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The time course of syllable frequency effects in the visual recognition of Korean morphologically complex nouns: an ERP study

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Introduction: The syllable frequency effect refers to that during the lexical decision task, words beginning with high-frequency syllables elicit slower responses than words beginning with low-frequency ones, indicating an inhibitory effect. However, previous studies in Korean have yielded mixed results. For morphologically simple words, an inhibitory or null effect has been observed, whereas in morphologically complex words, a facilitative effect has been reported. Unfortunately, the explanations for these mixed findings remain unclear. This study employed both behavioral and electrophysiological methods to investigate the temporal dynamics of the facilitative syllable frequency effect in Korean morphologically complex nouns. A secondary aim was to explore whether syllable frequency is modulated by stem length as a factor in morphological processing, at both the behavioral and neurophysiological levels.

Methods: Twenty-eight participants (mean age = 25.14, 9 female) performed a lexical decision task, responding whether visually presented stimuli were valid Korean words, while EEG data were recorded. The experimental condition included syllable frequency (2: High *vs*. low) and stem length (2: Long *vs*. Short).

Results: The behavioral data showed that lexical decision latencies were faster for morphologically complex nouns with higher syllable frequencies compared to those with lower frequencies. The ERP data revealed a significant syllable frequency effect on the P300 component, reflecting early visual word processing. However, no significant effect was found in the N400 component. Although stem length did not significantly influence behavioral results, it did show significant differences in N250 amplitudes. Notably, an interaction between syllable frequency and stem length had a significant effect on N400, in contrast to the behavioral findings.

Discussions: The findings suggest that, in the processing of morphologically complex words in Korean, syllable frequency serves as partial information that facilitates lexical decisions through the fast-guess mechanism, as proposed by the MROM-S model. Furthermore, the delayed time window for syllable processing may stemmed from a different stage of the processing between morphologically complex words and morphologically simple words. Lastly, stem length, as a form of morphological processing, may interact with syllable frequency during the lexical access stage.

KEYWORDS

syllable frequency effect, visual word recognition, morphologically complex nouns, syllable, lexical decision, ERP

1 Introduction

The effect of sub-lexical units—morphemes, graphemes, phonemes, and syllables—on visual word recognition is a central topic in psycholinguistics. Specifically, the initial syllable of a word plays an important role in visual word recognition studies. Previous research revealed the inhibitory syllable frequency effect, in which words with high-frequency first syllables are recognized more slowly than those with low-frequency ones in a visual lexical decision task (e.g., Carreiras et al., 1993). The authors attribute this effect to lexical competition. More specifically, when reading Spanish words, readers routinely decompose the initial syllable of the word, and the decomposed syllable activates all neighbors that begin with the same syllable. During this process, the syllabic neighbors, which have a higher occurrence frequency than the target word, interrupt the recognition of the target, leading to slower responses. This result has the significant implication that the initial syllable of a word can serve as an access unit during visual word recognition in Spanish.

A subsequent behavioral study supports this explanation (Perea and Carreiras, 1998). The researchers investigated whether the inhibitory syllable frequency effect arises from the number of syllabic neighbors or their higher frequency. They found that higher-frequency syllabic neighbors significantly inhibited lexical decision latency, while the number of syllabic neighbors tended to have a facilitative effect. Thus, they concluded that the inhibitory effect stemmed from the number of higher-frequency syllabic neighbors compared to the target words. Another behavioral study that manipulates two types of syllable frequency also supports this account (Conrad et al., 2008). One type of frequency is token frequency, which represents the cumulative occurrences of syllable neighbors. The higher token frequency implies a higher likelihood that higher-frequency syllable neighbors exist compared to the targets. The other frequency is type frequency, which indicates the number of syllable neighbors that share the same initial syllable. The authors found that higher token frequencies increase lexical decision latencies; in contrast, higher type frequencies facilitate the responses. They proposed that token frequency affects the lexical access stage, where more frequent neighbors interfere with the recognition of low-frequency target words, resulting in lexical competition. In contrast, type frequency influences the pre-lexical stage, where higher type frequency reflects typicality, resulting in faster response times. In conclusion, token frequency, driven by lexical competition, leads to inhibitory syllable frequency effects at the lexical level.

Another Spanish study demonstrated this assumption through an event-related potential (ERP) experiment (Barber et al., 2004). The authors hypothesized that lexical competition intensity varies with syllable frequency, leading to significant differences in the N400 component, which is primarily associated with lexical-semantic processing and particularly semantic activation (e.g., Holcomb et al., 2002; Kutas and Federmeier, 2011). According to the results, words beginning with high-frequency syllables elicited a more pronounced negative amplitude in the N400 component compared to words with low-frequency syllables. These findings suggest that words with high-frequency syllables activate more syllabic neighbors, resulting in greater semantic activation and increased lexical competition. Independent of word frequency, words with high-frequency initial syllables elicited reduced amplitude in the P200 component compared to those with low-frequency syllables, suggesting that this may reflect syllable processing. Similar amplitude differences in the P200 and N400 components based on syllable frequency have been reported not only in other Indo-European languages, such as German (Hutzler et al., 2004), French (Chetail et al., 2012), and European-Portuguese (Campos et al., 2021), but also in non-Indo-European languages such as Korean (e.g., Kwon et al., 2011; Kwon and Lee, 2015).

Furthermore, studies beyond Spanish have consistently demonstrated that syllables play a crucial role in visual word recognition. This has been observed not only in syllable-timed languages with clear syllable boundaries, such as Spanish (e.g., Álvarez et al., 2000, 2001, 2004; Carreiras and Perea, 2002; Perea and Carreiras, 1998), French (e.g., Chetail and Mathey, 2009; Conrad et al., 2007; Mathey et al., 2006; Mathey and Zagar, 2002), and Korean (e.g., Kim et al., 2023; Kwon et al., 2023; Kwon, 2012; Kwon et al., 2006; Lee et al., 2023), but also in stress-timed languages with less clear syllable boundaries, such as European-Portuguese (e.g., Campos et al., 2018, 2020, 2021) and German (e.g., Conrad and Jacobs, 2004). Despite the consensus on the importance of syllables, some languages have shown mixed results regarding the syllable frequency effect. For instance, a Spanish study reported a null effect in lexical decision latencies based on syllable frequency (Carreiras et al., 2006), whereas a German study found that syllable frequency exhibited a facilitative effect, resulting in faster and more accurate responses in visual lexical decision tasks with isolated syllables (Stenneken et al., 2007). In French, syllable frequency had either a facilitative or inhibitory effect, depending on the type of syllable (Mahé et al., 2014). Specifically, when the words contained high-frequency phonological syllables, they were responded to more slowly than words with low-frequency syllables. Conversely, they found a facilitative syllable frequency effect based on orthographic syllables. Similarly, previous research on Korean has yielded inconsistent results. Behavioral results reported either an inhibitory effect (Kwon, 2012) or a null effect (Jin et al., 2018; Kwon and Lee, 2015) during the visual recognition of nouns. On the other hand, during the recognition of morphologically complex words, facilitative effects were consistently reported (e.g., Kim et al., 2023; Kim and Nam, 2018; Kim et al., 2020; Kwon et al., 2023; Lee et al., 2023).

It should be noted that, while previous results suggested that the syllable frequency effect is more evident in languages with clear syllable boundaries and higher phoneme-to-grapheme correspondences (Kwon, 2020), the results for Spanish and Korean, which share these features, have been inconsistent. One plausible explanation for the mixed results in Korean is the neighborhood size effect. Orthographic neighbors are defined as a group of words that share the same length and letters but differ from the target word by only one letter. The number of such neighbors is referred to as "Coltheart's N" (Coltheart et al., 1977). For example, the neighbors of the word "pen" could be "men," "pin," and "pet," giving it a Coltheart's N of 3. Studies have shown that low-frequency words with more orthographic neighbors (i.e., a larger Coltheart's N) show faster lexical decision latencies than words with fewer orthographic neighbors (i.e., a smaller Coltheart's N), an effect known as the neighborhood size effect (Andrews, 1989, 1992, 1997). The author explained the results based on the multiple read-out model (hereinafter referred to as MROM; Grainger and Jacobs, 1996), an extension of the interactive activation model (IA; McClelland and Rumelhart, 1981). In MROM, when visually presented words are processed, information from visual features (e.g., vertical/horizontal lines, circles, etc.) is first processed at the prelexical level. This information is then passed on to the subsequent levels: the letter level and the word level. There are three criteria for determining a lexical decision. The first criterion is the "M," which is fixed and represents the activation of a single lexical word node. If the presented stimulus is identified as a specific word, the specific word node reaches its threshold, and a "yes" response is triggered. The second criterion is the global criterion (S), which means sum of the activation levels of all word nodes. Unlike the fixed M value, the S does not have a fixed value; it triggers a "yes" response when the summed global activation reaches the threshold, even in the absence of specific word identification. Lastly, the deadline criterion (T) represents temporal deadlines—if T is reached before the global threshold, a "no" response is generated. In MROM, setting T too low or setting M or S too high results in false "no" responses to words. According to MROM, the facilitative effect of neighborhood size occurs because an increase in neighborhood size leads to greater excitatory activation between the pre-lexical and lexical levels, which in turn accelerates reaching the global activation threshold (S). Thus, low-frequency words with a high number of their neighbors lead to increased global activation and reach the threshold (S) for "word" response faster than words with a low number of neighbors. However, high-frequency words can reach the threshold sufficiently through direct activation of their lexical unit (M); in the end, they are not influenced by the reverberating sub-lexical activation stemming from activated neighbors.

Unlike alphabetic languages such as English, in Korean, which has shallow orthographic depth and clear syllable boundaries due to its syllabic writing system, the unit of a neighbor is a "syllable" rather than a "letter" (Kwon et al., 2006). In addition, syllabic neighborhood is defined as a cohort of words sharing identical initial syllables. For instance, some of the neighbors of "사람" [s^{h}aram] (person) include "사랑" [s^{h}araŋ] (love), "사과" [s^{h}agwa] (apple), "사용법" [s^{h}ayoŋp'ʌp̚] (instructions). Kwon et al. (2006) revealed a facilitative effect of syllable neighborhoods, but only for words without neighbors of higher word frequency. The author elucidated the facilitative effect, explaining that the absence of high-frequency neighbors reduces the intensity of lexical competition among neighbors, and as activation increases from the lexical level to the pre-lexical level due to the large number of neighbors, the global activation level rises, thus leading to faster lexical decisions.

However, in Korean, the impact of type frequency, which reflects the number of neighbors, was also inconsistent (e.g., Jin et al., 2018; Kim et al., 2023; Kwon, 2012). Kwon (2012) reanalyzed previous lexical decision data (e.g., Kwon and Nam, 2011; Lee and Taft, 2009; Lee and Kwon, 2012) using step-wise regression. Kwon revealed that syllable type frequency was significant only for pseudo-nouns. Consistent with Kwon et al. (2015) and Jin et al. (2018) examined the impact of syllable type and token frequency on the lexical decision of Korean bisyllabic nouns. The results did not show significant differences in lexical decision latencies based on the number of syllabic neighbors—type frequency—when controlling for syllable token frequency. However, Kim et al. (2023) reanalyzed lexical data from 23,173 words across three datasets (Kim and Nam, 2018; Kim et al., 2020; Yi et al., 2017) and revealed a consistent facilitative effect of syllable type frequency in morphologically complex nouns, regardless of morphological form (simple vs. inflected), part of speech (nouns vs. verbs), measure of syllabic neighbors (length limited vs. length unlimited), and analysis method (hierarchical regression vs. linear-mixed effect model).

Along with syllable neighbors, morphemes can influence the syllable frequency effect. Previous studies demonstrated that morphemes can modulate this effect (e.g., Kwon et al., 2012; Kwon and Nam, 2011). Both studies manipulated syllable neighborhood density and morphological family size, showing that the morphological neighborhood can lessen the effect of the syllable neighborhood on lexical decision latency (Kwon and Nam, 2011) and the amplitudes of late processing of lexical access, particularly in the N400 component (Kwon et al., 2012). In a similar vein, Kim J. et al. (2022) and Kim et al. (2022a,b) examined the roles of morphology and lexico-semantics in the visual recognition of Korean morphologically complex verbs, revealing significant differences in lexical decision times and electrophysiological waveforms within the N250 component, which indicates the morphological processing of morphologically complex Korean words, as reported by a previous study (Kang et al., 2016). Specifically, words with longer stems exhibited longer lexical decision times and greater negative amplitudes compared to words with shorter stems within the N250 component. In addition, within the N400, the longer stem conditions showed greater negative amplitude. Researchers concluded that stem length could modulate early morphological processing during visual recognition of Korean morphologically complex words, and this effect persists in the later stages of lexical access.

Altogether, these findings raise questions about whether the syllable frequency effect could vary based on the stage of visual word recognition (i.e., pre-lexical vs. lexical), the measure of syllable frequency (i.e., type vs. token), the language in use, lexical types (i.e., morphologically simple word vs. morphologically complex word), and the influences of morphemes. However, there are a limited number of studies investigating the syllable frequency effect on the visual recognition of Korean morphologically complex words. Hence, in the current study, our primary aim is to examine the syllable token frequency effect during the recognition of morphologically complex nouns. It would be beneficial to investigate this issue more thoroughly by employing a high temporal resolution analytical approach, such as ERPs. Therefore, the current study employed behavioral and electrophysiological methods to investigate the effect of the frequency of the first syllable and the time course of its effect on the visual recognition of Korean morphologically complex nouns, replicating the paradigm from the previous lexical decision study (Kwon et al., 2023). Another aim of the present study is to ascertain whether the syllable frequency effect is modulated by the stem length at both the behavioral and neurophysiological levels. Finally, in the current study, we introduce the stem length condition as a morpheme condition to investigate whether the effect of syllable frequency can be modulated by morpheme.

The rationale for using morphologically complex words in the present study is as follows: According to Kim J. et al. (2022) and Kim et al. (2022a,b), a more suitable approach to studying lexical access in Korean is to focus on Eojeol—referred to as morphologically complex words. This is because Korean sentences are composed of morphologically complex words, separated by spaces, rather than individual words, as is common in many other writing systems. For example, the Korean sentence "아이가v학교에v갑니다." [aiga hak̚kʼyoe kamɲida] (The child goes to school) consists of three morphologically complex words, each separated by spaces. "아이가" [aiga] (the child is) and "학교에" [hak̚kʼyoe] (to school) are morphologically complex nouns made up of a noun and a grammatical morpheme, while "갑니다" [kamɲida] (goes) is a morphologically complex inflected verb, consisting of an inflected verb and a grammatical morpheme. Further, in the context of a Korean morphologically complex noun, used in the present study, such as "아이+ 가" [aiga] (the child is), the stem morpheme "아이" [ai] (children) provides semantic information, while the grammatical morpheme "가" [ga] (is) conveys syntactic information. Thus, these Korean morphologically complex words convey both semantic and syntactic information through the combination of stem and grammatical morphemes. Therefore, in this study, we used morphologically complex nouns to investigate the syllable frequency effect during lexical access.

Importantly, in the current study, unlike previous syllable studies, a syllable is defined as an orthographic unit. Many syllable studies have defined a syllable as the phonological form based on the phonological recoding hypothesis (e.g., Kim and Lee, 2023; Lee et al., 2003; Lee and Turvey, 2003; Lim et al., 2022; Lukatela et al., 1998, 2002). This theory posits that visually presented stimuli are automatically converted to their phonological form, subsequently activating phonological information, which assists in accessing the mental lexicon. Previous Korean syllable studies also defined syllables as phonological units based on the aforementioned hypothesis. However, recent studies have reported that in Korean visual recognition processing, orthographic syllables may play a more dominant role than phonological ones (e.g., Bae and Yi, 2010; Lim et al., 2022). In a study conducted by Bae and Yi (2010), the differential effects of phonological and orthographic syllables were examined through a form priming task. The task included four priming-target pair conditions: orthographic pairs (e.g., "숙소" [sʰuk̚śo]—"숙녀" [sʰuŋɲyʌ]), phonological pairs (e.g., "숭배" [**sʰuŋ**bɛ]—"숙녀" [**sʰuŋ**ɲyʌ]), orthographic-phonological pairs (e.g., "숙면" [**sʰuŋ**myʌn]—"숙녀'" [**sʰuŋ**ɲyʌ]), and unrelated pairs (e.g., "공감" [koŋgam]—"숙녀" [sʰuŋɲyʌ]). The results showed that responses were faster for orthographic and orthographic-phonological pairs compared to the unrelated condition. There was no significant difference in response times between orthographic and orthographic-phonological pairs; however, the phonological pairs exhibited a significant inhibitory effect. The authors explained that orthographic information plays a more dominant role in Korean visual recognition than phonological information. A recent study on Korean visual word recognition by Lim et al. (2022) explored the effects of phonological and orthographic information. Based on their meta-analysis, which revealed a dominant use of orthographic information over phonological information, they conducted a priming lexical decision task. The experimental prime-target conditions included identical (e.g., "외모" [wemo]—"외모" [wemo]), phonologically identical (e.g., "왜모" [wemo]—"외모 [wemo]), orthographically similar (e.g., "워모" [wʌmo]—"외모" [wemo]), and control (e.g., "궈파" [kuwʌpʰa]—"외모" [wemo]) pairs. The results revealed a facilitative priming effect solely in orthographically similar conditions and not in phonologically identical conditions. These findings consistently highlight the dominant role of orthographic syllables in Korean visual recognition.

This raises the question of which characteristics of Korean contribute to the dominance of orthographic information in visual word recognition. Given the syllabic writing system, Korean syllables, including consonant-vowel (CV) and consonant-vowel-consonant (CVC) structures, can be represented within a single square block (Pae et al., 2021). For example, the CV syllable "가 (ㄱ + ㅏ)" is structured horizontally (e.g., [ㄱ|ㅏ]), whereas the same CV syllable "구 (ㄱ + ㅜ)" can be arranged vertically (e.g., [ㄱ/ㅜ]). Likewise, the CVC syllable "감 (ㄱ + ㅏ + ㅁ)" follows a left-right-down format (e.g., [ㄱ|ㅏ/ㅁ]), while "국 (ㄱ+ㅜ+ㄱ)" adopts a top-down format (e.g., [ㄱ/ㅜ/ㄱ]). These square-shaped orthographic syllable blocks create narrow spaces between adjacent blocks, enhancing the clarity of orthographic syllable boundaries and making it easier to segment words into orthographic syllables. In addition, Korean exhibits consistent grapheme-to-phoneme mappings, which limits the influence of phonological changes (Pae et al., 2020). According to Kim et al. (2023), based on an analysis of 23,173 words across three datasets (Kim and Nam, 2018; Kim et al., 2020; Yi et al., 2017), the incidence of phonological changes is relatively low (nouns: 9.21%, morphologically complex nouns: 13.54%, simple verbs: 18.76%, inflected verbs: 20.93%). Thus, during Korean visual recognition, orthographic syllables are more noticeable than phonological ones.

To explore the temporal dynamics of syllable frequency in the visual recognition of Korean morphologically complex nouns, we selected the time windows of interest based on previous research: P200 and N400 (e.g., Chetail et al., 2012; Duarte Campos et al., 2022; Hutzler et al., 2004; Kwon et al., 2011; Kwon and Lee, 2015). However, there were inconsistencies in the components reflecting syllable processing in Korean. For example, Kwon and Lee (2015) examined the temporal dynamics of syllable frequency during a visual lexical decision of Korean nouns. The results showed an inhibitory effect of syllable frequency in the behavioral results, and syllable type frequency influenced the P200 and N400 amplitudes. More precisely, words beginning with a high-frequency syllable exhibited reduced amplitudes in the P200 time window, and more negative amplitudes in the N400 component compared to those with low syllable type frequencies. The authors suggested that P200 reflects syllable processing, and the observed amplitude differences indicate that high-frequency syllables are processed more efficiently than low-frequency syllables. Additionally, during the stage of lexical access, higher syllable type frequency increases syllable neighbor activation, as shown by the pronounced N400 amplitudes. In a later study, Lee et al.

(2019) conducted an ERP experiment to examine the influence of various lexical variables (i.e., number of consonant/vowels, number of morphemes, whole-word frequency, syllable token frequency, and number of meanings) on the behavioral and neurophysiological impact during lexical decision of morphologically complex verbs. In the behavioral results, they found a significant negative correlation between syllable token frequency and response latency, meaning that morphologically complex verbs with a higher initial syllable were responded to faster than words with a lower frequency one. Furthermore, according to the ERP result analyzing average amplitude within a specific time window with multiple regression, syllable frequency was a significant predictor in P300 components (300–500 ms); neither N400 nor P600 were significant. This result aligns with a French study, where the time range after 300 ms to onset to 550 ms reflects syllable frequency (Goslin et al., 2006). However, across both studies, the discrepancy in significant time windows between previous studies (P200 and P300) remains unexplained. The difference in the time window for the syllable frequency effect may stem from the distinct processing of morphologically simple vs. complex words. Previous studies have suggested that morphologically complex words undergo an additional step of decomposition into their constituent stem and grammatical morphemes during initial processing (e.g., Koh et al., 2008; Min and Yi, 2010). This early decomposition stage could explain the delayed syllable frequency effect, observed at P300 for morphologically complex words, compared to P200 for morphologically simple words. Thus, in the current study, P300 emerges as a key time window for examining syllable processing in Korean morphologically complex words.

In conclusion, the current study manipulated syllable frequency and stem length. We controlled for whole-word length, whole-word frequency, and the number of meanings, all of which could influence visual recognition. We manipulated the first syllable of nouns into high- and low-frequency conditions, following the token frequency criteria established in a previous study (Kwon et al., 2023). We also manipulated the stem length of 3-syllabic morphologically complex nouns, creating long and short stem conditions, which led to mono- and disyllabic stem conditions.

Our hypotheses were as follows: In the behavioral results, we hypothesized that if the facilitative syllable frequency effect is present during the lexical decision of Korean morphologically complex nouns, the high initial syllable frequency condition would result in faster responses than the low-frequency condition, regardless of stem length. In the electrophysiological results, the current study focused on the analysis of specific time windows of ERP components, including the N250, P200, P300, and N400. First, if early morphological processing is modulated by stem length, words with longer stems are expected to exhibit a pronounced N250, as reported in a previous study (Kim J. et al., 2022; Kim et al., 2022a,b). Second, following previous Korean studies, the syllable frequency effect is reflected in either the P200 (Kwon et al., 2011, 2015) or P300 components (Lee et al., 2019). Since previous studies reported different significant time windows for syllable frequency, the present study examined whether differential amplitudes in syllable frequency appear in the P200 or P300. If an additional step exists in the processing of morphologically complex words, it is possible that the P300 component may reflect syllable processing. Specifically, the low syllable frequency condition would exhibit greater positive amplitudes than the high syllable frequency condition. Lastly, it was anticipated that if the facilitative syllable frequency effect existed, there would be no significant difference in the N400 component due to a lack of lexical competition. Conversely, if the inhibitory syllable frequency effect is reported, an attenuated N400 amplitude would be observed in the low-frequency syllable condition.

2 Method

2.1 Participants

A total of thirty right-handed undergraduate students who were native speakers of Korean participated in the current study (10 females; 20–30 years old, mean = 24.97 ± 2.67, M ± SD). All participants had normal or corrected-to-normal vision. Written informed consent was obtained from participants prior to the experiment, and they received monetary compensation for their participation. Two participants were excluded from subsequent analysis due to excessive artifacts in the EEG data. Artifacts were defined as more than 40% of components exhibiting <1% brain activity and more than 90% muscle or eye-blink activity, as labeled by the ICLabel plugin (Version 1.4, Pion-Tonachini et al., 2019) in the EEGLAB (Delorme and Makeig, 2004). The remaining 28 participants (nine females) had an age range of 20–30 (25.14 ± 2.59). The Institutional Review Board of Korea University ethics committee approved the present study (IRB-2018-0099).

2.2 Materials

A list of 200 tri-syllabic morphologically complex nouns was chosen from the Sejong corpus (Kang and Kim, 2009), consisting of 15 million morphologically complex words. The selection of tri-syllabic morphologically complex nouns was based on the analysis of the Sejong corpus, which revealed that tri-syllabic nouns are the most common length among morphologically complex nouns. A morphologically complex noun follows a structure of "stem + suffix" and can exhibit variations in the length of its stem. For instance, the tri-syllable complex nouns "탑에서" [t^{h}abes^{h}ʌ] (at the tower) are composed of mono-syllabic noun stem "탑" [t^{h}ap̚] (tower) and the suffix "에서 [es^{h}ʌ] (at the), while "탑승을" [t^{h}ap̚śɯŋɯl] (to boarding) is formed from bi-syllabic noun stem "탑승" [t^{h}apśɯŋ] (boarding) and a suffix "을 [ɯl] (to). Hence, in the list, half of the morphologically complex nouns had tri-syllabic stems, while the other half had monosyllabic stems.

To manipulate the experimental variables of *Syllable frequency* (2: High vs. Low) and *Stem length* (2: Long vs. Short), complex nouns possessing a stem with a 1-syllable length were categorized as the "*Short*" condition, while ones that have a stem with a 2-syllable length were categorized as the "*Long*" condition. The first syllable frequency, token frequency, was calculated by summing the occurrences of all complex words that start with the same syllable in the Sejong corpus and all frequencies were log-transformed. Words with log-transformed first syllable frequencies above 4.3 were considered high-syllable frequency stimuli, while those with frequencies below 3.4 were considered low-syllable frequency stimuli (Kwon et al., 2023). This led to the formation of four distinct conditions, each comprising 50 target items. However, upon analysis, two specific stimuli were found to overlap between high- and low-frequency conditions, leading to their removal. Additionally, one stimulus from the low syllable frequency–long stem condition was excluded due to grammatical errors following the Korean Orthography Revision. To match the number of stimuli across conditions, we further excluded items with the closest match in whole-word frequency and syllable frequency from the other conditions, resulting in 48 items per condition.

All stimuli used in the study were carefully controlled for whole-word length, whole-word frequency, and the number of meanings. Firstly, to control the length of the whole-word, all stimuli were selected to be tri-syllabic morphologically complex nouns. Since previous studies have consistently reported that syllable frequency effects only appeared in low-frequency words (e.g., Conrad et al., 2009; Hutzler et al., 2004; Kwon, 2012, 2020), whole-word frequencies were statistically matched across all conditions so that the raw frequency of the stimuli was controlled to be below 100. To examine whole-word frequency differences between conditions, a two-way ANOVA was conducted. There were no differences in either the syllable frequency conditions [$F = 0$, $p = 0.99$], or the stem length condition [$t = 0$, $p = 0.99$]. Also, there was no interaction between syllable frequency and stem length [$t = 0$, $p = 0.99$]. Lastly, to control the number of meanings, target stimuli were selected when the target words had a single meaning according to both the Sejong corpus and the Korean standard dictionary. Stem frequency wasn't controlled in the current study, as previous studies consistently reported that during the visual recognition of morphologically complex words, the stem frequency didn't impose a significant impact on the recognition; only syllable frequency and whole-word frequency had a significant effect (Kwon et al., 2023; Lee et al., 2023).

The same number of pseudo-complex nouns were created for the lexical decision task (LDT) to match the length of the experimental stimuli, consisting of three syllables. All of them have the same suffix as the stimuli; half of them have a bi-syllabic suffix, and the other has a monosyllable suffix. The first syllable of pseudowords was selected from syllables that did not appear in the Sejong corpus. The second syllable was randomly selected on the second syllable of the stimuli limited in the long stem condition, because in short stem conditions, the second syllable of pseudowords was *part (first syllable)* of their suffix. Examples and descriptive statistics of lexical variables are presented in Table 1.

2.3 Procedure

Participants were seated in front of an LG 27-inch monitor with a resolution of 1920×1080 resolution and a refresh rate of 60 Hz. They maintained a screen-to-nasion distance of 65 cm using a chin rest, and their index fingers were positioned on the "z" (left index finger) and "/" (right index finger) keys on the keyboard. A lexical decision task was carried out while EEG was recorded in a sound-attenuated, electrically shielded booth with all the electronic devices kept outside the booth. Participants were instructed to decide as quickly and accurately as possible whether the target presented at the center of the screen was an existing complex noun or not. The assignment of the response keys for correct responses was counterbalanced across participants. Half of the participants were assigned the "z" key as the correct response, while the other half were assigned the "/" key as the correct response.

Each trial sequence was conducted in the following steps: First, an initial fixation point (+) appeared for 500 ms, after which a black screen appeared for 200 ms. The target stimulus was presented in a white font (Times New Roman, point size 25) against a black background for 1,500 ms. Participants were instructed to respond within 1,500 ms during the target presentation. Subsequently, a black screen was displayed as the inter-trial interval among the 700, 800, and 900 ms, incorporating a 100 ms jitter ($M = 850$ ms). The experimental sequence for the LDT is depicted in Figure 1.

The experimental session was initiated with 12 practice trials, and only the participants who achieved an accuracy rate above 80% during the practice phase were instructed to proceed to the experimental trials. The practice trials provided feedback (correct or wrong response) and an accuracy rate, while the experimental trials did not. The order of trials was fully randomized for each participant, and the presentation and duration of stimuli were controlled using E-prime 2.0 professional software (Psychology Software Tools, Inc., Pittsburgh, PA, United States).

2.4 Data acquisition

The electroencephalogram (EEG) data were recorded from 32 Ag/AgCl electrodes placed according to the 10–20 International System. The electrodes were as follows: Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, FC1, FC2, CP1, CP2, FC5, FC6, CP5, CP6, TP9, and TP10 (see Figure 2 for a detailed location for each channel). The electrodes were mounted on a cap using the BrainAmp amplifier system, and impedance was maintained below 10 KΩ during data acquisition. The sampling rate was 500 Hz, and a band-pass filter ranging from 0.01 to 60 Hz was applied to the continuous data. The online reference for the EEG was the left and right mastoids, and the data were converted to an average reference for offline. To detect eye blinks and movement, an electrooculogram (EOG) electrode was attached below the right eye.

2.5 Data analysis

The behavioral data were analyzed using R software (Version 4.12, R Core Team, 2022). The present study was analyzed through linear mixed effect models (LME). For the analysis of response time (RT), only correct responses were included; the lmer function from the lme4 packages was used (Bates et al., 2014), and for the analysis of accuracy rate (ACC), the glmer function was used in the same package. Both data were modeled with random intercepts of both participant and item to take individual differences of variances. In accuracy data, accuracy was transformed into a factor variable using the factor function in R since the dependent variable (ACC) is categorical (correct or incorrect). The LME models incorporated two experimental conditions as a fixed variable with interaction: *Syllable frequency* (2 levels: High vs. Low) and *Stem length* (2 levels: Short vs. Long), which were transformed into factor variables,

TABLE 1 Examples and descriptive statistics of experimental stimuli.

Syllable frequency	Stem length	*N*	Example	First syllable frequency (log)	Whole-word frequency (log)
High	Short	50	개+에게	4.72 (0.253)	0.922 (0.338)
	Long	50	개미+를	4.72 (0.253)	0.903 (0.362)
Low	Short	50	탑+에서	3.02 (0.290)	0.802 (0.490)
	Long	50	탑승+을	3.02 (0.290)	0.888 (0.377)
Statistics				$p < 0.001$ ($F = 42.19, p < 0.001$)	*n.s.* ($F = 0, p = 0.99$)

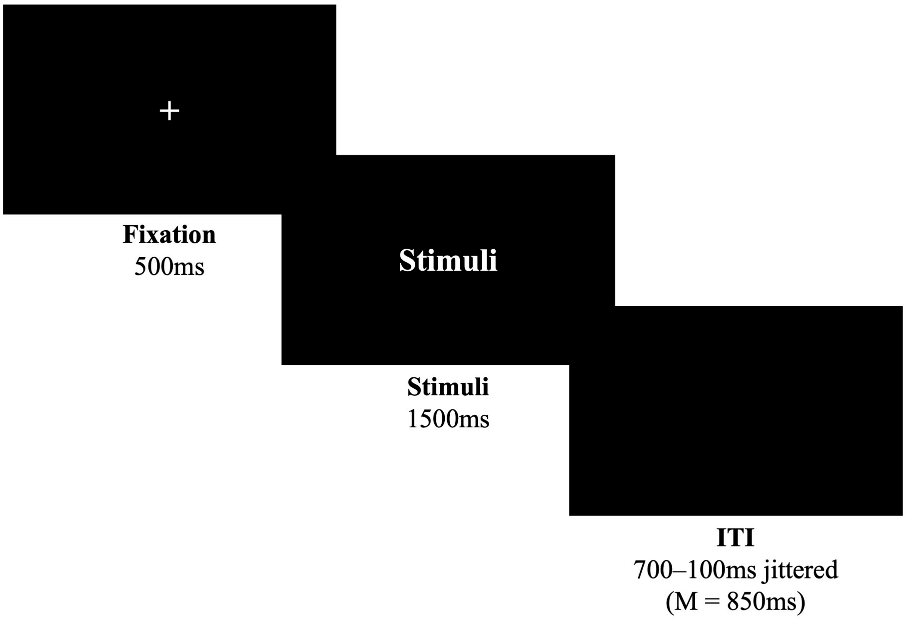

FIGURE 1
The experimental sequence of the lexical decision task.

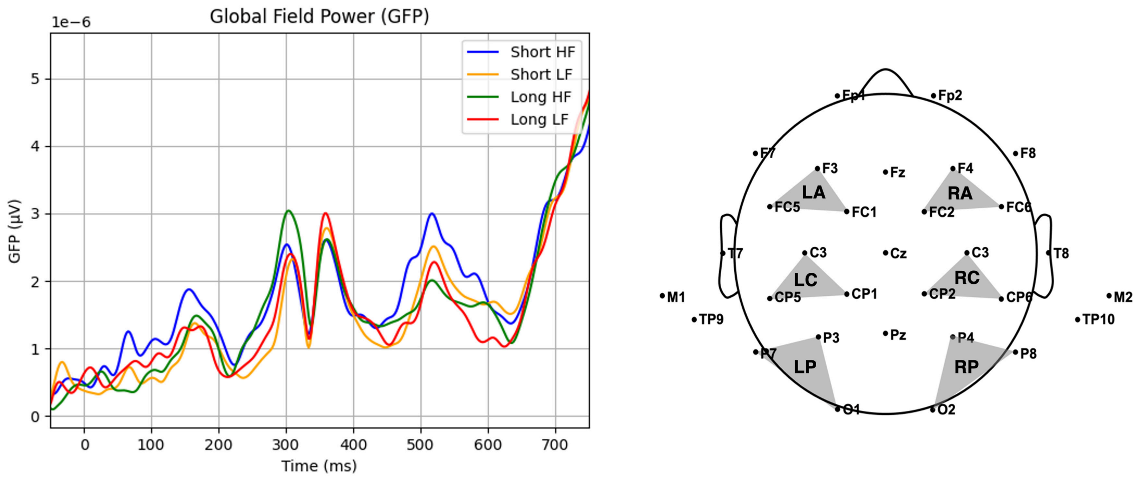

FIGURE 2
(Left) A plot of global field power (GFP) across four conditions. Short indicates a short stem, and long indicates a long stem. The HF is a high-syllable frequency, whereas the LF is a low-syllable frequency. **(Right)** The montage used for recording 32 channels of EEG. The shaded areas correspond to six regions of interest (ROIs): LA (left anterior), RA (right anterior), LC (left central), RC (right central), LP (left parietal), and RP (right parietal).

and whole-word frequency was introduced as well. Additionally, to prevent the compound effect of stem frequency, which was uncontrolled in the current study, stem frequency was introduced by the fixed variable. The stem frequency was calculated by the sum of the number of morphologically complex nouns containing the same stem.

Next, the EEG data were pre-processed using MATLAB scripts with the EEGALB toolbox (Delorme and Makeig, 2004). The data were then analyzed using R.For the visualization, both R and MNE-Python software (Version 1.3.1, Gramfort et al., 2013) were utilized. During the pre-processing phase, the continuous data were digitally filtered using a 30 Hz low-pass filter. Epochs of a duration of 1200 ms were time-locked from 200 ms prior to the target onset to 1,000 ms after the onset, associated with the correct response only. Independent Component Analysis (ICA) with the Infomax ICA algorithm was applied to minimize artifacts. The ICLabel Toolbox (Version 1.4, Pion-Tonachini et al., 2019) was used to automatically identify and remove artifacts related to eye blinks, muscle activity, and other potential sources of artifacts. Two participants who had a rejection rate of more than 40% in ICA were excluded from the subsequent analysis. The remaining 28 participants had an average rejection rate of ∼2.8%.

ERPs were analyzed by averaging the electrode groups in six different Regions of Interest (ROIs): left anterior (LA; F3, FC1, FC5), left central (LC; C3, CP1, CP5), left posterior (LP; P3, P7, O1), right anterior (RA; F4, FC2, FC6), right central (RC; C4, CP2, CP6), and right posterior (RP; P4, P8, O2) regions. To identify the time windows of interest (TOIs) of the ERP data, a plot of the Global Field Power (GFP) for each condition was plotted (see Figure 2). The GFP provides an impartial perspective on component latencies by simultaneously considering the topographical similarities of all recordings from each electrode (Skrandies, 1990). Based on the GFP measure and the prior research (Carreiras et al., 2005; Goslin et al., 2006; Kang et al., 2016; Kim J. et al., 2022; Kim et al., 2022a,b; Kwon and Nam, 2011), four time intervals were selected for each component: P200 (130–230 ms after the target onset), N250 (230–330 ms), P300 (330–430 ms), and N400 (450–650 ms).

Statistical analyses were conducted on the time window of 130–650 ms after target onset, specifically for the P200 (130–230 ms), N250 (230–330 ms), P300 (330–430 ms), and N400 (450–650 ms) components. Repeated-measures ANOVAs were performed on the averaged amplitude within each time window and ROIs using the ezANOVA function in the ez package (Lawrence, 2011) in R. The experimental variables included Syllable frequency (2: high, low), Stem length (2: 1 syllable, 2 syllables), Hemisphere (2: left, right), and Column (3: anterior, central, posterior). Follow-up condition-wise ANOVAs (Syllable frequency x Column x Hemisphere) were conducted to examine morphological effects in each syllable frequency condition. Furthermore, a paired-sample *t*-test was applied using the pairwise_t_test function in the rstatix package (Kassambara, 2023) in R to identify the interaction between stem length and ROIs. The Greenhouse-Geisser correction was applied to account for violations of sphericity in the ANOVAs, and the Bonferroni correction was used to address the multiple comparisons problem.

3 Results

3.1 Behavioral data

The mean and standard deviation of response time were calculated for participants. Outliers were excluded based on a criterion of more than 3 standard deviations from the mean ($M \pm 3$ *SD*), and there are no participants who were excluded using this criterion. Table 2 describes the mean response times (RT) and accuracy rates across the experimental conditions. The results of the LME are described in Table 3.

In the results of response time, syllable frequency exhibited a significant facilitative effect on the response time during visual recognition [$\beta = -0.05$, $SE = 0.02$, $t = -2.75$, $p = 0.007$]. Specifically, morphologically complex nouns with higher first syllable frequencies showed a faster response compared to those with lower ones. Also, despite controlling whole-word frequency, the effect of whole-word frequency also observed [$\beta = -0.00$, $SE = 0.00$, $t = -2.94$, $p = 0.003$]. In contrast, there were no significant differences in response time regarding stem length [$\beta = 0.02$, $SE = 0.02$, $t = 1.32$, $p = 0.19$], stem frequency [$\beta = 0.00$, $SE = 0.00$, $t = 0.41$, $p = 0.68$], and the interaction between syllable frequency and stem frequency [$\beta = -0.01$, $SE = 0.02$, $t = -0.56$, $p = 0.58$].

The identical model was adapted for the accuracy analysis. In contrast to the result of response latency, syllable frequency had no significant impact on the accuracy [$\beta = 0.49$, $SE = 0.37$, $z = 1.35$, $p = 0.18$]. Also, there was no significant difference in stem length [$\beta = -0.41$, $SE = 0.27$, $z = -1.50$, $p = 0.13$]. The whole-word frequency [$\beta = 0.01$, $SE = 0.01$, $z = 1.52$, $p = 0.13$], stem frequency [$\beta = 0.00$, $SE = 0.00$, $z = 1.70$, $p = 0.09$], and Syllable frequency x Stem length [$\beta = 0.55$, $SE = 0.46$, $z = 1.20$, $p = 0.23$] are also insignificant.

In the behavioral data analysis, consistent with previous studies of Korean morphologically complex words, a facilitative syllable frequency effect was observed on response time (e.g., Kim et al., 2023; Kwon et al., 2023; Lee et al., 2023). According to the previous study (Carreiras et al., 1993), the syllable frequency effect was defined as an inhibitory effect on lexical decision latency, so the current results are consistent with previous research.

As previously mentioned, the facilitative effect could be the syllable neighborhood effect, so further analysis of type syllable frequency was conducted. The syllable type frequency was calculated as the number of neighbors, starting with the same syllable with target. The model was the same with the analysis of token frequency, but in the type frequency analysis, the token frequency was replaced with type frequency, and it was not converted into a factor variable; the numeric log-transformed type frequency was introduced. In the results on response time, the facilitative effect of syllable type [$\beta = -0.03$, $SE = 0.01$, $t = -2.75$, $p = 0.006$] and whole-word frequency [$\beta = -0.00$, $SE = 0.01$, $t = -2.55$, $p = 0.011$] was found to be significant, consistent with the results of the token frequency. However, there was no significant effect of stem frequency, stem length, and the interaction between syllable frequency and stem frequency on response time. In line with the results of token frequency, no significant effect of syllable frequency was observed on the accuracy rate [$\beta = 0.25$, $SE = 0.23$, $z = 1.07$, $p = 0.29$]. Also, the variables of whole-word frequency and stem length did not exhibit significant differences, including the interaction between stem length and syllable frequency. However,

TABLE 2 Descriptive statistics of reaction times and accuracy rates.

Syllable frequency	Stem length	Response time (ms)		Accuracy (%)	
		M	*SD*	*M*	*SD*
High	Short	613.09	96.28	96.69	3.45
	Long	615.03	101.18	95.68	2.96
Low	Short	642.63	104.66	92.71	4.94
	Long	657.72	110.92	89.25	6.37

M, Mean; SD, Standard deviation.

TABLE 3 Results of linear mixed effect model of response time and accuracy for type and token frequency.

Fixed effects	Response time (ms)			Accuracy (%)		
	β	*SE*	*t*-value	β	*SE*	*z*-value
Model of token frequency						
(Intercept)	6.45	0.32	201.93***	2.93	0.25	11.72***
Syllable frequency	**−0.53**	**0.02**	**−2.75****	0.49	0.37	1.35
Stem length	0.02	0.02	1.32	−0.41	0.27	−1.50
Whole-word frequency	**−0.00**	**0.00**	**−2.94****	0.01	0.00	1.52
Stem frequency	0.00	0.00	0.41	0.00	0.00	1.70
Syllable frequency x Stem length	−0.01	0.03	−0.56	0.55	0.46	1.20
Model of type frequency						
(Intercept)	6.53	0.05	140.99***	2.41	0.66	3.62***
Syllable frequency	**−0.03**	**0.12**	**−2.75****	0.25	0.23	1.07
Stem length	0.05	0.05	0.97	−1.25	0.86	−1.45
Whole-word frequency	**−0.00**	**0.00**	**−2.55***	0.01	0.01	1.27
Stem frequency	0.00	0.00	0.23	0.00	0.00	1.94
Syllable frequency x Stem length	−0.01	0.02	−0.69	0.37	0.29	1.27

*p < 0.05.
**p < 0.01.
***p < 0.001.
Bold values indicate $p < 0.05$, except for the intercept.

stem length had a tendency to be significant in accuracy rate [$\beta = 0.00$, $SE = 0.00$, $z = 1.94$, $p = 0.052$].

Taken together, in the result of the syllable frequency during the lexical decision, the facilitative effect was observed in latency data regardless of frequency type (token vs. type) and stem length (monosyllabic stem vs. bisyllabic stem).

3.2 EEG data

Omnibus ANOVAs (*Syllable frequency x Stem length x Hemisphere x Column*) were conducted for each time window of interest (grand-averaged ERPs across experimental conditions and ROIs depicted in Figure 3). The results of these ANOVAs are reported in Table 4. In cases where an experimental factor (i.e., syllable frequency or stem length) interacted with any topographical factor, follow-up paired sample *t*-tests were performed to compare the syllable effect within each ROI.

3.2.1 P200 (130–230 ms)

In the 130–230 ms time window, there was no significant main effect of either syllable frequency [$F_{(1,27)} = 1.69$, $p = 0.20$, $\eta^2_G = 0.004$] or stem length [$F_{(1,27)} = 0.26$, $p = 0.61$, $\eta^2_G = 0.001$]. Additionally, the interaction between experimental and hemispheric factors was also insignificant.

3.2.2 N250 (230–330 ms)

Results from omnibus ANOVAs showed a significant interaction of Syllable frequency x Stem length with topographical factors across both Hemisphere and Column [$F_{(2,54)} = 3.37$, $p = 0.05$, $\eta^2_G = 0.000$]. Due to this interaction between Syllable frequency, Stem length, and topographical factors, follow-up condition-wise ANOVAs for each Syllable frequency and Stem length condition were conducted to scrutinize these interactions within each ROI.

The subsequent analysis revealed no significant simple main effect of stem length either in the low-frequency condition [$F_{(1,27)}$

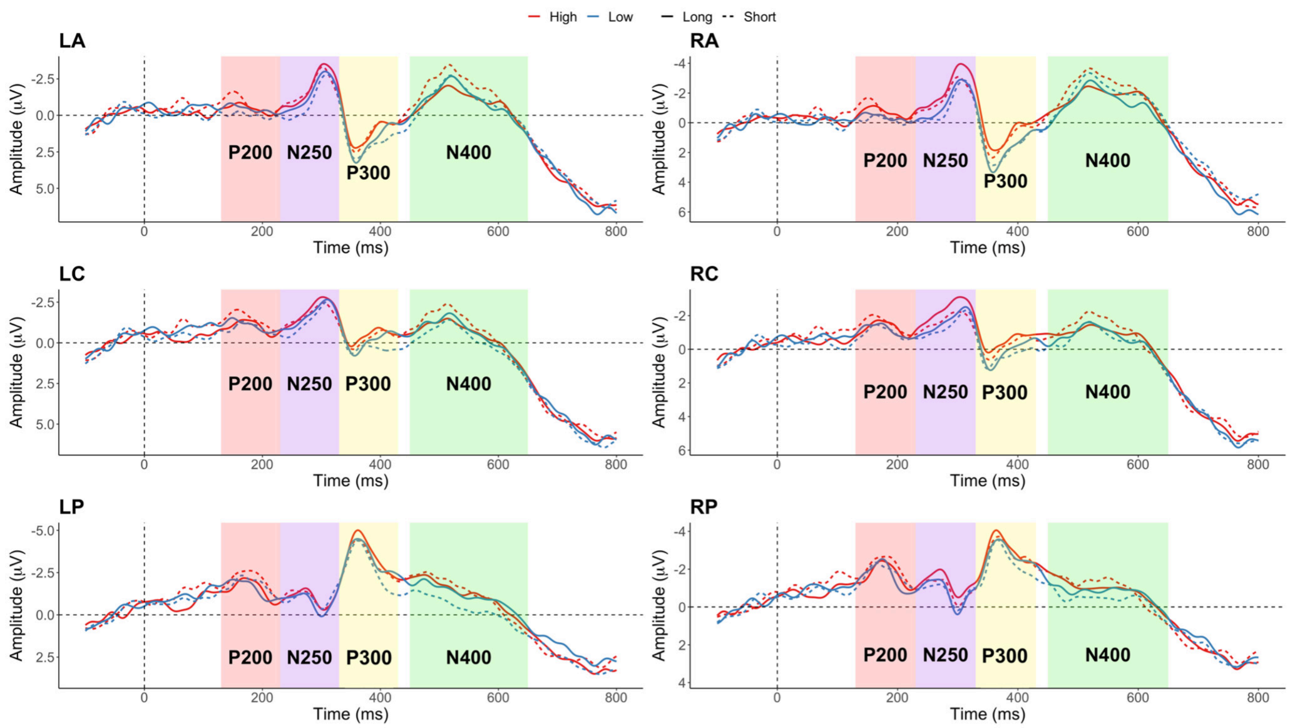

FIGURE 3
The grand-averaged event-related potentials (ERPs) across experimental conditions (High syllable frequency—red line, Low syllable frequency—blue line, Long stem—solid line, and Short stem—dashed line) at each ROIs. The colored region in the time window of P200 (red: 130–230 ms), N250 (purple: 230–330 ms), P300 (yellow: 330–430 ms), and N400 (green: 450–650 ms).

TABLE 4 Results of omnibus repeated measures ANOVAs.

Factor	Df	P200 (130–230 ms)	N250 (230–330 ms)	P300 (330–430 ms)	N400 (450–650 ms)
Syllable frequency	(1, 27)	-	-	5.05*	-
SF x Hemi	(1, 27)	-	-	-	-
SF x Col	(2, 54)	-	-	-	-
SF x H x C	(2, 54)	-	-	-	-
Stem length	(1, 27)	-	-	-	-
SL x H	(1, 27)	-	-	-	-
SL x C	(2, 54)	-	-	-	10.24***
SL x H x C	(2, 54)	-	-	-	-
Syllable frequency x Stem length	(1, 27)	-	-	-	-
SF x SL x H	(1, 27)	-	-	-	5.89*
SF x SL x C	(2, 54)	-	-	-	-
SF x SL x H x C	(2, 54)	-	3.37*	4.90*	-

SF, Syllable frequency; SL, Stem length; H, Hemisphere; C, Column.
*p < 0.05.
***p < 0.001.

$= 0.29$, $p = 0.60$, $\eta^2_G = 0.001$], or the high-frequency condition [$F_{(1,27)} = 0.69$, $p = 0.41$, $\eta^2_G = 0.002$]. But within the low-frequency condition, a significant three-way interaction of Stem length x Hemisphere x Column emerged [$F_{(2,54)} = 4.04$, $p < 0.001$, $\eta^2_G = 0.0001$]. Subsequent region-wise t-tests indicated that a longer stem length yielded more negative amplitudes in the anterior and central regions across both hemispheres [LA: $t = -5.69$; LC: $t = -4.39$; RA: $t = -3.06$; RC: $t = -4.36$; all $ps < 0.01$]. Conversely, in the left posterior region, a shorter stem length resulted in increased negative amplitudes, demonstrating a reversal effect [LP: $t = 2.63$; $p = 0.009$]. Within the high-frequency condition, a significant interaction between Stem length and Hemisphere was observed [$F_{(1,27)} = 5.76, p = 0.001, \eta^2_G = 0.001$]. A subsequent *post-hoc t*-test was conducted, revealing that morphologically complex nouns with longer stem lengths generated more negative amplitudes compared to their shorter counterparts in the left central, right anterior, central, and posterior regions [LC: $t = -3.05$; RA: $t = -7.15$; RC: $t = -9.36$; RP: $t = -5.96$; all $ps < 0.01$].

Furthermore, follow-up ANOVAs were also conducted to investigate the effect of syllable frequency. Neither the long stem [$F_{(1,27)} = 1.52, p = 0.23, \eta^2_G = 0.007$] nor the short stem conditions [$F_{(1,27)} = 1.02, p = 0.32, \eta^2_G = 0.001$] showed a significant simple main effect of syllable frequency. An interaction between Syllable frequency and Hemisphere was only significant in the long stem condition [$F_{(1,27)} = 5.23, p = 0.03, \eta^2_G = 0.001$]. The results of region wise *t*-test on the long stem length condition showed that the low syllable frequency condition elicited greater amplitude in all ROIs [LA: $t = -5.79$; LC: $t = -3.39$; LP: $t = -3.13$; RA: $t = -11.4$; RC: $t = -10.0$; RP: $t = -7.37$; all $ps < 0.001$].

3.2.3 P300 (330–430 ms)

Within the P300 epoch, omnibus ANOVAs indicated a significant main effect of syllable frequency [$F(_{1,27}) = 5.05$, $p = 0.03$, $\eta^2_G = 0.006$] and a significant interaction of Syllable x Stem x Hemisphere x Column [$F_{(2,54)} = 4.90, p = 0.01, \eta^2_G = 0.000$]. Subsequent region-wise *t*-tests of syllable frequency conducted on each ROI indicated that morphologically complex nouns with a high-frequency initial syllable produced reduced amplitudes compared to those with a low-frequency initial syllable across all ROIs [LA: $t = -12.6$; LC: $t = -9.67$; LP: $t = -6.99$; RA: $t = -16.8$; RC: $t = -13.7$; RP: $t = -8.79$; all $ps < 0.001$].

Due to the interaction between Syllable frequency and Stem length with topographical factors, follow-up condition-wise ANOVAs were conducted. These analyses did not reveal a significant simple main effect of stem length in either the high [$F_{(1,27)} = 0.39$, $p = 0.54, \eta^2_G = 0.001$] or low-frequency conditions [$F_{(1,27)} = 0.93, p = 0.34, \eta^2_G = 0.002$]. Notably, within the high-frequency condition, a significant interaction of Stem x Hemisphere x Column was observed [$F_{(2,54)} = 4.28, p = 0.002, \eta^2_G = 0.0001$]. Subsequent *post hoc* tests demonstrated that the short stem condition elicited larger amplitudes compared to the long stem condition across all ROIs, except the left anterior regions [LC: $t = -2.93$; LP: $t = -4.70$; RA: $t = -5.26$; RC: $t = -4.81$; RP: $t = -2.53$; all $ps < 0.01$].

The follow-up ANOVAs conducted to assess the syllable frequency effect revealed no significant simple main effect for both the long [$F_{(1,27)} = 1.97, p = 0.17, \eta^2_G = 0.004$] and short stem conditions [$F_{(1,27)} = 2.80, p = 0.11, \eta^2_G = 0.007$]. Nonetheless, the long stem length condition exhibited a significant Syllable frequency x Hemisphere x Column interaction [$F_{(2,54)} = 5.28, p = 0.008, \eta^2_G = 0.0001$], whereas this interaction was not significant in the short stem condition [$F_{(2,54)} = 0.65, p = 0.53, \eta^2_G = 0.000$]. Subsequent region-wise *post-hoc t*-tests within the long stem length condition revealed that the low syllable frequency condition elicited greater amplitude in all ROIs [LA: $t = -6.85$; LC: $t = -4.93$; RA: $t = -2.73$; RA: $t = -14.2$; RC: $t = -10.8$; RP: $t = -4.14$; all $ps < 0.01$].

3.2.4 N400 (450–650 ms)

In the Omnibus ANOVAs, neither the main effects of syllable frequency [$F_{(1,27)} = 1.81, p = 0.19, \eta^2_G = 0.002$] nor stem length [$F_{(1,27)} = 0.08, p = 0.78, \eta^2_G = 0.000$] reached significance level. Nevertheless, significant interactions emerged between Stem length and Column [$F_{(1,27)} = 10.24, p < 0.001, \eta^2_G = 0.001$], as well as between Syllable frequency x Stem length and the topographical factors of Hemisphere [$F_{(1,27)} = 5.89, p = 0.02, \eta^2_G = 0.0002$]. The region-wise *t*-test indicated that the anterior region yielded smaller amplitudes when the stem length was short [LA: $t = 9.90$; RA: $t = 13.2$; all $ps < 0.001$], while the posterior region exhibited greater amplitudes when the stem length was long [LP: $t = -12.0$; RA: $t = -5.43$; all $ps < 0.001$].

Subsequent follow-up ANOVAs were conducted to further investigate the interaction effect for each syllable frequency and stem length condition. The follow-up ANOVAs indicated that the simple main effect of stem length did not reach significance for both the high [$F_{(1,27)} = 0.66, p = 0.42, \eta^2_G = 0.001$] and low syllable frequency conditions [$F_{(1,27)} = 0.28, p = 0.60. \eta^2_G = 0.001$], However, significant interactions were observed between Stem x Hemisphere [$F_{(1,27)} = 4.75, p = 0.04, \eta^2_G = 0.001$], and Stem x Column [$F_{(2,54)} = 4.63, p = 0.014, \eta^2_G = 0.002$] only in the low frequency condition. Subsequent *t*-tests revealed that the long stem length condition generated greater amplitudes toward negativity in bilateral central and posterior regions [LC: $t = -8.52$; LP: $t = -18.4$; RC: $t = -2.31$; RP: $t = -9.80$; all $ps < 0.05$]. Conversely, in the right anterior regions, a reversal effect was observed [RA: $t = 8.63$; $p < 0.001$]. In the context of the syllable frequency effect, there were no significant simple main effects or interaction effects observed in either the long or short stem conditions.

In summary, the analysis of EEG data reveals that syllable frequency plays a significant role in modulating the amplitudes of early time window components (N250, P300) during visual morphologically complex word recognition. Particularly, syllable frequency of Korean morphologically complex nouns is reflected in the P300 components, not in the P200 components, showing greater amplitude in the low-frequency condition compared to the high-frequency condition. Conversely, within the N250 time window, the syllable frequency effect was only evident in morphologically complex nouns with a long stem condition. Furthermore, regarding the same time window, the stem length effect demonstrated that shorter stem lengths elicited significantly greater amplitudes compared to longer ones in the bilateral anterior and central regions. Lastly, in the late N400 time window, the stem length effect was observed exclusively in morphologically complex nouns with a low-frequency initial syllable. These interaction between stem length and syllable frequency indicates that the length of the stem can modulate the effect of syllable frequency on the electrophysiological level.

4 Discussion

This study examined the syllable frequency effect across different stem lengths in morphologically complex Korean nouns, using both behavioral and EEG measures. The key findings and implications are outlined below.

The LME analyses indicated that a facilitative syllable frequency effect emerged during the recognition of Korean morphologically complex nouns, regardless of stem length. Morphologically complex nouns with high-frequency initial syllables elicited faster responses than those with low-frequency ones. Our findings align with previous studies on the syllable frequency effect in morphologically complex nouns and verbs (e.g., Kim et al., 2023; Kim and Nam, 2018; Kim et al., 2020; Kwon et al., 2023; Lee et al., 2023), but diverges from the research using nouns (e.g., Jin et al., 2018; Kwon, 2012). As mentioned in the introduction, we assumed this was compounded by the syllable neighborhood effect. To further clarify this, we analyzed the effect of syllable type frequency, which refers to the number of syllabic neighbors, and observed the facilitative effect of syllable type frequency, indicating that words with dense syllabic neighbors respond faster than words with sparse ones, consistent with syllable neighborhood studies in Korean (e.g., Kim et al., 2023; Kwon et al., 2006). This is not quite surprising, as previous research has demonstrated a strong positive correlation between syllable type and token frequency (Conrad et al., 2008), a result replicated in a Korean study (Kwon, 2014; $r = 0.66$, $p < 0.001$) and also confirmed in the current study ($r = 0.98$, $p < 0.001$).

This raises the question of why both syllable type and token frequency facilitate visual lexical decision in Korean. This could be explained by the "fast-guess" mechanism introduced in the Multiple Read-Out Model (MROM; Grainger and Jacobs, 1996). However, although MROM accounts for general word recognition, the initial version did not include a specific stage for syllable processing. To address this and simulate the syllable frequency effect, Conrad et al. (2010) proposed MROM-S (Multiple Read-Out Model-Syllable Representation), an extended version of MROM that introduces a syllabic layer between the letter and word levels. Based on MROM-S, high-frequency syllables are more strongly activated than low-frequency syllables at the syllabic level. The higher activation at the syllabic level allows the global activation threshold to be reached more easily and faster, reducing the time required to produce a "yes" response with partial information. This suggests that syllable frequency in Korean morphologically complex word processing is likely more related to activation at the syllabic level than the word level. In contrast to previous studies suggesting that the syllable frequency effect stems from lexical competition among syllabic neighbors at the word level, the effect in Korean morphologically complex words may derive from the fast-guess mechanism at the syllabic level and not the word level. However, further research is needed to explore the impact of syllable frequency on different decision-making stages. We found no significant differences in N400 amplitudes based on syllable frequency in the current study. It is possible, however, that the overt lexical decision response may have influenced late positivity, which overlapped with N400 amplitudes (e.g., Donchin and Coles, 1988; Holcomb et al., 2002; Kwon et al., 2012). Moreover, previous findings regarding the relationship between N400 amplitudes and global activation have been inconsistent, with some studies reporting significant differences (e.g., Holcomb et al., 2002; Kwon et al., 2012) and others finding none (e.g., Braun et al., 2006). Therefore, additional experiments are necessary to better understand the influence of syllable frequency on global activation.

The second key finding is that syllable frequency was reflected in the P300 component, unlike previous studies, where it was observed in the P200 component (e.g., Barber et al., 2004; Chetail et al., 2012; Hutzler et al., 2004; Kwon et al., 2011; Kwon and Lee, 2015). Specifically, the low syllable frequency condition exhibited enhanced amplitudes than the high frequency condition, in accordance with earlier findings on Korean morphologically complex verbs (Lee et al., 2019). The difference in processing between morphologically simple words and morphologically complex words could explain the delayed timed window. Min and Yi (2010) used a masked priming lexical decision task to investigate whether Korean morphologically complex nouns have their own mental representation in the mental lexicon or are stored in a decomposed form with each stem morpheme and grammatical morpheme. In the results, they revealed that there was a noun priming effect when the prime morphologically complex nouns and the target nouns were identical; however, the frequency of morphologically complex nouns was not significant. These findings suggest that processing morphologically complex nouns begins with decomposing them into their stem and suffix, followed by stem activation. During this process, the activation of representation of morphologically complex nouns takes longer than morphologically simple nouns. The authors proposed three stages of Korean morphologically complex noun processing based on an affix stripping model (Taft and Forster, 1975): (1) decomposition of the stem morpheme and grammatical morpheme, (2) retrieval of separate representations for each in the mental lexicon, and (3) recombination of the stem morpheme and grammatical morpheme. Studies on Finnish, an agglutinative language with a very rich inflectional system, also found these additional steps for processing morphologically complex words in behavioral (Laine et al., 1999; Laine and Koivisto, 1998; Niemi et al., 1994), eye movements (Hyönä et al., 1995), and ERP results (Lehtonen et al., 2007). Therefore, these additional stages may explain the delayed processing of syllables observed for morphologically complex noun processing. However, there is still a limited number of studies directly comparing morphologically simple and complex words in Korean. To better understand this process, future research would be beneficial.

Third, the present study aligns with a prior study on Korean inflected verbs (Kim J. et al., 2022; Kim et al., 2022a,b) by observing the effect of stem length, a type of morphological processing, in both the early (N250) and later (N400) time windows. While the stem length effect did not reach statistical significance at the behavioral level, ERP findings revealed that longer stems elicited more pronounced negative amplitudes compared to shorter ones in anterior and central regions. It is well-documented that morphological factors evoke differences in amplitudes of N250, as reported in prior studies, including ERP studies (Morris et al., 2008; Morris and Stockall, 2012) and MEG research (Stockall et al., 2019), during the lexical processing of derived, inflected, and compound words. In the results of Morris and Stockall (2012), the N250 priming effect both regularly (e.g., *walked, birds*) and irregularly inflected words (e.g., *gave, geese*), supporting the idea that the morphological processing occurs in the rapid stage. Furthermore, in the current study, the stem length effect extended into the later stages of recognition, with the long stem condition showing more negative N400 amplitudes than the short stem condition. The early morphological effect continued to subsequent components, N400, which would reflect that increasing morphological complexity led to the greater processing costs in the later stage of lexical access, exhibiting the enhanced negative amplitude in the long stem condition consistent with a previous study (Coch et al., 2013).

Lastly, our results demonstrate that stem length interacts with the syllable frequency effect across both early and late stages of lexical decisions. The interaction between stem length and syllable frequency, observed through ERPs, suggests that although this interaction may not have reached significance at the behavioral level (as shown in Kwon et al., 2023), the temporal dynamics reveal that these two effects could indeed interact. We first assumed that this interaction is derived from the morphological information of the syllable. According to a previous study, morphological family size may influence the syllable frequency effect. Kwon and Nam (2011) employed bisyllabic Sino-Korean words to examine the relationship between morphological family size and syllabic (phonological/orthographic) neighborhood size. In their study, morphological family size refers to the group of words sharing the same Chinese letter, and syllable neighborhood size defines the number of words that share the first syllable with the target words. They found that stimuli with a larger morphological family size elicited faster and more accurate responses, consistent with studies in other languages (De Jong et al., 2000, 2002). Furthermore, the size of phonological syllabic neighborhoods may be modulated by morphological family size. Considering the idea that the syllable frequency effect could be affected by the Chinese-origin orthographic initial syllable, we conducted a behavioral analysis incorporating the origin of the first syllable (Chinese vs. Korean) as a fixed variable. The results revealed no significant differences in response latency or accuracy for both type and token frequency.

The second plausible explanation for the interaction between syllable frequency and stem length is as follows: We can make two assumptions regarding the behavioral results, given that the facilitative effect of syllable frequency stems from "fast-guess" processing at the syllabic level of MROM-S and longer stem length reflects greater morphological processing. We expect the condition with a short stem and high syllable frequency, which facilitates the initial syllable and reduces the processing demand of the short stem, to yield the fastest response time among the four experimental conditions. Conversely, we expect the condition with a low syllable frequency and a long stem to result in the longest response time due to the absence of syllable facilitation and the increased morphological processing burden of the longer stem. Although the interaction effect did not reach significance in the behavioral results, the descriptive statistics support the hypothesis (see Table 2).

Moreover, considering the facilitative effects of syllable frequency and the cognitive demands associated with stem length, certain assumptions about the N400 component can be drawn. First, with respect to syllable frequency, words containing high-frequency syllables may exhibit reduced N400 activation, as they already guess the "word" response before later processing. Similarly, words in the low-frequency syllable condition, with fewer syllable neighbors and lower word frequency, may elicit weaker semantic activation.

Considering that previous research has shown an increase in N400 amplitude with greater demands in morphological processing, and in light of the earlier assumptions, three hypotheses can be proposed. Firstly, in the high frequency condition, it is likely that there is no significant difference in amplitude between stem length conditions. Because regardless of stem length, a fast-guess mechanism readily responds to target words due to its high-frequency initial syllables. Secondly, in the low-frequency condition, it is possible that fast-guessing does not occur in either stem length condition. However, the long stem condition might result in greater semantic activation due to its more complex morphological processing, potentially leading to noticeable differences in the N400 component. Based on the ERP results, both hypotheses seem to be correct. In the high frequency condition, there is no significant difference in N400 amplitudes, and in the low frequency condition, morphologically complex nouns with longer stems showed higher negative amplitude in bilateral central and posterior regions. Furthermore, it seems unlikely that both stem length conditions would show a significant effect of syllable frequency on N400 amplitudes. In the high-syllable frequency condition, weak semantic activation might occur due to fast-guessing, while in the low-syllable frequency condition, weak semantic activation could result from having fewer syllable neighbors. The ERP results also validate this hypothesis. Taken together, the N400 results suggest that the facilitative effect of syllable frequency may be modulated by morphological processing, particularly stem length. The facilitative effect of syllable frequency is offset by morphological complexity; in other words, the effect is more pronounced when morphologically complex nouns exhibit lower morphological complexity.

The current study has certain limitations that should be acknowledged. Firstly, in this study, the first syllable of the pseudo-complex nouns was composed of syllables that do not appear in the Sejong corpus. Even though pseudo-complex nouns are not analyzed, their composition likely made it easier for participants to respond with "no" during the lexical decision task, resulting in lower task demand. Task demand refers to the cognitive requirements needed to perform a task, which can influence the subject's ability to complete it successfully. In this lexical decision task, however, identifying non-words may have been facilitated by their initial syllable, which could have affected participants' low criterion, ultimately leading to more liberal decisions (Kim and Nam, 2023). To address this, future studies should use pseudo-complex nouns whose first syllable appears in the corpus and control the frequency of the grammatical morphemes in morphologically complex nouns. This approach would not only increase task demand, leading participants to make more conservative decisions, but also allow for an analysis of the syllable frequency effect during pseudoword recognition. Additionally, in the current study, we extracted the whole-word frequency of morphologically complex nouns from the Sejong corpus. All stimuli were controlled for low-frequency words (below 100). Despite the small estimate value, we found that whole-word frequency had a significant effect on response time. This effect may stem from subjective familiarity, which was not included in the current study. Previous research has reported that subjective familiarity is an important factor in the visual recognition of Korean morphologically complex nouns (Kim et al., 2020; Kim J. et al., 2022; Kim et al., 2022a,b). However, Kim et al. (2024) controlled word frequency based on the Sejong corpus and found no significant differences in subjective familiarity between conditions. Despite these inconsistent results, it is possible that subjective familiarity could influence lexical decisions. To address the issue, future research should control both corpus-based frequency and subjective familiarity ratings.

In sum, this study has identified several key implications regarding the syllable frequency effect during the lexical decision of Korean morphologically complex nouns. First, morphologically complex nouns with high-frequency initial syllables showed a facilitative effect in the behavioral results, which was also reflected in the P300 ERP component. Given that no significant effect was observed in the N400, this suggests that the typicality of a word's first syllable enhances cumulative global activation, facilitating a "yes" response at an early stage of lexical processing (around 300 ms post-stimulus). This finding challenges the previous notion that syllable frequency primarily leads to inhibitory effects driven by lexical competition. In addition, the delayed ERP time window indicates that morphologically complex nouns may require additional processing stages compared to morphologically simple nouns. The significant effect of stem length at the neurophysiological level further suggests that, unlike previous findings (Kwon et al., 2023), stem length could interact with syllable frequency, compounding its effects. Overall, this study provides foundational insights into how syllable frequency influences the processing of Korean morphologically complex nouns, integrating both behavioral and electrophysiological data. Our findings suggest new directions for research, particularly in challenging the view of syllable frequency as purely inhibitory, at least regarding Korean morphologically complex nouns, which may inspire further cross-linguistic research in morphologically rich languages.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Institutional Review Board of Korea University Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SK: Formal analysis, Investigation, Writing – original draft, Validation. SL: Investigation, Methodology, Validation, Writing – review & editing. JK: Supervision, Formal analysis, Software, Visualization, Writing – review & editing. KN: Funding acquisition, Supervision, Writing – review & editing.

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Generative AI was just used for grammar check in the article. No content creation or data analysis was performed using AI tools.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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