters in visual stimuli due to the rapid access to high-level lexical information.

Then, the observed effects in the L2 learners may be explained by assuming that their coarse-grained lexical route is relatively underdeveloped compared to the fine-grained sublexical route. More specifically, it can be presumed that the lexical retrieval of unrelated word primes is either difficult to inhibit or slow to integrate into the final decision due to underdevelopment of the coarse-grained lexical route. This can explain a larger effect of repetition priming in the L2 learners than in the native speakers. Additionally, this can account for larger differences observed between the letter transposition and unrelated conditions, and as well as between the letter substitution and unrelated conditions; all of these patterns were primarily caused by a slow lexical retrieval of unrelated nonword primes in the L2 learners. In contrast, the conditions for letter transposition advantage and cost did not involve lexical retrieval of unrelated words, leading to responses statistically comparable to those of the native speakers.

However, the account based on the multiple route model has a significant caveat; it strongly predicts that the letter transposition advantage increases with language development. In this account, the refinement of the coarse-grained lexical route is expected to enhance the facilitative effect of letter-transposed primes (Colombo, Sulpizio, & Peressotti, 2017; Hasenäcker & Schroeder, 2022; Kezilas et al., 2017; Spinelli et al., 2022; Ziegler et al., 2014). The results of the L2 learners in the present study failed to show such a developmental pattern in the letter position advantage.

5.3.2.4. Influence of Formal Similarity: Segmented Analytic Processing

In an L1 developmental study by Hasenäcker and Schroeder (2022), the researchers suggested that the effects and their interpretation might vary depending on the nature of the baseline used in the estimation of letter transposition effects. Although they did not specifically refer to the letter substitution condition, it is worth investigating what lexical processing this condition actually represented in the native speakers and the L2 learners, especially since this condition was the baseline for letter transposition advantage.

The results of the native speakers strongly suggested that the letter-substituted primes were significantly less efficient at activating target words compared to the unrelated word primes. This implies that the formal similarity of word-initial and word-final positions did non-significantly assist target recognition when two completely irrelevant letters were present. In the L2 learners, however, the letter-substituted primes were statistically non-significantly different from the unrelated word primes. Therefore, two intervening internal letters might be as detrimental as in the native speakers when the primes shared the formal similarity of word-initial and word-final positions.

This suggests that the formal similarity might have played a different role in visual word recognition between the native speakers and the L2 learners. Table 44 summarizes the formal similarity between primes and targets in terms of letter identity and letter position. The identity primes have the highest formal similarity due to the perfectly matched letter identity and position. Next, the letter transposition primes follow, having perfectly identical letters but only partially matched letter positions. Third are the letter-substituted primes, characterized by partially matched letter identity and position. The least formally similar condition is the unrelated word primes (in the word targets).

An incremental pattern, consistent with the formal similarity between primes and targets, is observed in the latency data of L2 learners; identity is faster than letter transposition, which in turn is faster than the letter substitution and unrelated words. In the accuracies, a declining tendency exists in relation to the formal similarity; the most accurate condition is identity, followed by letter transposition, then letter substitution, and lastly unrelated words. However, no such patterns are observed in the data from the native speakers.

Table 44.

Formal Similarity between Primes and Targets in Each Condition, Presented with Reaction Times and Accuracies (in Parentheses) in the Word Targets

	ID	TR	SB	UN
Letter Identity	Identical	Identical	Partially Matched	Not Similar
Letter Position	Identical	Partially Matched	Partially Matched	Not Similar
Native Speakers of English	634.17 < (99.03)	651.49 < (97.81)	676.67 > (97.51)	664.03 (98.44)
L2 Learners of English	634.32 < (97.76)	656.75 < (96.83)	685.66 = (96.69)	692.79 (95.37)

Note. ID = identity; TR = letter transposition; SB = letter substitution; UN = unrelated; < = significantly smaller than any cells on the right; > = significantly larger than any cells on the right.

These patterns clearly indicate the underlying influence of formal similarity on the L2 visual word recognition. Thus, one cannot rule out that the advantage and cost of letter transposition in the L2 learners, while statistically comparable to the native speakers, are likely influenced by the formal similarity.

These findings may suggest an alternative hypothesis: segmented analytic processing in L2. In contrast to the previously suggested letter-by-letter analysis processing hypothesis, this hypothesis does not assume strictly serial letter-by-letter lexical processing. Rather, it is the combined formal similarity of letter identity and letter position in each segment that impacts the efficiency of lexical retrieval. For instance, a letter-transposed prime of *baisc* can facilitate the recognition of its target, basic because its segments such as *bai* and *sc* have a high degree of formal similarity to their target. Notably, this analytic processing is lexical in origin, as a lack of significant effects in the nonword targets demonstrates, except for the repetition priming.

This hypothesis is not unprecedented. A recent study by Jiang and Pae (2020) suggested that a nonword stimulus (e.g. brane) might result in the erroneous activation of a real word (e.g. brain) if this nonword has high orthographic similarity to it. Jiang and Wu (2022) further raised a possibility that the processing units might be smaller in the L2 learners than in the native speakers, which leads to a (more) analytic lexical processing. Additionally, Jiang and Wu (2022) raised a possibility that the L2 lexicon is extensively consisted of formal connections based on partial forms of real words; for instance, a word *sheep* (shee-p) may be connected with a word *sheet* (shee-t) in a non-nativelike manner. These studies point to a possibility that a segment (or partial form) of a word can aid in activating lexical representations.

Hence, the notably larger repetition priming effect observed in the L2 learners, compared to the native speakers, can be attributed to both the strong influence of formal similarity and the integration of retrieved lexical representations. In contrast to the native speakers, who only suffer a significant inhibition from unrelated lexical representation, a low level of aggregated formal similarity between primes and targets might further impede the L2 learners in the unrelated word condition. This situation of the unrelated word condition likely contributes to other significantly larger differences in the L2 learners than the native speakers between the letter transposition and unrelated conditions as well as between the letter substitution and unrelated conditions.

Furthermore, the revised analytic hypothesis can explain why the L2 learners exhibit significant advantage and cost of letter transposition, statistically comparable to the native speakers. As this hypothesis does not assume a serial letter-by-letter processing, three processing segments can be hypothesized, each of which is no more than three letters long in the present study: word-initial, word-internal, and word-final. Here, only the word-internal segments (two letters long) differ between the letter transposition and letter substitution conditions. The lengths of these segments are not extremely challenging to process, particularly when only one segment differ between two conditions. Furthermore, since the letter-transposed and letter-substituted primes lack lexical representations themselves, there is no need to integrate the information from irrelevant lexical representations. Hence, the L2 learners are able to perform as efficiently as the native speakers.

The remaining question pertains to the difference between the identity and letter substitution conditions. However, it is difficult to precisely explain why the L2 learners perform in a statistically comparable manner regarding this particular difference. One possibility is that a significant difference in the L2 learners, arising from less close formal similarity, coincidentally align with a significant difference in the native speakers, whose lexical retrieval is significantly impacted by two intervening letters. The indirect evidence for this explanation is the pattern observed in the lower proficiency group in this effect; for it is not entirely identical to the pattern in the native speakers as shown in Table 43. However, this issue remains unresolved.

5.3.2.5. Formal Similarity and Prime Pronounceability

One may argue that the pronounceability of primes might have influenced the results, Specifically, most of the letter-transposed and letter-substituted primes in the present study were unpronounceable, which can be attributed to the manipulation method used for letter transposition and substitution. Therefore, one may insist that the observed patterns concerning formal similarity might reflect sensitivity to phonology or sublexical processing related to phonemic units. For instance, a significant cost of letter transposition might arise from the delayed processing of unpronounceable letter-transposed primes, not necessarily indicating that the formal similarity itself incurred such a cost.

However, the evidence in the L1 literature suggests that the effects related to letter transposition are primarily orthographic in nature, as discussed in 2.1.2.2. Conditions and Factors of the Letter Transposition Advantage and 2.1.2.3. Implication of the Letter Transposition Advantage in L1. Conversely, however, phonology has been observed to contribute minimally or non-significantly to these effects (Perea & Carreiras, 2006, 2008).

It should be noted that phonology or sublexical phonological processing might not have aid significant in the present study. Not only in the letter transposition condition, but also in the letter substitution condition, were L2 learners required to activate the lexical representations of targets with unpronounceable nonword primes. If pronounceability had a critical role, it would be expected that these learners exhibited significantly slower responses in the letter substitution condition compared to the unrelated condition because the latter was clearly pronounceable.

However, the results from the L2 learners revealed that they demonstrated a significant facilitation in the letter substitution (unpronounceable) condition when compared to the unrelated (pronounceable) condition. These results strongly suggested that formal similarity was a primary driving factor in the processing of the L2 learners in the present study. Notably, the observed patterns in the present study might have been more challenging to interpret if pronounceable letter-transposed and letter-substituted primes had been used, as the facilitation of letter transposition or letter substitution could be attributed to an interplay between phonological and formal similarity.

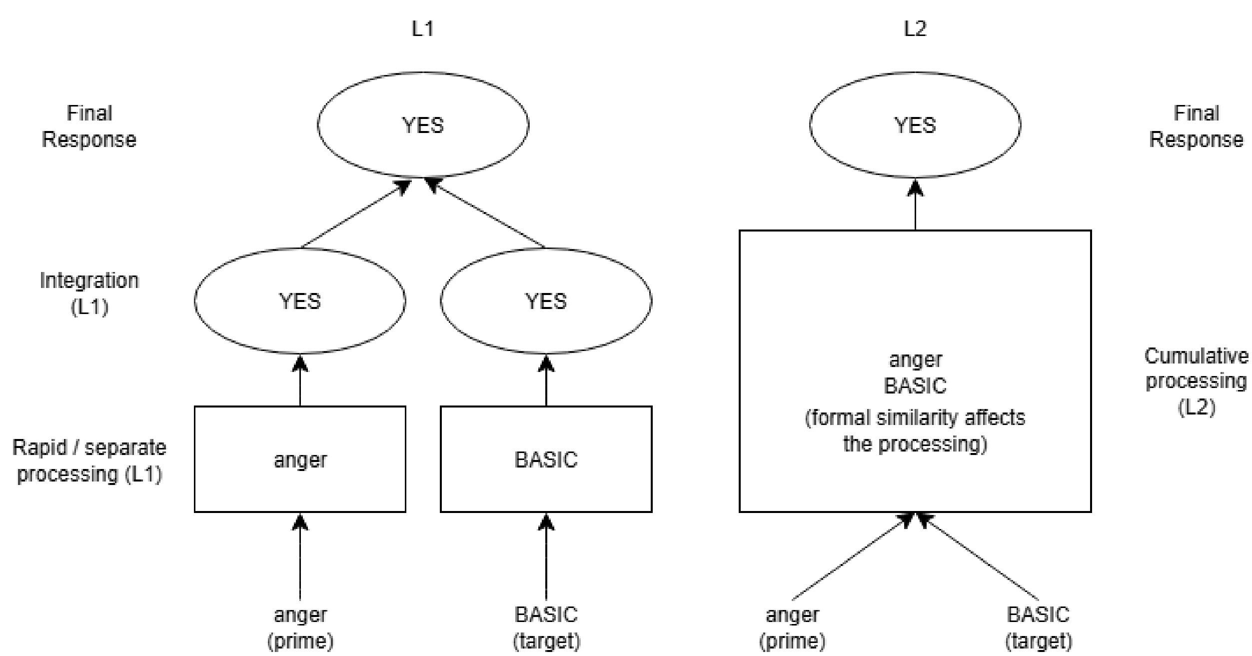
5.3.2.6. Formal Similarity and Prime Lexicality

The present study revealed that prime lexicality is a key factor in the native speakers' responses, as discussed in the earlier sections of 4.4. Post-hoc Latency Analysis with Bigram Frequency of Primes and 5.1.2. Slower Responses to Letter Substitution than Unrelated Words. This finding may be in line with a response congruency effect (Fernández-López, Marcet, & Perea, 2019; Loth & Davis, 2011). This effect refers to a phenomenon that word primes, even when unrelated to targets, generate faster responses to their targets compared to nonword primes. This phenomenon is expected to occur when the initially established response to primes (e.g. 'yes' for word primes) is congruent to the final response to targets (e.g. 'yes' for word targets). Therefore, it can be suggested that the native speakers of the present study demonstrated a high degree of efficiency in visual word recognition, to such an extent that they could formulate a preliminary response to targets based on primes. Alternatively, the native speakers' lexical retrieval was strongly robust to allow a rapid retrieval of lexical representations as well as the anticipation of lexical decision if both primes and targets were words. In these native speakers, the influence of formal similarity on lexical processing did not seem as significant as that of prime lexicality or response congruency.

Prime lexicality, however, did not affect the lexical processing of the L2 learners in the same manner as the native speakers. The key evidence is that both letter-substituted and unrelated primes to word targets produced statistically non-significantly different responses. Thus, a response congruency effect was either absent or significantly weak in the L2 learners, indicating that the lexical processing of the L2 learners was not robust enough to rapidly establish a preliminary response based on primes, at least regarding lexicality judgement. Accordingly, it can be inferred that the lexical decisions in the L2 learners were derived from the cumulative evaluation of both primes and targets, rather than an integration of separate preliminary (primes) and final (targets) responses. Then, it is plausible that this cumulative processing may lead to a significant role of the formal similarity because primes and targets were analyzed concurrently, allowing the formal overlap in terms of letter identity or letter position to contribute significantly to final responses, as shown in Figure 17.

Figure 17.

Schematic Representation of Lexical Processing in L1 and L2 With Regard To Formal Similarity Effect



A limitation of the present study is that word primes were always matched with word targets, which could have potentially skewed the responses towards a internally predetermined processing (e.g., any word prime guaranteed a 'yes' response). Hence, it could be argued that the use of unrelated nonword primes for word targets might be more effective because it would reduce any strategic processing based on prime lexicality. However, it should be noted that this approach might introduce an unwanted bias, as over half of the primes would be nonwords, which could also potentially affect participants' responses.

5.3.2.7. Formal Similarity and Lexical Representations in L2

The last question to address is the implication of formal similarity in L2 lexical representations. In the earlier section of 2.2.4. Non-nativelike Flexible Processing due to Imprecise Letter Position Encoding, the present study hypothesized a scenario where letter position is imprecisely encoded in L2 lexical representation; Yet, this hypothesis was not supported by the findings. However, this hypothesis did not take into account formal similarity, and the effect of formal similarity may not solely arise from non-nativelike lexical processing in L2.

Alternatively, it can be suggested that L2 lexical representations are poorly encoded in such a way that they allow significant activations based on formal similarity. That is, a well-established whole-word mapping between forms and meanings may not be viable for late L2 learners (Jiang & Feng, 2022; Jiang & Wu, 2022; Jiang & Zhang, 2021), contributing to these learners' reliance on formal similarity in lexical retrieval. It is also worth noting that the Multilink model (Dijkstra et al., 2018), a recent bilingual word recognition framework, incorporated formal similarity (based on Levenstein's distance) to explain both the processing and development of bilingual lexical representations. Although the effect of formal similarity may diminish in the later stage of development, this framework suggests that formal similarity persisted as a facilitatory factor because L2 lexical representations may not exert strong inhibition on formally similar candidates.

Therefore, the processing-based account of formal similarity is not inherently incompatible with the representation-based explanation. It can be presumed that a limited processing window in L2 resulted in fragmented inputs, further leading to the formation of L2 lexical representations based on formal similarity due to a lack of sufficient whole-word processing. Alternatively, it is also conceivable that L2 lexical representations are fundamentally constructed by formal similarity, which influences lexical processing in such a way that L2 visual word recognition often resorts to similarity in forms, especially when the processing window is restricted.

The representation-based explanation of formal similarity may provide further support to the fuzzy lexicon hypothesis (Bordag et al., 2022; Gor, 2018). In Ota et al. (2009), for instance, the lack of distinction between pseudo-homophones such as 'lock' and 'rock' fundamentally originated from a lack of clear phonemic distinction in L2 lexical representation. This "fuzziness" might be exacerbated by the formal similarity between such pseudo-homophones: 'l-ock' and 'r-ock.' In other words, poorly encoded lexical representations, particularly based on formal similarity, may create a fertile ground for 'fuzziness' to develop.

5.2.3 Summary of Possible Explanations

The Korean L2 learners of English in the present study provide the evidence for significant advantage and cost of letter transposition in L2 English. The sizes of letter transposition advantage and cost are compatible with the findings in the previous L1 studies. Therefore, the results seem to support the hypothesis of native-like flexible yet precise lexical processing in L2. However, not all the observed effects in the L2 learners are identical to those of the native speakers such as repetition priming effect, the difference between letter transposition and unrelated conditions, and the difference between letter substitution and unrelated conditions.

Hence, one may suspect that the nativelike performances of the L2 learners in certain effects do not truly reflect nativelike processing but are merely a result of L1 transfer. The first language of the L2 learners, Korean, demands high precision in letter identity and high flexibility in letter position. Therefore, Korean learners might transfer their highly developed abilities related to letter transposition only to achieve statistically comparable performance in the effects of letter transposition. However, this account cannot explain the discrepancies between the native speakers and the L2 learners in other effects. Furthermore, there is counter-evidence which suggests that the abilities pertinent to letter position might be language-independent. As a result, L1 transfer is unlikely to be the primary cause for nativelike effects, particularly related to letter transposition.

The Lexical Tuning Hypothesis (Castles et al., 2007) may provide partial explanation on the observed effects in the L2 learners. The hypothesis assumes that lexical processing is basically flexible, and formal overlap can facilitate lexical access particularly for developing learners with limited vocabulary. Consequently, developing learners are expected to show significant facilitation even resulted from a partial formal overlap. As vocabulary increases, this hypothesis expects that the reliance on formal overlap decreases, ultimately leading to the performance of the adult native speakers. The hypothesis can generally explain the observed effects in the L2 learners by assuming that these learners are developing learners as L1 children. However, one of the main predictions in this hypothesis is that only the vocabulary size decides the developmental trajectory in visual word recognition; thus, the same developmental patterns are expected in both L1 children and L2 learners. The results of the present study, however, show no such developmental trends between the two proficiency groups.

The results of the present study appear to be compatible with the multiple route model (Coltheart et al., 2001; Grainger et al., 2012; Grainger & Ziegler, 2011). This model proposes two separate processing routes: the serial, phonology-dependent fine-grained route and the non-serial, orthography-based coarse-grained route. Under this model, underdeveloped learners are expected to rely heavily on the fine-grained route, which may lead to slow and significantly interfered responses to unrelated words. Assuming that the L2 learners are underdeveloped, this could explain the large repetition priming effect, and the great differences between letter transposition and unrelated conditions as well as between letter substitution and unrelated conditions in the L2 learners. In contrast, letter transposition advantage and cost are expected to be nativelike, as they do not involve the retrieval of unrelated words. This model, however, predicts that letter transposition advantage increases with language development, the pattern of which is not observed in the present study between the two proficiency groups.

As Hasenäcker and Schroeder (2022) suggested, a close examination might be needed regarding what processing the baseline condition involves in the investigation of letter transposition. In the L2 learners, formal similarity appears to play an important role across the four prime type conditions, unlike in the native speakers. The latency data of the word targets reveals an incremental pattern consistent with the formal similarity in terms of letter identity and letter position between primes and targets. In contrast, the accuracy data of the word targets suggest an declining tendency in relation to the formal similarity.

Therefore, the present study suggests the segmented analytic processing hypothesis in L2. This hypothesis does not assume sequential letter-by-letter processing. Instead, the aggregated formal similarity of letter identity and letter position in each segment of a word is expected to influence the efficiency of the L2 visual word recognition. This hypothesis is based on the early noticeable studies such as Jiang and Pae (2020) and Jiang and Wu (2022); a smaller processing in the L2 learners compared to the native speakers resulted in the lexical processing of analytic nature.

Since the analytic processing in this hypothesis is lexical in nature, the formal similarity may interact with the ultimate integration of retrieved lexical representations. For instance, the L2 learners are expected to have a larger effect of repetition priming than the native speakers because a low level of formal similarity in the unrelated condition further reduced the speed of lexical retrieval only in the L2 learners. The nativelike performances in the letter transposition advantage and cost can be explained by the small size and short length of segments needed to process; for the L2 learners may be as efficient as the native speakers in such conditions.

There are three issues worth noting: prime pronounceability, prime lexicality, and implications of the formal similarity in L2 lexical representations. Whereas the present study used unpronounceable letter-transposed and letter-substituted primes, this manipulation effectively helped to differentiate between phonological and formal similarity. Additionally, L1 evidence suggests that phonology has a minor or non-significant role on the effects of letter transposition. Furthermore, prime lexicality was observed exclusively in the native speakers, suggesting that the response congruency effect specifically impacted the native speakers. Conversely, the L2 learners seemed to base their responses on a cumulative evaluation of both primes and targets. Lastly, the segmented analytic processing hypothesis of the present study is compatible with the representation-based explanation. This implies that a lack of well-established L2 lexical representations might manifest as, or be shaped by, a reliance on formal similarity in L2.

5.3. Conclusion

The present study investigated the advantage and cost of letter transposition in the L2 visual word recognition of the late Korean L2 learners of English, providing new insights into the L2 visual word recognition.

The L2 learners in the present study indeed demonstrated advantage and cost of letter transposition, all of which were statistically comparable to the native speakers. Based on these results, one may insist that the L2 learners had the same flexible yet precise lexical processing abilities as the native speakers, in such a way that the processing of letter identity information was accurately prioritized over the precise matching of letter-positional information even in the L2 visual word recognition.

However, the observed effects presented a rather complex picture. A comprehensive explanation for all the observed patterns could not be fully provided by any of the early suggested hypotheses or related existing models. Conversely, a strong influence from analytic processing based on the formal similarity between primes and targets must be incorporated, which aligns with the evidence for non-holistic, analytic processing in the L2 visual word recognition (c.f. Jiang & Feng, 2022; Jiang & Pae, 2020; Lemhöfer et al., 2008) and the findings of significant reliance on the surface form in late L2 learners (Heyer & Clahsen, 2015; Jiang, 2021; Jiang & Zhang, 2021; Taft, Li, & Aryanti, 2021).

Here, it is worth noting that the present study discovered the influence of formal similarity in the L2 learners when examining the difference between the letter substitution and unrelated word conditions. In the L1 literature, it has been common to focus primarily on the comparison of letter transposition and letter substitution conditions, or the comparison of identity and letter transposition conditions except for only a few studies such as Perea and Lupker (2003) and Yang et al. (2019). This is due to the fact that a prominent influence of formal similarity is not normally expected in L1; it is not observed in the native speakers in the present study. Without the inclusion of the unrelated word condition, however, the results of the present study might lead to a misleading conclusion: that the L2 learners possess the same processing abilities as the native speakers, showing significantly comparable advantage and cost of letter transposition.

As Hasenäcker and Schroeder (2022) and Kezilas et al. (2017) noted, the interpretation related to the effects of letter transposition requires careful consideration of the baseline and its nature. The letter substitution condition in the present study, the key baseline for the measurement of letter transposition advantage, shows a significant effect from formal similarity, an effect absent in the native speakers. Therefore, future investigation of letter transposition effects in L2 must consider that the letter substitution condition may provide a different kind of baseline compared to the native speakers.

One may argue that using unrelated nonword primes with all letters different from the targets could serve as a more effective baseline for the L2 learners when estimating letter transposition effects. However, it should be note that letter-transposed primes still contain the same word-initial and word-final identical overlaps as the corresponding letter-substituted primes; that is, the influence of formal similarity extends beyond letter-substituted primes to affect all the primes type, considering the observed patterns in the L2 learners. Rather, it would be more advisable to utilize various prime types to incorporate the impact of formal similarity.

Alternatively, one may choose to focus research on letter substitution in L2. Specifically, it could be investigated under which condition letter-substituted primes no longer demonstrate significant facilitation due to formal similarity, relative to unrelated word primes. Since the present study only substituted two internal letters, it might be further examined how many letters and at which positions a letter substitution condition yields the same inhibitory effect as an unrelated condition. For instance, each position of letters might not have the same weight in terms of the influence of formal similarity in such a way that atuwer for ANSWER produces faster responses than ansdvr for ANSWER.

What remains to consider is whether the analytic nature of L2 lexical processing represents the construction of L2 mental lexicon. This issue was addressed by Jiang and Wu (2022) and Jiang and Zhang (2021). In a word-association task, Jiang and Zhang (2021) discovered that L2 learners of English produced significantly more form-related but meaning-unrelated responses (13.30% - 14.08%) than native speakers (1.56%). Jiang and Wu (2022), in a lexical decision task with masked paradigm, L2 learners of English showed significant form-based priming effects in both word-initial (rubber for RUB) and word-final (stage for AGE) overlapping pairs, a phenomenon of which was not observed in native speakers. These reports indicated that the mental representations in L2 might be connected via form-based links, unlike those in native speakers. Then, the segments that L2 learners can process simultaneously might be used as an exploratory unit for such a form-based link in their mental lexicon. For instance, if L2 learners show significant advantages of letter transposition in pairs such as awsner vs. adster for ANSWER and anewsr vs. anuwvr for ANSWER as well as the effect of formal similarity in letter substitution, the results may indicate that even counter-intuitive segments such as a-nsw-er and an-swe-r can work as a form-based link in L2. Alternatively, proficiency might serve as a confounding variable; a significant effect in orthotactically irregular segments (such as a-nsw-er) might be only observed in L2 learners with low proficiency.

Then, another line of research worthy of pursuit would be the transposition advantage and cost of non-adjacent letters in L2. In L1 studies, the transposition of non-adjacent letters produces a significant advantage over letter substitution (Lupker et al., 2008; Perea & Carreiras, 2008; Perea & Lupker, 2004; Yang & Lupker, 2020), suggesting that the span of flexibility is not limited to two adjacent letters. The evidence of non-adjacent letter transposition advantage has been considered to be the evidence for the existence of highly coarse-grained route in the multiple-route model. In L2, it is unclear whether the span of flexibility is strongly restricted or rather unlimited due to a less interconnected lexicon with a comparatively small size of vocabulary. Therefore, future research can explore the effects of non-adjacent letter transposition with special consideration of potentially confounding factors such as re-syllabification or the distance between manipulated letters.

A potential confound is the robustness of lexical representations. The present study exclusively investigated the words mandated in school curricula, and well-recognized in a written pilot test by a sample from the target population. Therefore, it is highly likely that the lexical representations of the word stimuli have been strongly established compared to other L2 words in the mental lexicon of L2 learners. Weakly or newly represented lexical items in L2 may not exhibit a significant cost of letter transposition, even with a significant advantage of letter transposition. However, a caution is necessary in this investigation, as the results may be rather strongly related to the capacity of short-term memory such as working memory (c.f. Martin & Ellis, 2012). An exploratory measure may be needed to confirm the existence of mental lexical representations in the items under investigation.

In this context, word frequency may be another confound for the effect of letter transposition. Comparatively highly frequent words are used in the present study to ensure that the L2 learners have well-established lexical representations of the stimuli. Although the native speakers show significant advantage and cost of letter transposition across a wide range of word frequencies, late L2 learners may not have fully-developed lexical representations for rarely occurring lexical items in such a way that precision deteriorates with word frequency. If so, even the higher proficiency group may exhibit a significantly reduced cost of letter transposition; the cost of letter transposition in the lower proficiency group may decrease even further. Again, one should exercise caution when testing low frequency stimuli, as a test may actually tap into the span of short-term visuospatial memory.

A practical application of the present study can involve the adaptation of letter transposition or substitution to identify which segments of lexical representations are poorly established in L2 learners, and thus susceptible to formal similarity. While contrasting less-specified segments is suggested to be beneficial for L2 learners (Baxter et al., 2022), achieving this requires highly accurate identification of such segments, especially in word-internal positions. The use of letter transposition or substitution could serve as a valuable tool for identifying the word-internal segments particularly susceptible to formal similarity, offering a practical benefits for instruction and learning.

In sum, the present study discovered the presence of letter transposition advantage and cost in the late Korean L2 learners of English. The experiment replicated many previous findings in L1 studies, confirming the advantage and cost of letter transposition both in the native speakers and L2 learners of English. However, the results of the L2 learners were not identical to that of the native speakers, and further explanation was required; the formal similarity between primes and targets may have impacted on the performances of the L2 learners. The observed effects in the L2 learners indicated that, unlike the native speakers, investigating L2 learners may necessitate a broad view, encompassing comparisons across diverse prime types. Future research is required to verify the role of possible confounding variables such as the robustness of lexical representations and word frequency. Furthermore, questions remain as to whether the effects of letter transposition in the present study can be generalized to different sets of stimuli as well as various levels of proficiency.

Appendices

Appendix I. Mean Word Frequencies of the Stimuli in the Studies of Letter Transposition in L1 Adults

		Mean Word Frequency (per one million)	**Frequency Database Used**
Perea & Lupker (2003b)	Exp. 1	78	(Kučera & Francis, 1967)
	Exp. 3	127	(Kučera & Francis, 1967)
Perea & Lupker (2004)	Exp. 1	42	(Alameda & Cuetos Vega, 1995)
	Exp. 2	28	(Alameda & Cuetos Vega, 1995)
	Exp. 3	69	(Alameda & Cuetos Vega, 1995)
	Exp. 4	69	(Alameda & Cuetos Vega, 1995)
Schoonbaert & Grainger, (2004)	Exp. 3	80, 85	(New, Pallier, Brysbaert, & Ferrand, 2004)
Perea et al. (2008)	Exp. 1	23	(Davis & Perea, 2005)
	Exp. 2	23	(Davis & Perea, 2005)
Perea & Carreiras (2008)	Exp. 1	37	(Davis & Perea, 2005)
	Exp. 2	39	(Davis & Perea, 2005)
Lupker et al. (2008)	Exp. 1	34	(CELEX)
		48.3	(Kučera & Francis, 1967)
	Exp. 2	6.1	(CELEX)
Perea & Acha (2009)		19	(Davis & Perea, 2005)
Perea & Pérez (2009)		Not reported Used as a controlling factor	(Amano & Kondo, 1999)
Norris et al. (2010)	Exp. 1	92.6	(Kučera & Francis, 1967)
	Exp. 2	92.1	(Kučera & Francis, 1967)

		Mean Word Frequency (per one million)	Frequency Database Used
Lupker et al. (2012)	Exp. 1	37.3	(CELEX)
	Exp. 2	13.3, 14.5	(Kučera & Francis, 1967)
Perea et al. (2012)		Reported but incomparable	It was unclear whether the reported numbers are calculated per one million.
Yang et al. (2019)	Exp. 1	4.37	(SUBTLEX-CH)
	Exp. 2	Not reported Used as a controlling factor	
	Exp. 3	Not reported Used as a controlling factor	
	Exp. 4	Not reported Used as a controlling factor	
Colombo et al. (2020)	Exp. 1	48.69	(Goslin, Galluzzi, & Romani, 2014)
	Exp. 2	47.91	(Goslin et al., 2014)
	Exp. 3	11.87	(Goslin et al., 2014)
	Exp. 4	11.87	(Goslin et al., 2014)
Yang & Lupker (2020)	Exp. 1	4.5	(SUBTLWF)
	Exp. 2	14.3	(SUBTLWF)
	Exp. 3	84.6	(SUBTLWF)
Yang et al. (2020)	Exp. 1	1.63	(SUBTLEX-CH)
	Exp. 2	3.38	(SUBTLEX-CH)
	Exp. 3	1.58	(SUBTLEX-CH)
	Exp. 4	1.63	(SUBTLEX-CH)
	Exp. 5	1.54	(Amano & Kondo, 1999)
Meade et al. (2021)		109.14, 108.88	(SUBTLEX-US)

Note: The numbers recorded as discernibility below were an excerpt from Mueller and Weidemann (2012)'s first experiment (accuracy). The results of the second experiment in Mueller and Weidemann (2012) were not included since there existed an exceptionally strong impact of the mask (e.g. the letter 'I' was the most dissimilar (hard to discern) letter to almost every other letter).

Discernibility A from B: How accurately the letters in (A) could be discerned from the letters in (B) when the correct answers were the letters in (A).

Discernibility B from A: How accurately the letters in (B) could be discerned from the letters in (A) when the correct answers were the letters in (B).

Substituted Letter (A)	Substituting Letter (B)	Discernibility of A from B	Discernibility of B from A
A	W	0.73	0.75
B	L	0.89	0.71
C	Y	0.79	0.88
D	E	0.82	0.70
E	V	0.84	0.82
F	I	0.85	0.77
G	J	0.87	0.64
H	S	0.77	0.83
I	Q	0.75	0.80
J	X	0.81	0.71
K	R	0.78	0.77
L	G	0.81	0.77
M	Z	0.88	0.81
N	T	0.76	0.81
O	F	0.84	0.74
P	M	0.86	0.86
Q	N	0.84	0.80

Substituted Letter (A)	Substituting Letter (B)	Discernibility of A from B	Discernibility of B from A
R	A	0.88	0.66
S	U	0.82	0.82
T	O	0.85	0.78
U	H	0.82	0.77
V	K	0.90	0.79
W	D	0.82	0.80
X	P	0.77	0.81
Y	C	0.88	0.79
Z	B	0.87	0.87

Appendix III. List of the Word Stimuli

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Word	
basic	baisc	bauqc	anger	BASIC
become	beocme	beyfme	murder	BECOME
beside	beisde	beuqde	degree	BESIDE
blonde	bolnde	bgfnde	cattle	BLONDE
blood	bolod	bgfod	stand	BLOOD
board	borad	bowad	admit	BOARD
border	broder	bfader	appeal	BORDER
bread	berad	bavad	shock	BREAD
break	berak	bavak	white	BREAK
brief	biref	baqef	flash	BRIEF
bright	birght	baqght	assume	BRIGHT
broad	borad	bafad	noble	BROAD
build	bulid	buqgd	queen	BUILD
bullet	blulet	bhglet	lesson	BULLET
career	craeer	cwaeer	bridge	CAREER
cause	casue	cahue	alone	CAUSE
charge	chrage	chwage	master	CHARGE
claim	calim	cgwim	sharp	CLAIM
clean	celan	cgvan	major	CLEAN
clear	celar	cgvar	wrong	CLEAR
close	colse	cgfse	start	CLOSE
cloud	colud	cgfud	apply	CLOUD
coast	cosat	cowut	awake	COAST

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Word	
comedy	coemdy	cozvdy	manner	COMEDY
corner	croner	cfaner	lawyer	CORNER
count	conut	cohtt	earth	COUNT
crazy	carzy	cawzy	until	CRAZY
create	cerate	cavate	valley	CREATE
crisis	cirsis	caqsis	gather	CRISIS
cross	corss	cafss	price	CROSS
crowd	corwd	cafwd	legal	CROWD
decent	deecnt	deyvnt	bother	DECENT
decide	deicde	deyqde	island	DECIDE
defeat	deefat	deivat	branch	DEFEAT
defend	deefnd	deivnd	appear	DEFEND
design	deisgn	deuqgn	status	DESIGN
detail	deatil	deowil	square	DETAIL
device	deivce	dekqce	palace	DEVICE
dirty	drity	dqaty	north	DIRTY
double	dobule	dohlle	yellow	DOUBLE
dozen	doezn	dobvn	royal	DOZEN
dream	deram	davam	mouth	DREAM
drink	dirnk	daqnk	quite	DRINK
drive	dirve	daqve	truth	DRIVE
during	duirng	duaqng	jacket	DURING
fault	falut	fahgt	paper	FAULT
fellow	flelow	fvglow	bottle	FELLOW
flight	filght	fgqght	garden	FLIGHT
floor	folor	fgfor	month	FLOOR

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Word	
flower	folwer	fgfwer	accept	FLOWER
follow	flolow	ffglow	dinner	FOLLOW
force	froce	fface	smile	FORCE
front	fornt	fafnt	child	FRONT
future	fuutre	fuohre	middle	FUTURE
giant	ginat	giwtt	union	GIANT
glass	galss	ggwss	begin	GLASS
great	gerat	gavat	since	GREAT
green	geren	gaven	judge	GREEN
ground	gorund	gafund	rather	GROUND
group	gorup	gafup	stick	GROUP
guest	guset	guvut	shame	GUEST
guide	gudie	guqee	angle	GUIDE
health	helath	hewgth	object	HEALTH
heart	herat	hewat	along	HEART
heavy	hevay	hewky	above	HEAVY
hurry	hrury	hhary	black	HURRY
joint	jonit	joqtt	crash	JOINT
learn	leran	lewan	table	LEARN
leave	levae	lewke	place	LEAVE
likely	liekly	lirvly	gentle	LIKELY
loose	losoe	lofue	serve	LOOSE
marine	mairne	maaqne	assure	MARINE
mental	mnetal	mvttal	empire	MENTAL
motion	moiton	mooqon	patrol	MOTION
movie	moive	mokqe	throw	MOVIE

Prime				Target
Identity	**Letter Transposition**	**Letter Substitution**	**Unrelated Word**	
nation	naiton	naoqon	expect	NATION
nature	nautre	naohre	handle	NATURE
notice	noitce	nooqce	random	NOTICE
peace	pecae	pewye	blame	PEACE
permit	premit	pvamit	affect	PERMIT
person	preson	pvason	number	PERSON
piece	picee	pivye	crime	PIECE
plain	palin	pgwin	argue	PLAIN
planet	palnet	pgwnet	choose	PLANET
plant	palnt	pgwnt	enter	PLANT
point	ponit	poqtt	house	POINT
police	ploice	pfgice	chance	POLICE
policy	poilcy	pogqcy	though	POLICY
powder	pwoder	pfdder	expert	POWDER
pride	pirde	paqde	storm	PRIDE
prince	pirnce	paqnce	effect	PRINCE
prison	pirson	paqson	forget	PRISON
prize	pirze	paqze	chain	PRIZE
quick	qucik	quqyk	enjoy	QUICK
ready	reday	rewey	whole	READY
reason	resaon	rewuon	sister	REASON
recent	reecnt	reyvnt	divine	RECENT
remain	reamin	rezwin	battle	REMAIN
remote	reomte	rezfte	orange	REMOTE
remove	reomve	rezfve	spring	REMOVE
repeat	reepat	remvat	jungle	REPEAT

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Word	
report	reoprt	remfrt	wonder	REPORT
resist	reisst	reuqst	breath	RESIST
route	rotue	rohoe	flesh	ROUTE
scene	secne	syvne	press	SCENE
search	serach	sewach	golden	SEARCH
season	sesaon	sewuon	injury	SEASON
senior	seinor	setqor	barrel	SENIOR
sense	snese	svtse	field	SENSE
series	seires	seaqes	lonely	SERIES
settle	stetle	svotle	normal	SETTLE
shift	sihft	ssqft	bride	SHIFT
simple	smiple	sqzple	entire	SIMPLE
single	snigle	sqtgle	market	SINGLE
slide	silde	sgqde	charm	SLIDE
slight	silght	sgqght	winter	SLIGHT
smoke	somke	szfke	prove	SMOKE
smooth	somoth	szfoth	dollar	SMOOTH
snake	sanke	stwke	plate	SNAKE
speak	sepak	smvak	alive	SPEAK
speed	seped	smved	blind	SPEED
stable	satble	sowble	attack	STABLE
steady	setady	sovady	either	STEADY
steel	setel	sovel	moral	STEEL
story	sotry	sofry	dance	STORY
strike	stirke	staqke	mostly	STRIKE
strong	storng	stafng	toward	STRONG

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Word	
suffer	sfufer	shifer	relief	SUFFER
supply	spuply	shmply	course	SUPPLY
sweat	sewat	sdvat	metal	SWEAT
switch	siwtch	sdqtch	advice	SWITCH
threat	therat	thavat	sample	THREAT
throat	thorat	thafat	simply	THROAT
travel	tarvel	tawvel	mother	TRAVEL
treat	terat	tavat	level	TREAT
trial	tiral	taqal	south	TRIAL
trust	turst	tahst	small	TRUST
twice	tiwce	tdqce	grand	TWICE
value	vaule	vaghe	alert	VALUE
virgin	vrigin	vqagin	change	VIRGIN
weight	wegiht	weqjht	lovely	WEIGHT
world	wrold	wfald	guess	WORLD
worry	wrory	wfary	stuff	WORRY
write	wirte	waqte	tough	WRITE

Appendix IV. List of the Nonword Stimuli

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Nonword	
aliom	ailom	agqom	tello	ALIOM
argin	arign	arjqn	vuint	ARGIN
atson	atosn	atufn	coreg	ATSON
ature	autre	aohre	bince	ATURE
bacin	baicn	bayqn	tangi	BACIN
bisth	bitsh	biuoh	artor	BISTH
blont	bolnt	bgfnt	steaf	BLONT
bonth	bnoth	bftth	voten	BONTH
brost	borst	bafst	dolio	BROST
calte	clate	cwgte	stanf	CALTE
chost	cohst	csfst	munta	CHOST
conna	cnona	cftna	ghink	CONNA
coreb	croeb	cfaeb	freen	COREB
crore	corre	cafre	songa	CRORE
doron	droon	dfaon	heset	DORON
dreet	deret	davet	fronp	DREET
drice	dirce	daqce	edope	DRICE
enpel	enepl	enmvl	litha	ENPEL
fedia	feida	feeqa	injot	FEDIA
fenre	fnere	fvtre	werve	FENRE
ferad	fread	fvaad	titor	FERAD
fiast	fisat	fiwut	prape	FIAST
finip	fiinp	fitqp	titla	FINIP

Prime				Target
Identity	**Letter Transposition**	**Letter Substitution**	**Unrelated Nonword**	
flean	felan	fgvan	ehert	FLEAN
frare	farre	fawre	operi	FRARE
fruin	furin	fahin	risex	FRUIN
geast	gesat	gewut	buede	GEAST
gelle	glele	gvgle	thear	GELLE
gelon	gleon	gvgon	angeb	GELON
gence	gnece	gvtce	brote	GENCE
gerif	geirf	geaqf	tabin	GERIF
gonar	goanr	gotwr	neast	GONAR
gonet	gnoet	gftet	honad	GONET
grell	gerll	gavll	smone	GRELL
hadre	hdare	hwere	elalt	HADRE
hedal	hdeal	hveal	tearl	HEDAL
heert	heret	hevat	ablen	HEERT
hende	hnede	hvtde	wateb	HENDE
herun	heurn	heahn	abong	HERUN
hinup	hiunp	hithp	altep	HINUP
katon	kaotn	kaofn	carep	KATON
keala	kelaa	kewga	stasp	KEALA
lenie	leine	letqe	aonta	LENIE
licar	liacr	liywr	roond	LICAR
mecan	meacn	meywn	edeba	MECAN
nabre	nbare	nwlre	dearl	NABRE
nemen	neemn	nezvn	alhen	NEMEN
noute	notue	nohoe	sondo	NOUTE
olten	oletn	olovn	smein	OLTEN

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Nonword	
opane	oapne	omwne	antuc	OPANE
pesin	peisn	peuqn	ratia	PESIN
porad	poard	poawd	moona	PORAD
priop	pirop	paqop	siola	PRIOP
ralen	raeln	ragvn	dinor	RALEN
ralve	rlave	rwgve	doung	RALVE
riend	rined	rivtd	udion	RIEND
slerk	slrek	slvak	funti	SLERK
sotel	stoel	sfoel	binyl	SOTEL
tason	taosn	taufn	agink	TASON
tathe	ttahe	twohe	befin	TATHE
terpe	trepe	tvape	ralon	TERPE
tidow	tiodw	tiefw	igeal	TIDOW
tisit	tsiit	tquit	bingu	TISIT
titha	ttiha	tqoha	blesg	TITHA
tolio	tloio	tfgio	spari	TOLIO
toron	toorn	toafn	angli	TORON
trelt	terlt	tavlt	ohion	TRELT
triol	tirol	taqol	slond	TRIOL
tront	tornt	tafnt	binga	TRONT
ubine	uibne	ulqne	astef	UBINE
whina	wihna	wsqna	steeg	WHINA
zonet	zoent	zotvt	miteb	ZONET
bicten	bciten	bqyten	ohtion	BICTEN
carrew	crarew	cwarew	gerunk	CARREW
ceddle	cdedle	cvedle	enrach	CEDDLE

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Nonword	
chresh	chersh	chavsh	buaint	CHRESH
cierce	cirece	civace	lirade	CIERCE
ciston	csiton	cquton	iodina	CISTON
darret	draret	dwaret	roupon	DARRET
datten	dtaten	dwoten	lingko	DATTEN
dervix	drevix	dvavix	forepo	DERVIX
destle	dsetle	dvutle	timang	DESTLE
diance	dinace	diwtce	pedlam	DIANCE
drance	darnce	dawnce	tefall	DRANCE
droton	dorton	dafton	tignor	DROTON
duntan	dnutan	dhttan	sidang	DUNTAN
ferpor	frepor	fvapor	missat	FERPOR
fonsil	fnosil	fftsil	sicnen	FONSIL
fotion	foiton	fooqon	helong	FOTION
frinte	frnite	frqtte	dretin	FRINTE
friven	firven	faqven	hoison	FRIVEN
gatina	gaitna	gaoqna	tinear	GATINA
gatrix	gtarix	gworix	deptet	GATRIX
getain	geatin	geowin	fesire	GETAIN
gitron	gtiron	gqoron	comato	GITRON
gousin	gosuin	gohuin	lasteg	GOUSIN
greven	gerven	gavven	rilica	GREVEN
harrew	hrarew	hwarew	tootre	HARREW
hecede	heecde	heyvde	ispale	HECEDE
heteor	heetor	heovor	averpe	HETEOR
hittel	htitel	hqotel	iglore	HITTEL

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Nonword	
hotion	hoiton	hooqon	tetide	HOTION
jingre	jnigre	jqtgre	leseat	JINGRE
kentor	knetor	kvttor	dentaw	KENTOR
kullen	klulen	khglen	elaven	KULLEN
lonnet	lnonet	lftnet	posang	LONNET
lormal	lromal	lfamal	mathom	LORMAL
luffin	lfufin	lhifin	tastod	LUFFIN
lustle	lsutle	lhutle	ohigin	LUSTLE
maltef	mlatef	mwgtef	teisha	MALTEF
mediap	meidap	meeqap	abalea	MEDIAP
menith	meinth	metqth	tevise	MENITH
mennel	mnenel	mvtnel	teport	MENNEL
mithen	mtihen	mqohen	pamale	MITHEN
morrew	mrorew	mfarew	pettem	MORREW
nistil	nsitil	nqutil	treset	NISTIL
oustel	osutel	ohutel	soresk	OUSTEL
outrin	oturin	ohorin	escert	OUTRIN
paisin	pasiin	paquin	uminal	PAISIN
pallir	plalir	pwglir	tiporf	PALLIR
permin	premin	pvamin	tierad	PERMIN
phrine	phirne	phaqne	lasino	PHRINE
platad	paltad	pgwtad	deadel	PLATAD
pliche	pilche	pgqche	uldone	PLICHE
poniel	poinel	potqel	sinpul	PONIEL
ponsul	pnosul	pftsul	otelot	PONSUL
rarren	rraren	rwaren	elinit	RARREN

Prime				Target
Identity	Letter Transposition	Letter Substitution	Unrelated Nonword	
raurel	raruel	rahael	ponbon	RAUREL
rillar	rlilar	rqglar	iftend	RILLAR
rineal	rienal	ritval	astion	RINEAL
sasten	ssaten	swuten	leruse	SASTEN
sefine	seifne	seiqne	pistip	SEFINE
shelte	shlete	shvgte	pherub	SHELTE
sodern	soedrn	soevrn	veware	SODERN
sormal	sromal	sfamal	pegend	SORMAL
susion	suison	suuqon	tenign	SUSION
tegion	teigon	tejqon	starab	TEGION
thiele	tihele	tsqele	poplat	THIELE
thosen	thsoen	thfuen	rammal	THOSEN
toffin	tfofin	tfifin	infoct	TOFFIN
tollar	tlolar	tfglar	dehear	TOLLAR
totion	toiton	tooqon	inmato	TOTION
vinale	vianle	vitwle	intike	VINALE
wenote	weonte	wetfte	pichen	WENOTE

Appendix V. Descriptive Statistics of the Words and the Nonwords

Abbreviations

BG Mean: mean bigram count (based on 40,000 words) reported in Balota et al. (2007)
BG Pos.: sum of bigram counts by position (based on 40,000 words) reported in Balota et al. (2007)
BG Sum: sum of bigram counts (based on 40,000 words) reported in Balota et al. (2007)
COCA: word frequency (per million) in Corpus of Contemporary American English (Davies, 2008)
KF: word frequency (per million) in Kučera and Francis (1967)'s
Log(COCA): log-transformed value of COCA (base = *e*)
Log(KF): log-transformed value of KF (base = *e*)
Log(SUB): log-transformed value of SUB (base = *e*)
M: mean
Max: maximum value
Min: minimum value
N. Accuracy: native speakers' lexical decision accuracy reported in Balota et al. (2007)
OLD20: orthographic Levenshtein distance 20 by Yarkoni, Balota, and Yap (2008)
Ortho. N.: number of orthographic neighbors reported in Balota et al. (2007)
SD: standard deviation
SUB: word frequency (per million) in Brysbaert and New (2009)

Words (Total) (n = 144)

	M	**SD**	**Min**	**Median**	**Max**
Frequency					
COCA	127.42	133.96	8.44	79.92	737.66
Log(COCA)	4.42	0.92	2.13	4.38	6.60
SUB	82.38	108.06	10.18	43.22	820.86
Log(SUB)	3.89	0.97	2.32	3.77	6.71
KF	106.13	112.67	20.00	67.50	787.00
Log(KF)	4.31	0.80	3.00	4.21	6.67
Neighborhood Density					
Ortho. N.	2.89	1.49	1.00	3.00	6.00
OLD20	1.81	0.17	1.55	1.80	2.50

	M	SD	Min	Median	Max
Bigram					
BG Sum	16,886.57	7,350.25	4,897.00	16,301.50	40,187.00
BG Mean	3,703.18	1,429.27	980.40	3,523.25	8,037.40
BG Pos.	3,064.85	1,213.67	1,042.00	2,941.00	8,216.00

5 Letter Words (*n* = 72)

	M	SD	Min	Median	Max
Frequency					
COCA	142.48	156.32	15.61	86.96	737.66
Log(COCA)	4.51	0.92	2.75	4.47	6.60
SUB	119.01	136.77	11.75	68.03	820.86
Log(SUB)	4.26	1.02	2.46	4.22	6.71
KF	119.88	130.89	20.00	82.50	787.00
Log(KF)	4.42	0.82	3.00	4.41	6.67
Neighborhood Density					
Ortho. N.	3.22	1.36	1.00	3.00	6.00
OLD20	1.75	0.10	1.55	1.75	1.95
Bigram					
BG Sum	13,034.60	4,968.16	4,897.00	12,254.00	22,953.00
BG Mean	3,258.65	1,242.04	1,224.25	3,063.50	5,738.25
BG Pos.	2,465.54	800.52	1,042.00	2,475.00	5,396.00

6 Letter Words (*n* = 72)

	M	SD	Min	Median	Max
Frequency					
COCA	112.36	104.88	8.44	74.74	565.24

	M	SD	Min	Median	Max
Log(COCA)	4.33	0.90	2.13	4.31	6.34
SUB	45.75	44.34	10.18	29.80	236.16
Log(SUB)	3.51	0.75	2.32	3.39	5.46
KF	92.39	88.76	20.00	58.50	585.00
Log(KF)	4.20	0.78	3.00	4.07	6.37
Neighborhood Density					
Ortho. N.	2.56	1.54	1.00	2.00	6.00
OLD20	1.86	0.20	1.55	1.85	2.50
Bigram					
BG Sum	20,738.54	7,327.64	4,902.00	19,858.50	40,187.00
BG Mean	4,147.71	1,465.53	980.40	3,971.70	8,037.40
BG Pos.	3,664.17	1,259.68	1,060.00	3,594.50	8,216.00

Nonwords (Total) (n = 144)

	M	SD	Min	Median	Max
Neighborhood Density					
Ortho. N.	1.69	0.90	1.00	1.00	5.00
Bigram					
BG Sum	10,349.85	2,233.79	6,897.00	9,944.50	17,894.00
BG Mean	2,300.79	419.06	1,724.25	2,196.08	3,686.25
BG Pos.	1,610.93	507.52	461.00	1,570.00	3,109.00
Accuracy					
N. Accuracy	0.98	0.01	0.97	0.97	1.00

5 Letter Nonwords (*n* = 72)

	M	SD	Min	Median	Max
Neighborhood Density					
Ortho. N.	1.79	0.93	1.00	2.00	5.00
Bigram					
BG Sum	9,232.81	1,516.50	6,897.00	9,158.50	14,745.00
BG Mean	2,308.20	379.12	1,724.25	2,289.63	3,686.25
BG Pos.	1,357.25	467.54	461.00	1,288.00	3,109.00
Accuracy					
N. Accuracy	0.98	0.01	0.97	0.97	1.00

6 Letter Nonwords (*n* = 72)

	M	SD	Min	Median	Max
Neighborhood Density					
Ortho. N.	1.60	0.86	1.00	1.00	4.00
Bigram					
BG Sum	11,466.90	2,276.91	8,804.00	10,523.50	17,894.00
BG Mean	2,293.38	455.38	1,760.80	2,104.70	3,578.80
BG Pos.	1,864.61	409.69	937.00	1,807.00	3,064.00
Accuracy					
N. Accuracy	0.98	0.01	0.97	0.97	1.00

Appendix VI. Descriptive Statistics of the Unrelated Words

Abbreviations

BG Mean: mean bigram count (based on 40,000 words) reported in Balota et al. (2007)
BG Pos.: sum of bigram counts by position (based on 40,000 words) reported in Balota et al. (2007)
BG Sum: sum of bigram counts (based on 40,000 words) reported in Balota et al. (2007)
COCA: word frequency (per million) in Corpus of Contemporary American English (Davies, 2008)
KF: word frequency (per million) in Kučera and Francis (1967)'s
Log(COCA): log-transformed value of COCA (base = *e*)
Log(KF): log-transformed value of KF (base = *e*)
Log(SUB): log-transformed value of SUB (base = *e*)
M: mean
Max: maximum value
Min: minimum value
N. Accuracy: native speakers' lexical decision accuracy reported in Balota et al. (2007)
OLD20: orthographic Levenshtein distance 20 by Yarkoni, Balota, and Yap (2008)
Ortho. N.: number of orthographic neighbors reported in Balota et al. (2007)
SD: standard deviation
SUB: word frequency (per million) in Brysbaert and New (2009)

Words (Total) (*n* = 144)

	Mean	**SD**	**Min**	**Median**	**Max**
Frequency					
COCA	126.25	122.62	11.97	88.00	690.24
Log(COCA)	4.42	0.94	2.48	4.48	6.54
SUB	94.41	116.98	10.08	48.02	602.67
Log(SUB)	3.97	1.04	2.31	3.87	6.40
KF	120.81	127.49	20.00	69.50	628.00
Log(KF)	4.37	0.89	3.00	4.24	6.44
Neighborhood Density					
Ortho. N.	3.22	2.07	0.00	3.00	10.00
OLD20	1.84	0.22	1.45	1.80	2.55

	Mean	SD	Min	Median	Max
Bigram					
BG Sum	17,547.72	7,490.98	3,747.00	16,640.50	42,631.00
BG Mean	3,892.74	1,581.92	936.75	3,656.48	8,561.50
BG Pos.	2,993.31	1,354.65	783.00	2,787.00	7,511.00

5 Letter Words (n = 72)

	M	SD	Min	Median	Max
Frequency					
COCA	151.73	144.82	11.97	112.44	690.24
Log(COCA)	4.57	1.01	2.48	4.72	6.54
SUB	116.82	132.19	12.51	63.45	602.67
Log(SUB)	4.23	1.03	2.53	4.15	6.40
KF	138.24	144.67	20.00	74.50	628.00
Log(KF)	4.47	0.95	3.00	4.31	6.44
Neighborhood Density					
Ortho. N.	3.85	2.00	1.00	4.00	10.00
OLD20	1.75	0.16	1.45	1.75	2.35
Bigram					
BG Sum	15,328.01	6,333.47	3,747.00	13,754.50	34,246.00
BG Mean	3,832.00	1,583.37	936.75	3,438.63	8,561.50
BG Pos.	2,433.64	894.42	783.00	2,404.00	5,060.00

6 Letter Words (n = 72)

	M	SD	Min	Median	Max
Frequency					
COCA	100.76	88.32	12.30	73.86	447.53

	M	SD	Min	Median	Max
Log(COCA)	4.27	0.85	2.51	4.30	6.10
SUB	72.00	94.29	10.08	33.44	487.22
Log(SUB)	3.72	1.00	2.31	3.51	6.19
KF	103.38	104.75	20.00	65.50	472.00
Log(KF)	4.27	0.81	3.00	4.18	6.16
Neighborhood Density					
Ortho. N.	2.60	1.94	0.00	2.00	10.00
OLD20	1.93	0.23	1.45	1.85	2.55
Bigram					
BG Sum	19,767.42	7,890.66	5,313.00	18,984.50	42,631.00
BG Mean	3,953.48	1,578.13	1,062.60	3,796.90	8,526.20
BG Pos.	3,552.99	1,497.89	982.00	3,465.50	7,511.00

Appendix VII. Detailed Lexical and Sublexical Properties of the Words

Abbreviations

BG Mean: mean bigram count (based on 40,000 words) reported in Balota et al. (2007)
BG Pos.: sum of bigram counts by position (based on 40,000 words) reported in Balota et al. (2007)
BG Sum: sum of bigram counts (based on 40,000 words) reported in Balota et al. (2007)
COCA: word frequency (per million) in Corpus of Contemporary American English (Davies, 2008)
KF: word frequency (per million) in Kučera and Francis (1967)'s
og(COCA): log-transformed value of COCA (base = *e*)
Log(SUB): log-transformed value of SUB (base = *e*)
Log(KF): log-transformed value of KF (base = *e*)
N. Accuracy: native speakers' lexical decision accuracy reported in Balota et al. (2007)
OLD20: orthographic Levenshtein distance 20 by Yarkoni, Balota, and Yap (2008)
Ortho. N.: number of orthographic neighbors reported in Balota et al. (2007)
SUB: word frequency (per million) in Brysbaert and New (2009)

5 Letter Words (n = 72)

Word	**Frequency**						**Neighborhood**		**Bigram**		
	COCA	**Log (COCA)**	**SUB**	**Log (SUB)**	**KF**	**Log (KF)**	**Ortho. N.**	**OLD20**	**BG Sum**	**BG Mean**	**BG Pos.**
basic	74.73	4.31	15.57	2.75	171	5.14	4	1.80	12,369	3,092.25	2,772
blood	138.42	4.93	186.12	5.23	121	4.80	4	1.70	8,100	2,025.00	1,602
board	128.10	4.85	64.16	4.16	239	5.48	3	1.70	9,845	2,461.25	2,095

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
bread	35.08	3.56	28.33	3.34	41	3.71	6	1.55	14,625	3,656.25	3,111
break	214.86	5.37	221.08	5.40	88	4.48	6	1.65	13,283	3,320.75	2,965
brief	33.46	3.51	14.35	2.66	73	4.29	2	1.85	12,426	3,106.50	2,197
broad	56.71	4.04	14.73	2.69	84	4.43	2	1.70	8,392	2,098.00	2,640
build	231.69	5.45	48.08	3.87	86	4.45	2	1.85	5,728	1,432.00	1,535
cause	171.83	5.15	310.04	5.74	130	4.87	2	1.75	11,994	2,998.50	2,942
claim	116.84	4.76	25.39	3.23	98	4.58	1	1.85	8,746	2,186.50	2,024
clean	60.36	4.10	121.24	4.80	70	4.25	3	1.70	18,091	4,522.75	2,459
clear	169.77	5.13	171.82	5.15	219	5.39	2	1.85	16,812	4,203.00	2,344
close	140.69	4.95	219.43	5.39	234	5.46	3	1.60	9,992	2,498.00	2,306
cloud	47.47	3.86	11.75	2.46	28	3.33	2	1.70	8,363	2,090.75	1,575
coast	53.49	3.98	26.69	3.28	61	4.11	3	1.65	16,086	4,021.50	4,861
count	74.17	4.31	89.96	4.50	49	3.89	3	1.80	16,869	4,217.25	5,396
crazy	88.42	4.48	272.27	5.61	34	3.53	1	1.95	7,866	1,966.50	2,299
cross	61.95	4.13	55.04	4.01	55	4.01	6	1.70	11,690	2,922.50	2,959
crowd	66.43	4.20	37.37	3.62	53	3.97	2	1.75	7,327	1,831.75	2,581
dirty	30.22	3.41	66.45	4.20	36	3.58	1	1.90	8,379	2,094.75	2,910
dozen	35.20	3.56	24.14	3.18	52	3.95	4	1.85	9,674	2,418.50	1,624

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
dream	105.53	4.66	133.29	4.89	64	4.16	4	1.65	14,160	3,540.00	2,738
drink	85.49	4.45	247.39	5.51	82	4.41	5	1.75	22,232	5,558.00	2,533
drive	195.73	5.28	153.14	5.03	105	4.65	1	1.65	11,962	2,990.50	2,201
fault	42.58	3.75	104.12	4.65	22	3.09	2	1.80	4,897	1,224.25	1,376
floor	123.15	4.81	100.63	4.61	158	5.06	3	1.85	10,969	2,742.25	2,294
force	211.49	5.35	70.67	4.26	230	5.44	3	1.70	9,884	2,471.00	2,896
front	83.76	4.43	181.55	5.20	221	5.40	2	1.80	18,748	4,687.00	3,052
giant	31.78	3.46	27.06	3.30	23	3.14	1	1.90	16,334	4,083.50	1,989
glass	95.47	4.56	60.71	4.11	99	4.60	3	1.75	12,139	3,034.75	2,165
great	701.90	6.55	820.86	6.71	665	6.50	4	1.85	21,086	5,271.50	3,436
green	96.61	4.57	72.47	4.28	116	4.75	5	1.75	18,717	4,679.25	3,675
group	474.28	6.16	73.76	4.30	390	5.97	2	1.90	10,195	2,548.75	2,619
guest	66.28	4.19	39.94	3.69	39	3.66	2	1.80	21,881	5,470.25	1,666
guide	43.17	3.77	17.84	2.88	36	3.58	3	1.75	8,128	2,032.00	1,464
heart	217.87	5.38	244.18	5.50	173	5.15	4	1.65	14,645	3,661.25	3,053
heavy	78.88	4.37	47.29	3.86	110	4.70	2	1.90	7,546	1,886.50	2,071
hurry	26.75	3.29	173.65	5.16	36	3.58	4	1.80	5,592	1,398.00	1,928
joint	31.96	3.46	27.55	3.32	39	3.66	3	1.75	21,050	5,262.50	1,826

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
learn	314.85	5.75	118.57	4.78	84	4.43	3	1.80	16,709	4,177.25	2,673
leave	627.03	6.44	560.71	6.33	205	5.32	4	1.70	14,026	3,506.50	2,491
loose	24.31	3.19	41.78	3.73	53	3.97	4	1.65	10,843	2,710.75	2,515
movie	192.11	5.26	122.96	4.81	29	3.37	1	1.90	8,627	2,156.75	1,790
peace	91.15	4.51	69.61	4.24	198	5.29	5	1.80	11,862	2,965.50	3,140
piece	166.70	5.12	124.49	4.82	129	4.86	1	1.80	11,086	2,771.50	1,616
plain	20.62	3.03	21.82	3.08	48	3.87	4	1.70	21,999	5,499.75	2,972
plant	119.15	4.78	27.61	3.32	125	4.83	5	1.55	18,302	4,575.50	3,152
point	487.50	6.19	236.53	5.47	395	5.98	3	1.75	22,879	5,719.75	2,494
pride	25.10	3.22	27.67	3.32	42	3.74	6	1.65	15,071	3,767.75	3,626
prize	29.54	3.39	22.39	3.11	28	3.33	3	1.75	11,206	2,801.50	2,871
quick	76.17	4.33	108.67	4.69	68	4.22	3	1.85	8,548	2,137.00	1,503
ready	149.22	5.01	387.80	5.96	143	4.96	4	1.75	13,671	3,417.75	4,108
route	41.10	3.72	21.35	3.06	43	3.76	3	1.70	18,390	4,597.50	3,118
scene	118.83	4.78	74.65	4.31	106	4.66	2	1.85	16,963	4,240.75	1,863
sense	228.13	5.43	131.80	4.88	311	5.74	3	1.80	19,335	4,833.75	3,359
shift	45.86	3.83	22.82	3.13	41	3.71	3	1.70	6,410	1,602.50	1,780
slide	30.66	3.42	17.82	2.88	20	3.00	5	1.65	13,375	3,343.75	1,808

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
smoke	32.95	3.49	65.43	4.18	41	3.71	4	1.65	5,180	1,295.00	1,042
snake	19.13	2.95	22.35	3.11	44	3.78	6	1.60	5,865	1,466.25	1,346
speak	297.60	5.70	187.18	5.23	110	4.70	4	1.70	8,529	2,132.25	1,764
speed	63.95	4.16	41.25	3.72	83	4.42	5	1.65	14,613	3,653.25	2,014
steel	30.10	3.40	18.45	2.92	45	3.81	4	1.70	21,514	5,378.50	2,893
story	435.22	6.08	220.78	5.40	153	5.03	4	1.70	16,532	4,133.00	2,329
sweat	15.61	2.75	21.86	3.08	23	3.14	3	1.70	12,763	3,190.75	1,729
treat	102.15	4.63	51.88	3.95	26	3.26	2	1.70	22,953	5,738.25	3,715
trial	93.41	4.54	49.37	3.90	134	4.90	3	1.80	17,709	4,427.25	2,717
trust	78.27	4.36	178.18	5.18	52	3.95	3	1.60	15,257	3,814.25	2,550
twice	62.00	4.13	62.57	4.14	74	4.30	3	1.95	8,342	2,085.50	1,044
value	197.01	5.28	21.51	3.07	200	5.30	4	1.75	8,962	2,240.50	1,735
world	737.66	6.60	455.22	6.12	787	6.67	1	1.85	7,126	1,781.50	2,133
worry	120.09	4.79	287.02	5.66	55	4.01	4	1.85	8,024	2,006.00	2,510
write	442.96	6.09	126.80	4.84	106	4.66	5	1.55	18,998	4,749.50	2,940

6 Letter Words (n = 72)

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
become	565.24	6.34	115.57	4.75	361	5.89	1	2.45	14,636	2,927.20	2,932
beside	34.24	3.53	15.18	2.72	78	4.36	2	1.80	24,293	4,858.60	2,933
blonde	8.44	2.13	13.92	2.63	20	3.00	1	1.90	21,468	4,293.60	2,482
border	65.88	4.19	17.18	2.84	20	3.00	4	1.75	26,193	5,238.60	5,873
bright	59.87	4.09	44.41	3.79	87	4.47	4	1.80	10,548	2,109.60	2,520
bullet	29.48	3.38	38.24	3.64	28	3.33	6	1.80	16,860	3,372.00	4,001
career	122.21	4.81	45.20	3.81	67	4.20	4	1.80	33,100	6,620.00	7,280
charge	97.55	4.58	89.39	4.49	122	4.80	1	1.80	14,894	2,978.80	3,074
comedy	25.48	3.24	11.80	2.47	39	3.66	1	2.15	18,690	3,738.00	5,137
corner	74.57	4.31	52.53	3.96	115	4.74	6	1.70	29,115	5,823.00	8,216
create	316.84	5.76	25.27	3.23	54	3.99	2	1.75	29,734	5,946.80	4,602
crisis	74.21	4.31	16.65	2.81	82	4.41	2	2.00	21,974	4,394.80	3,454
decent	22.91	3.13	28.10	3.34	20	3.00	4	1.75	22,537	4,507.40	4,539
decide	206.89	5.33	50.41	3.92	40	3.69	3	1.75	15,596	3,119.20	3,622
defeat	23.70	3.17	11.37	2.43	31	3.43	1	1.90	18,232	3,646.40	3,507
defend	56.22	4.03	18.80	2.93	21	3.04	1	1.90	17,293	3,458.60	3,767
design	111.81	4.72	16.20	2.79	114	4.74	1	2.15	22,851	4,570.20	3,481

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
detail	100.18	4.61	19.39	2.96	72	4.28	3	1.85	16,269	3,253.80	3,515
device	80.96	4.39	18.16	2.90	55	4.01	1	1.90	14,424	2,884.80	3,341
double	35.84	3.58	62.71	4.14	56	4.03	3	1.85	14,377	2,875.40	3,347
during	426.60	6.06	75.92	4.33	585	6.37	4	1.85	33,012	6,602.40	3,728
fellow	34.88	3.55	58.57	4.07	63	4.14	5	1.70	12,951	2,590.20	3,216
flight	64.60	4.17	59.69	4.09	46	3.83	5	1.55	9,912	1,982.40	1,741
flower	49.26	3.90	22.76	3.13	23	3.14	4	1.65	19,389	3,877.80	4,325
follow	302.38	5.71	123.20	4.81	97	4.57	3	1.80	12,051	2,410.20	3,703
future	148.96	5.00	103.49	4.64	227	5.42	1	2.30	15,254	3,050.80	2,272
ground	157.81	5.06	72.47	4.28	186	5.23	1	1.80	15,844	3,168.80	3,091
health	302.37	5.71	40.27	3.70	105	4.65	2	1.85	15,805	3,161.00	2,703
likely	149.26	5.01	25.76	3.25	151	5.02	1	2.00	15,405	3,081.00	1,704
marine	26.27	3.27	14.08	2.64	55	4.01	3	1.70	35,459	7,091.80	6,126
mental	60.12	4.10	19.65	2.98	43	3.76	3	1.80	25,441	5,088.20	3,768
motion	42.53	3.75	18.96	2.94	55	4.01	3	1.75	25,562	5,112.40	3,167
nation	201.43	5.31	20.49	3.02	139	4.93	2	1.85	32,781	6,556.20	3,245
nature	131.29	4.88	45.16	3.81	191	5.25	1	1.95	23,576	4,715.20	2,694
notice	100.41	4.61	59.25	4.08	59	4.08	1	1.90	19,967	3,993.40	2,403

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
permit	33.32	3.51	12.10	2.49	77	4.34	1	2.25	24,274	4,854.80	3,794
person	333.31	5.81	212.88	5.36	175	5.16	1	1.85	30,060	6,012.00	4,043
planet	70.31	4.25	38.73	3.66	21	3.04	3	1.70	21,104	4,220.80	3,886
police	220.58	5.40	236.16	5.46	155	5.04	2	1.85	17,810	3,562.00	3,407
policy	241.87	5.49	27.02	3.30	222	5.40	2	2.45	15,401	3,080.20	3,148
powder	17.96	2.89	16.04	2.78	28	3.33	2	1.80	21,586	4,317.20	4,684
prince	32.94	3.49	45.08	3.81	33	3.50	2	1.85	28,430	5,686.00	4,142
prison	72.38	4.28	66.04	4.19	42	3.74	2	1.90	24,008	4,801.60	4,346
reason	297.65	5.70	193.29	5.26	241	5.48	1	1.95	24,336	4,867.20	5,317
recent	152.76	5.03	13.12	2.57	179	5.19	6	1.70	25,940	5,188.00	5,179
remain	194.94	5.27	33.22	3.50	93	4.53	2	1.85	30,033	6,006.60	5,689
remote	24.10	3.18	13.98	2.64	32	3.47	2	1.80	22,566	4,513.20	4,703
remove	104.21	4.65	21.25	3.06	58	4.06	1	1.80	16,620	3,324.00	3,612
repeat	52.66	3.96	33.02	3.50	26	3.26	3	1.80	24,063	4,812.60	4,617
report	202.43	5.31	108.00	4.68	174	5.16	3	1.75	18,768	3,753.60	4,312
resist	28.06	3.33	12.88	2.56	22	3.09	1	1.90	37,225	7,445.00	5,330
search	69.88	4.25	48.37	3.88	66	4.19	1	1.95	17,364	3,472.80	3,577
season	219.22	5.39	31.47	3.45	105	4.65	2	1.90	20,059	4,011.80	3,792

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
senior	76.64	4.34	26.25	3.27	34	3.53	1	2.00	23,737	4,747.40	3,369
series	141.22	4.95	20.16	3.00	130	4.87	2	1.95	40,187	8,037.40	4,871
settle	61.86	4.12	42.02	3.74	23	3.14	5	1.60	16,068	3,213.60	3,923
simple	132.93	4.89	89.31	4.49	161	5.08	6	1.60	14,475	2,895.00	3,285
single	149.84	5.01	72.08	4.28	172	5.15	5	1.55	34,114	6,822.80	3,885
slight	23.45	3.15	10.18	2.32	53	3.97	4	1.60	10,070	2,014.00	1,575
smooth	27.29	3.31	18.27	2.91	42	3.74	1	1.95	9,167	1,833.40	1,060
stable	24.72	3.21	13.20	2.58	30	3.40	3	1.65	21,841	4,368.20	3,686
steady	22.31	3.11	22.71	3.12	41	3.71	1	1.90	21,439	4,287.80	2,666
strike	74.90	4.32	45.57	3.82	50	3.91	6	1.60	19,029	3,805.80	2,969
strong	195.24	5.27	86.86	4.46	202	5.31	4	1.85	32,147	6,429.40	3,496
suffer	83.16	4.42	22.51	3.11	33	3.50	4	1.75	16,942	3,388.40	4,312
supply	55.37	4.01	18.67	2.93	102	4.62	2	2.40	8,512	1,702.40	2,143
switch	32.64	3.49	28.12	3.34	43	3.76	4	1.75	9,328	1,865.60	1,557
threat	86.36	4.46	20.76	3.03	42	3.74	2	1.80	22,626	4,525.20	2,908
throat	30.28	3.41	36.02	3.58	51	3.93	1	1.85	16,393	3,278.60	2,173
travel	86.04	4.45	33.37	3.51	61	4.11	2	1.85	17,308	3,461.60	3,834
virgin	13.42	2.60	18.84	2.94	35	3.56	1	2.50	19,750	3,950.00	3,746

Word	Frequency						Neighborhood		Bigram		
	COCA	Log (COCA)	SUB	Log (SUB)	KF	Log (KF)	Ortho. N.	OLD20	BG Sum	BG Mean	BG Pos.
weight	93.17	4.53	36.27	3.59	91	4.51	3	1.65	4,902	980.40	1,275

Appendix VIII. Detailed Lexical and Sublexical Properties of the Nonwords

Abbreviations

BG Mean: mean bigram count (based on 40,000 words) reported in Balota et al. (2007)
BG Pos.: sum of bigram counts by position (based on 40,000 words) reported in Balota et al. (2007)
BG Sum: sum of bigram counts (based on 40,000 words) reported in Balota et al. (2007)
N. Accuracy: native speakers' lexical decision accuracy reported in Balota et al. (2007)
Ortho. N.: number of orthographic neighbors reported in Balota et al. (2007)

5 Letter Nonwords (*n* = 72)

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
aliom	1	9,537	2,384.25	680	0.97
argin	1	10,744	2,686.00	992	1.00
atson	1	10,575	2,643.75	538	0.97
ature	1	10,816	2,704.00	893	1.00
bacin	2	10,122	2,530.50	1,510	0.97
bisth	1	8,263	2,065.75	2,064	0.97
blont	4	10,273	2,568.25	1,096	1.00
bonth	2	9,711	2,427.75	2,181	1.00
brost	2	7,128	1,782.00	1,716	0.97
calte	3	9,633	2,408.25	2,012	0.97
chost	3	7,121	1,780.25	1,362	1.00
conna	3	8,872	2,218.00	3,109	0.97
coreb	2	10,008	2,502.00	3,079	1.00
crore	2	10,235	2,558.75	1,975	1.00
doron	2	10,091	2,522.75	1,524	0.97
dreet	1	7,162	1,790.50	1,442	0.97
drice	2	7,194	1,798.50	1,232	0.97
enpel	1	7,293	1,823.25	1,092	1.00

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
fedia	1	8,053	2,013.25	810	0.97
fenre	2	9,016	2,254.00	1,299	0.97
ferad	1	10,894	2,723.50	1,313	1.00
fiast	2	6,937	1,734.25	1,056	0.97
finip	1	9,739	2,434.75	1,126	0.97
flean	3	9,187	2,296.75	1,291	0.97
frare	2	10,995	2,748.75	2,107	0.97
fruin	2	8,373	2,093.25	1,175	0.97
geast	4	8,043	2,010.75	1,580	0.97
gelle	1	7,978	1,994.50	1,647	0.97
gelon	2	9,020	2,255.00	1,078	0.97
gence	5	8,057	2,014.25	1,285	0.97
gerif	1	10,750	2,687.50	1,278	1.00
gonar	3	9,359	2,339.75	1,688	0.97
gonet	2	8,596	2,149.00	1,745	1.00
grell	1	8,641	2,160.25	1,441	0.97
hadre	2	7,134	1,783.50	1,148	0.97
hedal	2	9,832	2,458.00	907	1.00
heert	1	9,784	2,446.00	1,245	1.00
hende	1	9,928	2,482.00	1,748	0.97
herun	2	10,431	2,607.75	1,164	1.00
hinup	1	8,657	2,164.25	827	0.97
katon	1	10,267	2,566.75	1,045	1.00
keala	1	7,796	1,949.00	1,307	0.97
lenie	2	10,003	2,500.75	1,189	0.97
licar	1	9,808	2,452.00	1,003	1.00
mecan	1	8,329	2,082.25	1,305	0.97
nabre	1	7,550	1,887.50	913	1.00

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
nemen	2	8,843	2,210.75	1,276	1.00
noute	1	7,811	1,952.75	1,575	0.97
olten	2	9,880	2,470.00	1,227	0.97
opane	1	7,607	1,901.75	976	0.97
pesin	1	14,745	3,686.25	1,764	0.97
porad	1	7,990	1,997.50	1,631	1.00
priop	2	7,477	1,869.25	1,536	0.97
ralen	1	13,406	3,351.50	1,680	0.97
ralve	4	8,182	2,045.50	1,204	1.00
riend	1	9,705	2,426.25	722	0.97
slerk	2	10,278	2,569.50	995	0.97
sotel	2	7,816	1,954.00	1,518	0.97
tason	4	8,717	2,179.25	1,087	0.97
tathe	3	9,130	2,282.50	1,303	0.97
terpe	1	12,488	3,122.00	1,411	0.97
tidow	1	6,897	1,724.25	461	0.97
tisit	1	11,411	2,852.75	1,577	0.97
titha	1	9,422	2,355.50	809	0.97
tolio	2	7,920	1,980.00	1,246	0.97
toron	2	10,869	2,717.25	1,546	0.97
trelt	1	8,335	2,083.75	1,478	0.97
triol	2	8,368	2,092.00	1,275	1.00
tront	2	11,455	2,863.75	1,773	0.97
ubine	1	10,161	2,540.25	735	1.00
whina	2	9,640	2,410.00	1,088	1.00
zonet	3	8,274	2,068.50	1,612	0.97

6 Letter Nonwords (*n* = 72)

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
bicten	1	12,258	2,451.60	1,818	0.97
carrew	1	10,197	2,039.40	2,534	1.00
ceddle	4	10,051	2,010.20	1,356	1.00
chresh	1	12,093	2,418.60	1,819	0.97
cierce	3	10,465	2,093.00	937	0.97
ciston	1	13,282	2,656.40	2,394	0.97
darret	1	9,973	1,994.60	2,339	0.97
datten	2	13,598	2,719.60	2,275	0.97
dervix	1	9,794	1,958.80	1,794	0.97
destle	2	14,491	2,898.20	3,064	0.97
diance	1	9,510	1,902.00	1,774	0.97
drance	3	10,019	2,003.80	1,875	1.00
droton	1	9,416	1,883.20	1,997	1.00
duntan	1	10,593	2,118.60	1,509	0.97
ferpor	1	10,830	2,166.00	1,509	1.00
fonsil	2	10,182	2,036.40	2,220	0.97
fotion	4	13,386	2,677.20	1,537	1.00
frinte	1	17,560	3,512.00	2,168	1.00
friven	1	9,842	1,968.40	1,828	0.97
gatina	1	17,894	3,578.80	1,859	0.97
gatrix	1	9,404	1,880.80	1,513	0.97
getain	2	12,256	2,451.20	1,986	1.00
gitron	1	11,192	2,238.40	1,451	0.97
gousin	1	12,097	2,419.40	2,228	1.00
greven	1	11,487	2,297.40	2,089	0.97
harrew	1	9,539	1,907.80	2,266	0.97
hecede	2	11,769	2,353.80	1,501	1.00

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
heteor	1	10,494	2,098.80	1,754	1.00
hittel	1	10,064	2,012.80	1,575	1.00
hotion	4	13,990	2,798.00	1,541	0.97
jingre	1	16,148	3,229.60	1,371	0.97
kentor	1	11,852	2,370.40	1,674	1.00
kullen	1	9,907	1,981.40	1,883	0.97
lonnet	2	10,070	2,014.00	2,154	1.00
lormal	2	9,550	1,910.00	1,710	0.97
luffin	2	8,804	1,760.80	1,517	0.97
lustle	4	9,450	1,890.00	2,030	1.00
maltef	1	9,957	1,991.40	2,054	1.00
mediap	2	10,096	2,019.20	1,025	0.97
menith	1	10,575	2,115.00	1,585	1.00
mennel	3	9,932	1,986.40	1,582	0.97
mithen	1	10,437	2,087.40	1,754	1.00
morrew	1	9,147	1,829.40	2,039	0.97
nistil	2	14,051	2,810.20	2,499	1.00
oustel	2	12,837	2,567.40	2,094	0.97
outrin	2	14,074	2,814.80	2,330	0.97
paisin	1	13,369	2,673.80	2,445	0.97
pallir	2	9,336	1,867.20	2,197	1.00
permin	2	16,675	3,335.00	2,649	1.00
phrine	1	12,846	2,569.20	1,554	0.97
platad	1	9,905	1,981.00	1,495	1.00
pliche	1	9,083	1,816.60	1,298	0.97
poniel	1	10,186	2,037.20	2,132	0.97
ponsul	1	9,432	1,886.40	2,106	0.97
rarren	2	15,011	3,002.20	2,729	0.97

Nonword	Ortho. N	BG Sum	BG Mean	BG Pos.	N. Accuracy
raurel	1	11,208	2,241.60	1,459	0.97
rillar	1	10,907	2,181.40	1,656	1.00
rineal	2	16,923	3,384.60	1,545	1.00
sasten	2	13,964	2,792.80	2,772	1.00
sefine	2	12,448	2,489.60	1,650	1.00
shelte	2	9,544	1,908.80	1,565	0.97
sodern	1	10,553	2,110.60	2,289	1.00
sormal	2	8,863	1,772.60	1,737	0.97
susion	1	11,140	2,228.00	1,685	0.97
tegion	2	12,521	2,504.20	1,259	1.00
thiele	1	8,812	1,762.40	1,870	1.00
thosen	1	9,209	1,841.80	1,796	0.97
toffin	1	9,664	1,932.80	1,645	0.97
tollar	2	9,265	1,853.00	1,878	0.97
totion	4	14,162	2,832.40	1,459	1.00
vinale	1	15,579	3,115.80	1,968	0.97
wenote	1	10,399	2,079.80	1,603	0.97

Appendix IX. Response Classification Table

Entire datapoints

		Truth	
		Word	**Nonword**
Response	Word	Hit 15,993 (48.71%)	False Alarm 427 (1.30%)
	Nonword	Miss 422 (1.29%)	Correct Rejection 15,989 (48.70%)

Native Speakers of English

		Truth	
		Word	**Nonword**
Response	Word	Hit 8,060 (49.10%)	False Alarm 157 (0.96%)
	Nonword	Miss 148 (0.90%)	Correct Rejection 8,051 (49.04%)

Korean L2 Learners of English

		Truth	
		Word	**Nonword**
Response	Word	Hit 7,933 (48.33%)	False Alarm 270 (1.64%)
	Nonword	Miss 274 (1.67%)	Correct Rejection 7,938 (48.36%)

Appendix X. Signal Detection Theory Measures

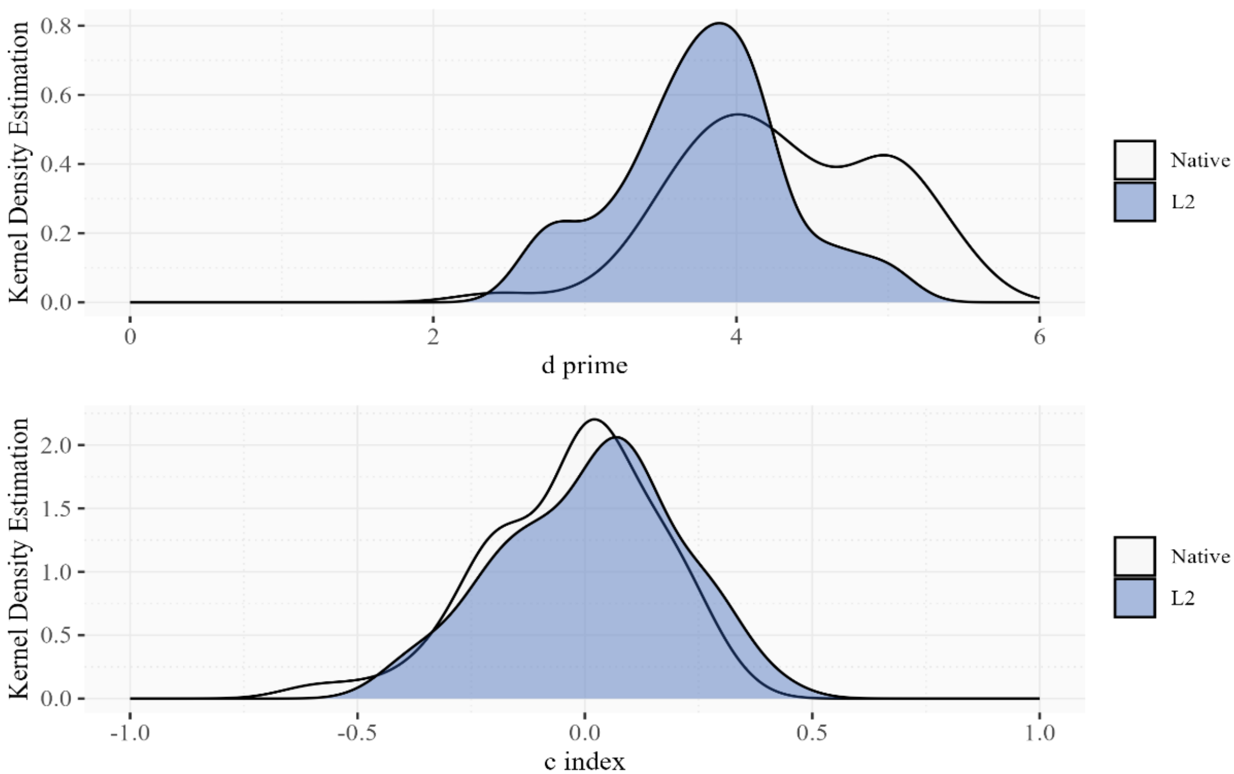
Note. D prime estimated each participant's sensitivity based on the hit and false-alarm rates. For instance, a *d* prime value of zero indicated a complete lack of sensitivity, while a high value of *d* prime implied a high sensitivity to correct answers. The analysis of each participant's responses revealed that the native speakers of English had a mean *d* prime of 4.32, with the values ranging from 2.42 to 5.40. The Korean L2 learners of English had lower *d* prime values than the native speakers, showing a mean *d* prime of 3.77, with the values ranging between 2.64 and 5.02. The results suggested that all the participants were able to discriminate correct answers to reasonable degrees.
Note. C index was also calculated in order to evaluate each participant's response bias. A *c* index value of zero implied that a participant provided unbiased answers between 'yes' or 'no'. A positive *c* index indicated that answers were biased towards 'no' (conservative), while a negative *c* index suggested that answers were biased towards 'yes' (liberal). The native speakers of English had a mean *c* index of -0.03 with the values ranging from -0.60 to 0.31. On the other hand, the Korean L2 learners of English demonstrated a mean *c* index of 0.01 with the values ranging from -0.42 to 0.42.

	M	**SD**	**Min**	**Max**
		Native Speakers of English		
d prime	4.32	0.67	2.42	5.40
c index	-0.03	0.19	-0.60	0.31
		Korean L2 Learners of English		
d prime	3.77	0.55	2.64	5.02
c index	0.01	0.19	-0.42	0.42

Note. M = mean; SD = standard deviation, Min = minimum value; Max = maximum value.

Appendix XI. Distribution of D Prime and C Index Scores

Note. The *c* index values centered around zero, providing no strong evidence that a certain group had a strong bias towards either 'yes' or 'no'.



Appendix XII. Final Note: Challenges Associated with Online Recruitment Platforms

The main issue that the present study found with online recruitment platforms is the authenticity or reliability of prescreening data. This does not imply that pre-screening data from online platforms is inherently biased or unreliable. Regarding possible issues, the present study would like to present two key points:

1. A significant number of applicants might not have paid close attention to the pre-screening questions.
2. Even if they did, their current circumstances might have changed since they answered the questions.

First, applicants might have experienced significant fatigue due to the sheer volume of pre-screening questions. Many online platforms aim to offer highly elaborated pre-screening data, leading to lengthy pre-screening questionnaires that demand significant attention. Although this provides diverse opportunities for many future researchers, it could be questionable whether the quality of responses is high. Applicants might not have fully focused on every question. For instance, as for a question such as "Is English your primary language?" an applicant might not fully grasp the nuance of the word "primary." Thus, they might have simply answered "yes" because they speak English, by interpreting this question as "Do you speak English?"

In a traditional offline experiment, a researcher could easily address this issue by verifying each applicant's linguistic backgrounds via emails or other means before the experiment starts. However, it is often impossible or difficult in online recruitment platforms for a researcher to directly contact to all the possible applicants in the same manner. Even if attempted, participants might contend they were unfairly compensated, especially when their participation was rejected. This could cause significant disputes on online platforms.

A brief validation section can resolve this issue effectively. In the present study, the key requirements were selected based on the results of pilot studies, and they were presented to applicants before the consent form. This approach can minimize the risk of including ineligible applicants. Crucially, however, the validation section must not simply repeat the same pre-screening questions. As many pre-screening questions on online recruitment platforms often lack the detailed explanation of linguistic background information, this additional validation procedure can provide important and necessary information for applicants, ensuring that all participants satisfy the requirements.

Second, applicants might have answered pre-screening questions a considerable time ago; therefore, their pre-screening data might not accurately reflect their current situation. While biological age is the most obvious example, this issue can arise from other linguistic background information, such as their current location of residency or their current use of the language to investigate. For instance, an applicant might have answered "United States" to a question such as "Where is your current location of residency" when they completed the pre-screening questionnaire. However, the same applicant may now be living outside the United States, primarily using languages other than English.

Again, introducing a brief validation session can address this issue very easily. A concise yet comprehensive question about applicants' current situation would be sufficient. For example, if a researcher wants to recruit participants whose primary language is English, they could ask: "Are you currently using English most of the time every day?" For clarity, one may add a number, such as "most of the time (90%)."

In fact, many platforms such as Prolific do recommend a short validation process. Therefore, future researchers might well implement such a validation process to ensure they collect the appropriate sample. However, it is important to note that these online recruitment platforms do not recommend (actually prohibit) an additional screening procedure; that is, asking extra questions that were not included in the pre-screening, and rejecting applicants based on these extra questions.

Online recruitment platforms undoubtedly offer significantly new opportunities for many researchers including linguists. However, a caution is needed with regard to the easily accessible and thus convenient pre-screening data. To obtain a truly appropriate sample from a targeted population, researchers must consider which validation procedures are necessary and how they can be implemented.

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