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The Time Course of Activation of Semantic and Orthographic Information in Morphological Decomposition by Korean Adults and Developing Readers

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The current study examined the involvement of semantic and orthographic information in the processing of derived words in Korean Hangul. Sixth grade children and adults participated in four masked priming lexical decision experiments in which the prime duration varied from 36, 48, 57, and 72 ms (in Experiments, 1, 2, 3, and 4, respectively). Morphological (M), semantic (S), and orthographic (O) relatedness between prime-target pairs were manipulated. There were four types of Korean prime-target pairs: (1) -M-S+O: *도시락-도시, scandal-scan*, (2) +M-S+O: *구두쇠-구두, archer-arch*, (3) +M+S+O: *음악가-음악, bravely-brave*, and (4) -M+S-O: *반대이의*, *accuse-blame*. There were several key findings: (1) adults showed significant priming effects at 57 and 72 ms in +M+S+O and significant priming effects at 72 ms in +M-S+O; (2) less skilled readers showed significant facilitation at 36 ms in +M+S+O; and (3) in -M-S+O, both skilled and less skilled readers show significant inhibition across four prime durations. The different time course of +M+S+O priming for adults and children may be due to developing readers' smaller lexicon and less competition for semantic activation of the monosyllabic suffix (e.g., *가* in *음악가*), which is a homograph in Korean Hangul. The consistent orthographic inhibition for both age groups suggest that orthographic information is activated early and continues to play an important role throughout the course of Korean visual word recognition. The current study extends previous research with readers of Roman alphabets to readers of an alpha-syllabary orthography written in a non-linear spatial layout with more clear-cut syllable boundaries. Taken together, it appears that the involvement of semantic and orthographic information in the decomposition of morphologically complex word may vary depending on the characteristics of the orthography.

Keywords: Korean, morphological decomposition, semantic information, orthographic information, developing readers

INTRODUCTION

There are two main theoretical approaches to explain how morphologically complex words are represented and processed. First, the localist approach of Obligatory Decomposition, put forth by Taft and his colleagues (Taft and Forster, 1975; e.g., Taft, 1979, 2004; Taft and Ardasinski, 2006) considered morphological decomposition to be achieved through the analysis of sublexical orthographic information and it would be applied indiscriminately to affixed (e.g., *teacher*) or pseudo-affixed words (e.g., *corner*). Second, the distributed-connectionist approach (Rueckl and Raveh, 1999; Plaut and Gonnerman, 2000) proposes that learned representations of complex words mediate form and meaning. The learned internal representations develop to the extent of semantic overlap between stem and whole word. Therefore, pseudo-affixed words (e.g., *corner*) or semantically opaque complex words (e.g., *witness*) have representations that are different from those of their stems in these models. This approach would predict that only semantically transparent complex words are decomposed and able to activate the representations of the stems.

Studies employing the partial repetition priming paradigm showed that lexical decision of the target word (e.g., *brave*) was facilitated by the prior presentation of an inflectionally or derivationally related prime (e.g., *bravely*) across a variety of languages and orthographies (Hebrew: Frost et al., 1997; English: Marslen-Wilson and Tyler, 1997, 1998; Marslen-Wilson and Zhou, 1999; French: Longtin and Meunier, 2005; Meunier and Longtin, 2007; Korean: Kim et al., 2015). However, it is unclear whether decomposition is obligatory for all morphological structures or whether it is semantically based since the *brave-bravely* pair not only is morphologically related but also related in semantics and orthography (i.e., +M+S+O in which M stands for morphology, S stands for semantics, and O stands for orthography). Therefore, one critical question in this line of research concerns whether decomposition is morphological, orthographic, or semantic-based, or a combination of two or more factors. Previous studies examining this research question have mostly involved Roman alphabetic orthographies (e.g., English, Dutch, and French) with adult population (e.g., Rastle et al., 2004; Marslen-Wilson et al., 2008). The goal of the current study was to investigate the influence of semantic and orthographic factors on morphological decomposition by comparing several prime/target conditions with adult and developing readers of Korean, a non-Roman alphabetic orthography.

Morphological Decomposition in Adult Readers

The masked priming paradigm (Forster and Davis, 1984) has been commonly used to examine how semantic and orthographic information affects morphological decomposition at the earliest stage of visual word recognition. In masked priming, a forward mask (e.g., #####) is briefly presented, followed by the prime word (e.g., *department*), which may or may not be followed by a backward mask, and finally the target word (e.g., *DEPART*) is presented. The presence of the mask greatly reduces the visibility of the prime and if prime duration is short, participants may not consciously perceive the prime. Comparing the priming effects of +M+S+O (e.g., *teacher-TEACH*) and +M-S+O (related in morphology and form but semantically unrelated, e.g., *corner-CORN*) would reveal whether semantic transparency is necessary for decomposition. Comparing the priming effects of +M-S+O and -M-S+O (merely orthographically overlapped e.g., *dialog-DIAL* because *-og* is not a suffix) would indicate whether morphological structure is necessary for decomposition. Finally, varying the duration of +M-S+O primes would reveal the time course of activation of semantic information during the processing of morphologically complex words. Previous masked priming studies have generally produced two consistent findings. First, +M-S+O produced stronger priming effects than -M-S+O, suggesting that morphological decomposition is not merely orthographic and it appears to be triggered solely by the presence of affixes (Rastle et al., 2004; Rastle and Davis, 2008). Second, priming effects for +M-S+O is significant only with short prime duration suggests that morpho-orthographic segmentation occurs independent of meaning and fades away as primes become visible (Rastle et al., 2000).

Previous research showed that prime-target pairs with semantically transparent relationship (e.g., *cleaner-CLEAN* +M+S+O) and those with apparent morphological relationship but not clear semantic relationship (e.g., *dealer-DEAL* +M-S+O) produced significant and equivalent priming effects at 42 ms prime duration (Rastle et al., 2004). Even when the primes could not be parsed perfectly into stem and affix (e.g., *fetish-FETE*), significant priming effects were still shown at 42 ms prime duration, suggesting that morpho-orthographic decomposition occurs for complex words without clear morphemic boundaries (McCormick et al., 2008). In a masked transposed-letter (TL) priming study, significant priming effects were found in non-word TL stems combined with real suffixes (e.g., *ish* as in *wranish-WARN*) but not in non-word TL stems combined with non-morphemic endings (e.g., *el* as in *wranel-WARN*) with 40 ms prime duration (Beyersmann et al., 2011). In addition to readers of English, morpho-orthographic segmentation was observed in readers of other alphabetic orthographies including French (Longtin et al., 2003), Russian (Kazanina et al., 2008) and Dutch (Diependaele et al., 2005). Although studies (Feldman and Soltano, 1999; Rastle et al., 2000, 2004; Badecker and Allen, 2002; Boudelaa and Marslen-Wilson, 2005; Longtin and Meunier, 2005; Marslen-Wilson et al., 2008) have found significant facilitation for +M+S+O and +M-S+O primes in short prime durations (e.g., 43 and 72 ms), when primes were clearly visible (>200 ms prime duration) in visual priming or in cross-modal priming in which participants were consciously aware of the primes [(Longtin et al., 2003), Experiment 2; Gonnerman et al., 2007; Rueckl and Aicher, 2008], significant facilitation only occurred for +M+S+O (i.e., *TEACHER-teach*) but not for +M-S+O (i.e., *CORNER-corn*). The form-then-meaning hypothesis in word recognition assumes that a word's orthographic form must be processed before its meaning can become available (Feldman et al., 2009). Affixes may be represented as highly productive sublexical morphemic units that are accessed at very early stages of visual word recognition (Beyersmann et al., 2011). A letter chunk that successfully matches an affix representation (e.g., *-ish* in *wranish*) is rapidly identified. After affix-stripping, the remaining letter strings *wran* (even if it is a non-word) activate the representation of *warn*, producing priming. Since the priming effect cannot be attributed to form or semantic overlap between *wranish* and *WARN*, it seems that orthographic analysis is dependent on morphemic structure and it arises at a very early stage before meaning is involved.

In contrast to the facilitative priming effects produced by primes with morphologically decomposable endings (e.g., *corner*-CORN), target words preceded by orthographically overlapped primes with non-morphological endings have generally produced an inhibitory or null effect (e.g., *market-MARK, scandal-SCAN*, neither *-et* nor *-dal* is a suffix in English) (e.g., Rastle et al., 2000, 2004; Marslen-Wilson et al., 2008). Based on the localist approach (Taft and Forster, 1975; Taft, 1979, 2004; Taft and Ardasinski, 2006), non-decomposable endings cannot be stripped from the stem and therefore, words like *market* and *scandal* are processed as whole words. Based on the connectionist approach (Rueckl and Raveh, 1999; Plaut and Gonnerman, 2000), the lexical representations of *market* and *MARK* are not connected since their degree of semantic overlap is very low. Both theoretical approaches would suggest that activation of the lexical representation of the prime would create competition for the activation of the representation of the target word, slowing down lexical decision.

Taken together, previous literature suggests that morphological decomposition occurs automatically and rapidly at the early stage (e.g., shorter than 72 ms) of word recognition. This decomposition process is likely to be based on the orthographic analysis of whether the stimulus contains morphemic structure, irrespective of its lexical, semantic, or syntactic characteristics (Rastle and Davis, 2008). When semantic information is activated, later in the stage of word recognition (e.g., >200 ms), decomposition switched from orthographic-based to semantic-based.

Morphological Decomposition in Developing Readers

To date, only a handful of studies have used the priming paradigm to examine morphological processing in children (Feldman et al., 2002; Rabin and Deacon, 2008; Casalis et al., 2009; Quémart and Casalis, 2014, 2015). Understanding how developing readers process morphologically complex words is important because previous research has shown that morphological awareness in earlier grades predicts reading achievement in later grades (Deacon and Kirby, 2004; Tong et al., 2009; Lam et al., 2012) and morphology training could lead to significant gains in children's word recognition abilities (Chow et al., 2008; Wu et al., 2009). In addition, strong associations have been found between the abilities to manipulate inflectional and derivational morphemes and children's vocabulary knowledge (Champion, 1997; Kuo and Anderson, 2006). Since children have smaller vocabulary size than adults, morphological processing could be fundamentally different between developing and expert readers.

Particularly relevant to the current research question of morphological decomposition, Quémart et al. (2011) found non-semantic-based decomposition in young children. French third, fifth, and seventh graders showed significant priming effects in +M+S+O (e.g., *singer-SING*) +M-S+O (e.g., *corner-CORN*) at 60 and 250 ms prime durations, although the magnitude of priming was significantly greater in +M+S+O at 250 ms. At 800 ms, significant facilitation was observed in +M+S+O and -M+S-O (e.g., *tulip-FLOWER*) but not in +M-S+O. These results provided evidence for morpho-orthographic decomposition among young readers at the early stage of word processing (until 250 ms) while semantic activation only plays a crucial role in morphological processing in the later time course (800 ms). However, in another masked priming study with 57 ms prime duration in Hebrew-speaking fourth and seventh graders (Schiff et al., 2012), while both age groups of children showed significant priming effect in the +M+S condition, only the seventh graders showed significant priming effect in the +M-S condition. These results were inconsistent with Quémart et al. (2011) who found significant facilitation in +M-S+O at 60 ms prime duration in French third and fifth graders. This discrepancy in previous studies may be due to the different characteristics of the orthography, suggesting that there may be cross-linguistic differences in how semantic and orthographic information influences morphological decomposition. The current study aimed to extend these findings to developing readers of Korean, an agglutinative language with a transparent non-Roman alphabetic orthography.

Morphological Processing in Korean Readers

Few studies have examined the influence of semantic and orthographic factors on morphological decomposition in both adult and developing readers of other writing systems. For example, research with adult Hebrew readers has found root primes facilitated the naming and lexical decision of target words that are derived from these words (Frost et al., 1997; Deutsch et al., 1998). Zhou et al. (1999) investigated the interaction between morphological and orthographic information in reading Chinese compound words. +M+S+O primes (e.g., 华丽 *magnificent*– 华贵 *luxurious*) showed facilitation with 57 ms or 200 ms prime durations while -M-S+O prims(e.g., 华侨 *overseas Chinese*– 华贵 *luxurious*) showed inhibition with 200 ms prime duration. Since this study used compound words and Chinese has very limited derivation, these results are less comparable to previous studies using Roman alphabets. Therefore, the current study chose to focus on Korean Hangul for two reasons. First, Korean Hangul is written in a non-linear spatial layout, similar to Chinese characters. Korean graphemes are composed in a square-like block (each corresponding to a syllable), in which the graphemes are arranged left to right and top to bottom. Note that a Hangul letter is not a stroke, some letters may be composed of more than one stroke. A Hangul letter is also not a syllable, each syllable is composed of more than one letter. A Hangul letter is similar to an alphabetic letter in terms of its function.

Each Hangul letter represents a grapheme and corresponds to a phoneme.

Because the Hangul syllable blocks are separated, there is a clear syllable boundary for a Hangul word (e.g., 안녕하십니까 /an nyeong ha sim ni ka/, *hello*). This visually prominent syllable boundary makes the morpheme boundary in Korean Hangul more clear-cut than that in English. This unique feature of the Korean writing system may encourage morphological decomposition to a greater degree than English in which the morpheme boundary can be blurred in words, such as "writer" or "desirable."

The second reason for choosing Korean was that it has a very rich morphology. Particularly, Korean Hangul has very productive, derivational complex word formation, similar to English. Most derivations are generated through affixation. Suffixes are more important than prefixes in deriving new words in Hangul: they are more productive and carry more syntactic functions (Sohn, 1999). For example, the suffix 이 can be added to an adjective, such as 넓 (wide) to form a noun 넓이 (width). The suffix 이 can also be added to a verb, such as 먹 (eat) to form a noun 먹이 (food). This feature of Korean derivation allows us to study morphological processing using the masked priming paradigm similar to previous studies (e.g., Rastle et al., 2000, 2004; Marslen-Wilson et al., 2008) and make the results comparable to those obtained from Roman alphabets.

The Korean language has a simple syllable structure in which there are no initial consonant clusters in syllables; final consonant clusters are limited. Most of words contain one to three syllables. This simpler syllable structure may pose less of a phonemic-level phonological decoding challenge for learning to read Korean in comparison to learning to read English. The grapheme-to-phoneme correspondence in Korean is almost one-to-one except for a few phonological alternations depending on the context that involved changing the sound of the final consonant in a syllable. The highly transparent Korean orthography may put a heavier weight on morphemic information in learning to read.

The Present Study

Native-Korean speaking children in sixth grade and adults were tested using the masked priming paradigm. There were five types of Korean prime-target pairs: (1) orthographically overlapped only (-M-S+O: *도시락-도시*, *scandal-scan*), (2) orthographically overlapped, morphologically decomposable but semantically unrelated (+M-S+O: *구두쇠-구두*, *archer-arch*), (3) morphologically decomposable, semantically related, and orthographically overlapped (+M+S+O: *음악가-음악*, *bravely-brave*), (4) semantically related only (–M+S-O: *반대-이의*, *accuse-blame*), and (5) unrelated (-M-S-O: *장식품–음악*, *ornament-music*).

Following the study by Marslen-Wilson et al. (2008) with adults, we selected three prime durations: 36, 48, and 72 ms. In addition, we added a prime duration of 57 ms based on the study by Castles et al. (1999) with children in grades 2–6. Since Castle et al. were able to show robust form priming effects at 57 ms with second graders and Quémart and Casalis (2014) showed priming effects at 60 ms with third graders, it is expected that the 12-years-old children in the current study would be able to show priming effects at shorter prime durations. The shorter prime durations would allow us to locate the potential earliest time point at which automatic activation of morphological information occurs in children and adults.

The current study was guided by the following research questions: (1) what is the time course of activation of semantic and orthographic information in reading Korean derived words? and (2) what are the differences between Korean skilled and less skilled readers in their sensitivity to semantic and orthographic information in morphological processing? For the first question research, based on previous research with English readers (e.g., Rastle et al., 2000, 2004; Marslen-Wilson et al., 2008), we hypothesized that for Korean adults readers, if morpho-orthographic decomposition occurs at an earlier time course when the primes are unlikely to be visible, there should be facilitative priming effects, similar in magnitude, in both +M+S+O and +M-S+O at 36, 48, and 57 ms (i.e., significantly shorter response latencies and higher accuracy in these conditions compared to -M-S-O). If the involvement of semantic information arises at a later stage, priming effects should be stronger in +M+S+O than in +M-S+O at 72 ms prime duration. In addition, the -M-S+O condition would produce an inhibitory (i.e., significantly longer response times and lower accuracy in this condition compared to -M-S-O) or non-significant priming effect since orthographic overlap alone is not sufficient to facilitate word recognition and could even trigger lexical competition mechanisms.

For the second research question, based on the studies with French fourth graders by Casalis et al. (2009) we hypothesized that Korean sixth graders would show facilitative priming effects in +M+S+O, indicating semantic-based decomposition, as well as inhibitory priming effect in -M-S+O at 72 ms prime duration, suggesting that the orthographic overlap prime creates competition for the activation of the intended lexical representation for the target word. In addition, based on Quémart et al.'s (2011) study with Grade 3–7 French children, we hypothesized that, Korean Grade 6 children would show facilitative priming effects in +M+S+O and +M-S+O at 57 ms, suggesting that morpho-orthographic decomposition may also arise rapidly in less skilled readers. There may also be a significant priming effect -M+S-O at 72 ms since semantic information tends to be activated later in the time course. To the best of our knowledge, no previous studies have used 36 or 48 ms prime durations with young children. However, grade 6 children may be able to show patterns of priming effects at these shorter prime durations that are similar to adults (i.e., facilitation in +M+S+O and +M-S+O and inhibition in -M-S+O) considering that they were more advanced/readers compared to children at lower grades.

In the following four experiments, we compared skilled vs. less skilled native Korean-speaking readers on their activation of semantic and orthographic information in reading Korean derived words at 36, 48, 57, and 72 ms prime durations, respectively.

EXPERIMENT 1

Participants

The participants were native Korean-speaking children in grade 6 and adults. Our decision to recruit sixth graders was based on a pilot study including fourth graders using the same experimental materials, in which we could not observe any reliable priming effects. Grade 6 children, on the other hand, have reading skills that are distinguishable from adults yet are cognitively developed enough to show robust effects in the following masked priming experiment with very short prime durations. There were 28 children ($M_{\text{age}} = 12.0$, $SD = 0.4$, 19 boys) and 32 adults ($M_{\text{age}} = 23.9$, $SD = 4.0$, 15 males). The children participants were recruited from an elementary school in a predominantly middle-class suburb area of Seoul, South Korea. The adult participants were recruited from major universities in Seoul. Based on reports from schoolteachers, the children did not have any reading difficulties. All of the participants had normal or corrected-to-normal vision and thus had no difficulty with reading words on a computer monitor.

Ethics Statement

The current study was approved by the Institutional Review Board (IRB) at the authors' institutions. Written informed consent was obtained from all adult participants and from parents of all non-adult participants prior to the experiments.

Design and Materials

A 2 (age: sixth graders and adults) × 2 (prime type: related [experimental] and unrelated [control]) × 4 (condition: -M-S+O vs. +M-S+O vs. +M+S+O vs. -M+S-O) design was employed. The prime duration was 36 ms. Age group was a between-participant factor while condition and prime type were within-participant factors. Critical stimuli consisted of prime-target pairs co-varying in morphological decomposability, semantic relatedness, and orthographic relatedness. There were four types of prime-target pairs: (1) orthographically overlapped only (-M-S+O: *도시락-도시, scandal-scan*), (2) orthographically overlapped, morphologically decomposable but semantically unrelated (+M-S+O: *구두쇠-구두, archer-arch*), (3) morphologically decomposable, semantically related, and orthographically overlapped (+M+S+O: *음악가-음악, bravely-brave*), and (4) semantically related only (–M+S-O: *반대이의, accuse-blame*). There were a total of 88 related prime-target pairs (22 in each condition) (**Appendix A**). In addition, 88 unrelated primes for each target word (e.g., *장식품 [ornament]–음악 [music]*) were created. Two item lists were constructed so that participants did not see the same target item more than once. Specifically, if the target was preceded by the related prime in List 1, then it was preceded by the unrelated prime in List 2, and vice versa. Participants were randomly assigned to one of the two lists. In addition, forty-four unrelated prime-target pairs (22 suffixed prime-target pairs and 22 non-suffixed prime-target pairs) were generated to lower the ratio of relatedness proportion (0.33) in order to reduce the possibility of participants guessing the characteristics of the experimental items. However, these unrelated prime-target pairs were not included in the lexical decision task for children participants to shorten the length of the experiment. In addition, to ensure the same number of "Yes" and "No" responses, 132 word–non-word pairs were generated for adults and 88 of those word–non-word pairs were used for children.

TABLE 1 | Descriptive statistics of the semantic relatedness ratings for the four experimental conditions.

	Semantically related conditions		Semantically unrelated conditions	
Condition	+M+S+O	-M+S-O	-M-S+O	+M-S+O
Mean	7.12	7.14	1.51	1.78
SD	0.34	0.78	0.40	0.57

The manipulation of semantic relatedness between prime-target pairs was based on pre-experimental ratings. Six native Korean speakers from the same population where the adult participants were drawn rated how related the prime was to the meaning of the target on a 9-point Likert scale, with 1 being not related at all in meaning and 9 being very related in meaning (**Table 1**). Only items with mean semantic relatedness ratings at 6 or above were included in the semantically related conditions (+M+S+O and -M+S-O) and items with mean ratings at 3 or below were included in the semantically unrelated conditions (+M-S+O and -M-S+O). *T*-test results showed that the semantic relatedness ratings between the derived primes and stem targets were significantly higher in the +M+S+O condition than in the +M-S+O condition [$t_{(42)} = -37.76$, $p < 0.01$]. Also, there was no significant difference in semantic relatedness ratings between +M-S+O and -M-S+O [$t_{(42)} = -1.79$, $p = 0.08$] and between +M+S+O and -M+S-O [$t_{(42)} = -0.12$, $p = 0.91$].

Furthermore, primes and targets were matched as closely as possible across the four conditions for the number of graphemes and frequencies (general frequency, children's visual word frequency, and syllable frequency). General frequencies were obtained from a database provided by the National Academy of the Korean Language with a frequency count of 1 per 1.5 million (available on http://www.korean.go.kr). Since this general frequency may not truly reflect children's daily exposure to visual words, textbook frequency obtained from the same database was used to calculate frequency information for children. The textbook frequency was based on 20 elementary school textbooks and 10 middle school textbooks (including nine seventh grade textbooks and one ninth grade textbook). ANOVA (**Table 2**) showed that the four conditions were closely matched on the number of graphemes in the primes, general and textbook frequency comparing among the primes and among the target words (all ps > 0.1). However, there was a significant difference in the number of graphemes in targets ($p < 0.01$) in which the number of graphemes in +M+S+O and -M+S-O were significant larger than that in -M-S+O. This was because the target words in -M-S+O were a combination of monosyllabic and disyllabic words whereas target words in the other conditions were

TABLE 2 | Stimulus characteristics for items across the four conditions.

Property	Conditions				ANOVA
	-M-S+O	+M-S+O	+M+S+O	-M+S-O	
Number of graphemes (T)	3.27	3.86	5.00	4.64	$F_{(3, 84)} = 15.86$, $p < 0.01$
Number of graphemes (P)	6.18	6.55	7.86	7.59	$F_{(3, 84)} = 0.50$, n.s.
General frequency (T)	367.45	257.14	300.27	243.23	$F_{(3, 84)} = 0.30$, n.s.
General frequency (P)	30.14	29.91	66.55	67.64	$F_{(3, 84)} = 0.75$, n.s.
Textbook frequency (T)	20.55	25.41	25.09	14.73	$F_{(3, 84)} = 0.48$, n.s.
Textbook frequency (P)	1.86	3.32	5.73	3.68	$F_{(3, 84)} = 0.34$, n.s.
Syllable frequency for suffix	26,486	40,765	39,912	N/A	$F_{(3, 63)} = 0.72$, n.s.

T, target; P, prime.

majority disyllabic. Furthermore, general frequency and textbook frequency were matched between the related (experimental) primes and unrelated (control) primes [$t_{(180)} = -0.015$, $p = 0.99$, $t_{(180)} = 0.15$, $p = 0.88$, respectively]. Finally, syllable frequencies for the suffixes across the conditions (except -M+S-O since items in this condition do not have suffixes) were well-matched. Syllable frequency for disyllabic suffixes was calculated by averaging the frequency of the first and second syllable. For example, the suffix for the derived word 하마터면 is 터면 and 터면 has two syllables (터 and 면) but one morpheme (터면). There were three such items in -M-S+O, two in +M-S+O, and one in +M+S+O. One-way ANOVA showed no significant difference in syllable frequency across the three conditions ($p > 0.1$).

Procedure

Participants were randomly assigned to each prime duration to minimize the influence of reading abilities on their lexical decision performance. The masked priming lexical decision experiment (Forster and Davis, 1984) was implemented in E-prime (Schneider et al., 2002), which automatically randomized the order of the trials and collected accuracy and response time data. In each trial, the fixation sign (+) was presented for 250 ms, followed by a forward mask (###########) for 800 ms to minimize prime visibility. Then the prime word (e.g., *음악가 [musician]*) was presented for 36 ms and immediately followed by the target (e.g., *음악 [music]*). The participants were instructed to respond as accurately and quickly as possible by pressing the "O" key with the right index finger if they determined the visual target was a real word, and the "X" key with the left index finger if they determined the target was a non-word. The answer keys were the same for all participants regardless of handedness. The target disappeared as soon as a response was made or after 3,000 ms from the onset of the target. Before starting the experimental session, each participant performed eight practice trials with feedback to familiarize with the procedure. Participants were given a short break after half of the trials.

Data Analysis

Response time (RT) data for incorrect responses were excluded from analysis (5.4% of data loss). RT data that were below 400 ms and 2.5 standard deviations above the individual means were also deleted (additional 3.1% of data loss). RT data were log-transformed to improve normality. All subsequent analyses were carried out in R Studio, an open-source programming environment for statistical computing (R Development Core Team, 2008). Unaveraged RT data were submitted to generalized linear mixed-effects modeling using the lmerTest package (Kuznetsova et al., 2013). Accuracy data were submitted to the same modeling method but with the binomial function and *p*-values were based on the *Wald* z distribution using the car package (Fox and Weisberg, 2011). Planned multiple comparisons of means were conducted using the Simultaneous Tests for General Linear Hypotheses from the multcomp package (Hothorn et al., 2008) with Tukey contrasts and adjusted *p*-values. The model was built based on a forward algorithm in which the baseline model was a regression line of log RT or accuracy rates with random intercepts for subjects and items. Each fixed effect, including age group (Grade 6 vs. adults), prime type (related vs. unrelated), condition (-M-S+O vs. +M-S+O vs. +M+S+O vs. -M-S+O), and list (1 vs. 2), and interaction terms were individually added to the model and tested by comparing the log likelihood ratio to that of the simpler model. Only effects that significantly improved the model fit were retained. After the fixed effects and interaction terms had been established, a random slope was individually added for each of the significant fixed effects. Random slopes that did not significantly improve the model fit were removed.

Motivated by our theoretical question of the difference in the time course of morphological processing between developing and skilled readers, we also separated the data by age group and compared the priming effects (the difference in RT and accuracy rates between related and unrelated conditions) of each experimental condition. Both log RT and accuracy data (**Tables 3**, **4**; **Figures 1**, **2**, respectively) were analyzed in each prime duration and each age group using mixed-effect models with main effects of prime type and condition, an interaction between the two, and random intercepts for subjects and items. Planned multiple comparisons were conducted for the interaction between prime type and condition.

TABLE 3 | Mean RT (ms) and standard deviation of Grade 6 children and adults across the four experiments.

SOA (ms)	Condition	Grade 6			Adults		
		Unrelated	Related	Priming	Unrelated	Related	Priming
36	-M-S+O	842 (252)	888 (287)	−46	654 (188)	666 (202)	−12
	-M+S-O	810 (236)	801 (233)	9	631 (178)	624 (179)	7
	+M-S+O	842 (253)	831 (284)	11	655 (189)	652 (218)	3
	+M+S+O	813 (252)	772 (248)	41*	615 (182)	607 (194)	8
48	-M-S+O	878 (280)	907 (292)	−29	660 (162)	719 (230)	−59***
	-M+S-O	904 (280)	855 (286)	49*	651 (184)	637 (181)	14
	+M-S+O	842 (234)	852 (275)	−11	685 (208)	670 (216)	15
	+M+S+O	839 (249)	803 (254)	37^	633 (158)	618 (184)	15
57	-M-S+O	840 (261)	870 (259)	−30	660 (176)	692 (187)	−32**
	-M+S-O	835 (261)	846 (298)	−11	644 (159)	637 (185)	7
	+M-S+O	878 (292)	811 (240)	67^	664 (207)	675 (228)	−11
	+M+S+O	813 (290)	784 (228)	29	625 (188)	594 (159)	31**
72	-M-S+O	893 (303)	887 (287)	6	672 (163)	682 (173)	−10
	-M+S-O	836 (257)	816 (272)	20	657 (172)	633 (164)	24
	+M-S+O	829 (238)	816 (237)	13	668 (153)	649 (174)	19*
	+M+S+O	801 (239)	794 (250)	7	622 (152)	590 (121)	32*

*^p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001. Priming is the difference between unrelated and related conditions. Positive values indicate facilitation and negative values indicate inhibition.*

TABLE 4 | Mean accuracy rates and standard deviation of Grade 6 children and adults across the four experiments.

Prime duration (ms)	Condition	Grade 6			Adults		
		Unrelated	Related	Priming	Unrelated	Related	Priming
36	-M-S+O	0.942 (0.235)	0.873 (0.333)	−0.068*	0.952 (0.215)	0.912 (0.284)	−0.040^
	-M+S-O	0.918 (0.274)	0.935 (0.246)	0.017	0.974 (0.158)	0.986 (0.119)	0.011
	+M-S+O	0.935 (0.247)	0.935 (0.247)	0.000	0.957 (0.202)	0.935 (0.247)	−0.023
	+M+S+O	0.942 (0.235)	0.945 (0.229)	0.003	0.983 (0.130)	0.986 (0.119)	0.003
48	-M-S+O	0.946 (0.226)	0.882 (0.323)	−0.064**	0.943 (0.232)	0.946 (0.226)	0.003
	-M+S-O	0.933 (0.250)	0.952 (0.214)	0.019	0.989 (0.106)	0.986 (0.119)	−0.003
	+M-S+O	0.956 (0.206)	0.970 (0.170)	0.015	0.983 (0.130)	0.969 (0.174)	−0.014
	+M+S+O	0.939 (0.239)	0.943 (0.233)	0.003	0.991 (0.092)	0.989 (0.106)	−0.003
57	-M-S+O	0.918 (0.275)	0.894 (0.308)	−0.024	0.970 (0.170)	0.932 (0.253)	−0.039*
	-M+S-O	0.911 (0.285)	0.943 (0.232)	0.032	0.980 (0.140)	0.991 (0.092)	0.011
	+M-S+O	0.953 (0.213)	0.920 (0.271)	−0.032	0.983 (0.130)	0.966 (0.182)	−0.017
	+M+S+O	0.945 (0.227)	0.948 (0.221)	0.003	0.989 (0.106)	0.986 (0.119)	−0.003
72	-M-S+O	0.938 (0.242)	0.853 (0.355)	−0.085***	0.957 (0.202)	0.935 (0.247)	−0.023
	-M+S-O	0.956 (0.205)	0.949 (0.221)	−0.008	0.977 (0.149)	0.989 (0.106)	0.011
	+M-S+O	0.973 (0.163)	0.943 (0.233)	−0.030	0.988 (0.111)	0.988 (0.111)	0.000
	+M+S+O	0.986 (0.118)	0.941 (0.237)	−0.045	0.991 (0.092)	0.980 (0.140)	−0.011

*^p < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001. Priming is the difference between unrelated and related conditions. Positive values indicate facilitation and negative values indicate interference.*

A similar data analysis procedure was used for all subsequent experiments. Given the large amount of comparisons, we focused our discussion on significant results only.

Results and Discussion

The most parsimonious model with the best fit to the RT data (4,815 data points, **Table 5**, upper part) included effects of age group, prime type, condition, a two-way interaction between prime type and condition, a by-subject random slope for age group and a random intercept for item. The most parsimonious model with the best fit to the accuracy data (5,252 data points, **Table 5**, lower part) included main effects of age group, prime type, and condition, a two-way interaction between age and condition, and a two-way interaction between prime type and

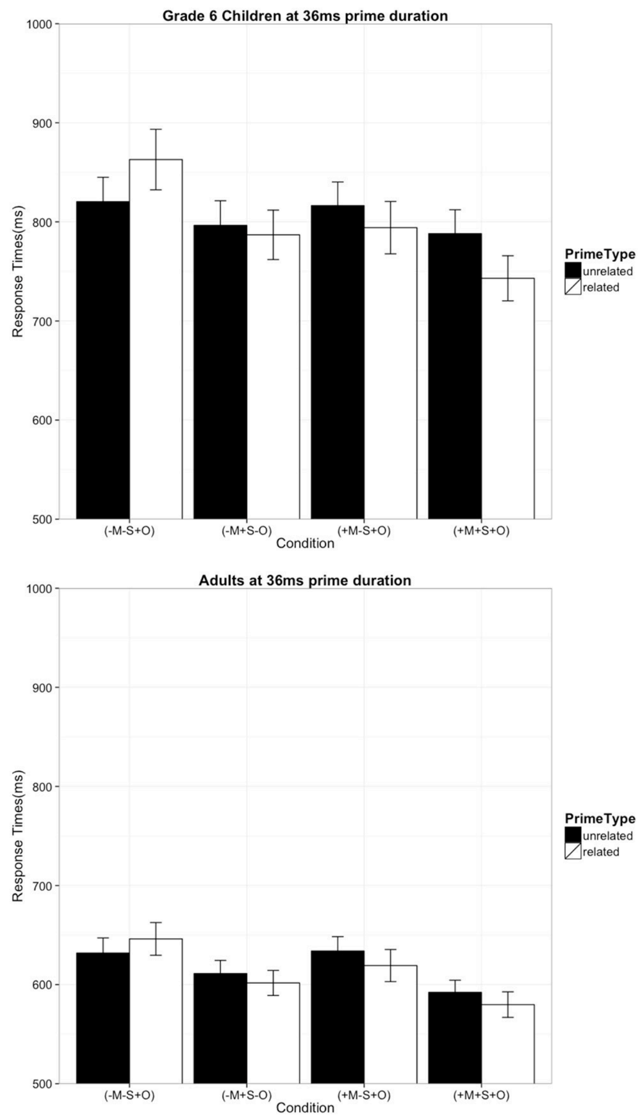

FIGURE 1 | Priming effects in reaction times in Experiment 1.

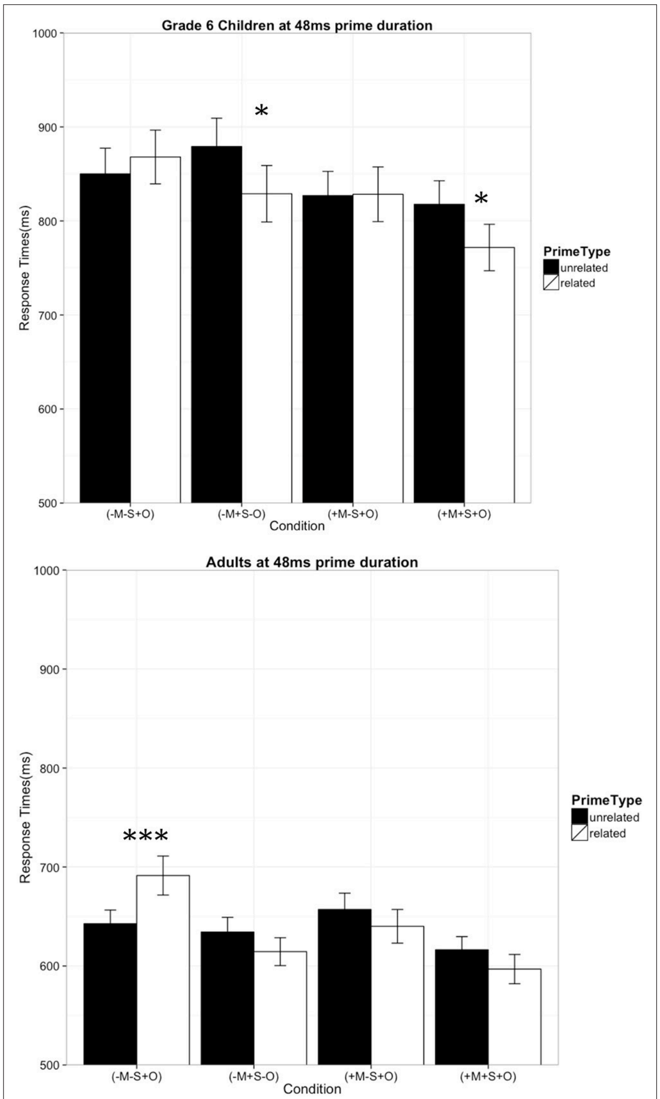

FIGURE 2 | Priming effects in reaction times in Experiment 2 (*$p < 0.05$, ***$p < 0.001$).

condition, and a three-way interaction among age group, prime type, and condition, a by-subject random intercept and a by-item random intercept.

Planned comparison showed that, at 36 ms prime duration, RT data showed a significant facilitative priming effect (41 ms) in +M+S+O ($p = 0.024$) for grade 6 children only. For accuracy, grade 6 children showed a significant inhibitive priming effect in -M-S+O at 36 ms (−6.8%, $p = 0.011$) while adults showed a marginally significant inhibitive priming effect in -M-S+O (−4%, $p = 0.07$). These results suggest that morphological decomposition for semantically related and orthographically overlapped primes (e.g., 음악가-음악, *bravely-brave*) occurred as early as 36 ms for Korean children. In addition, orthographic information was activated at 36 ms and interfered with children's word recognition at this very early stage.

EXPERIMENT 2

Participants

Twenty-eight grade 6 children ($M_{age} = 11.9$, $SD = 0.6$, 12 boys) and 32 adults ($M_{age} = 28.0$, $SD = 3.6$, 15 males) recruited from the same participants pool as that in Experiment 1.

Design, Materials and Procedure

The same design, materials and procedure were used as those in Experiment 1, except that the prime duration was changed to 48 ms.

Results and Discussion

The loss of RT data due to incorrect responses was 4.1% and there was an additional 3.7% loss after removal of RT data that were below 400 ms and 2.5 standard deviations above the individual means. The most parsimonious model with the best fit to the RT data (4,701 data points, **Table 6**, upper part) included effects of age group, prime type, condition, a two-way interaction between prime type and condition, a two-way interaction between age and condition, a by-subject random slope for age group and a random intercept for item. The most parsimonious model with the best fit to the accuracy data (5,084 data points, **Table 6**, lower part) included main effects of age group, prime type, and condition, a two-way interaction between age and condition, and a two-way interaction between prime type and condition, and a three-way interaction among age group, prime type, and condition, a by-subject random intercept and a by-item random intercept.

At 48 ms prime duration, for RT data, grade 6 children showed a significant facilitative priming effect (49 ms) in -M+S-O ($p = 0.037$) and a marginally significant facilitative priming effect (37 ms) in +M+S+O ($p = 0.086$). Adults showed a significant inhibitive priming effect (−59 ms) in -M-S+O ($p < 0.001$). For accuracy data, children showed a significant inhibitive priming effect in -M-S+O (−6.4%, $p = 0.008$) while adults did not show any significant priming effect. These results suggest semantic information was activated as early as 48 ms for developing readers. Furthermore, both children and adults were sensitive to orthographic information at this early stage of word recognition.

TABLE 5 | Results from the ANOVA approach to linear mixed-effects model analysis of log RT and accuracy rates in Experiment 1 with 36 ms prime duration.

Fixed effects	Sum Sq	Mean Sq	Num DF	Den DF	*F*-value	Pr(>F)
Log RT						
Age group	0.556	0.556	1	26.5	81.186	<0.001
Prime type	0.036	0.036	1	4668.5	5.270	0.021
Condition	0.150	0.050	3	83.8	7.302	<0.001
Prime type × Condition	0.164	0.055	3	4668.5	8.000	<0.001

Fixed effects	Sum Sq	Mean Sq	Num DF	*F*-value	Pr(>F)
Accuracy					
Age group	14.560	14.560	1	14.560	<0.001
Prime type	4.781	4.781	4	4.781	0.052
Condition	5.962	1.987	3	1.987	0.118
Prime type × Condition	12.805	4.268	4	4.268	0.004
Age group × Condition	15.621	5.207	3	5.207	0.001

Age group = sixth graders vs. adults. Prime type = related vs. unrelated. Condition = -M-S+O vs. +M-S+O vs. +M+S+O vs. -M+S-O.

TABLE 6 | Results from the ANOVA approach to linear mixed-effects model analysis of log RT and accuracy rates in Experiment 2 with 48 ms prime duration.

Fixed effects	Sum Sq	Mean Sq	Num DF	Den DF	*F*-value	Pr(>F)
Log RT						
Age group	0.491	0.491	1	34.1	70.918	<0.001
Prime type	0.054	0.054	1	4552.1	7.775	0.005
Condition	0.114	0.038	3	81.6	5.479	<0.001
Age group × Condition	0.141	0.046	3	4584.3	6.765	<0.001
Prime type × Condition	0.290	0.097	3	4552.3	6.765	<0.001

Fixed effects	Sum Sq	Mean Sq	Num DF	*F*-value	Pr(>F)
Accuracy					
Age group	26.990	26.990	1	26.990	<0.001
Prime type	1.343	1.343	1	1.343	0.321
Condition	6.856	2.285	3	2.285	0.077
Prime type × Condition	3.320	1.107	3	1.107	0.342
Age group × Condition	12.464	4.155	3	4.155	0.004

Age group = sixth graders vs. adults. Prime type = related vs. unrelated. Condition = -M-S+O vs. +M-S+O vs. +M+S+O vs. -M+S-O.

TABLE 7 | Results from the ANOVA approach to linear mixed-effects model analysis of log RT and accuracy rates in Experiment 3 with 57 ms prime duration.

Fixed effects	Sum Sq	Mean Sq	Num DF	Den DF	*F*-value	Pr(>F)
Log RT						
Age group	0.451	0.451	1	61.8	65.120	<0.001
Prime type	0.015	0.015	1	4787.8	2.158	0.142
Condition	0.148	0.049	3	83.9	7.114	<0.001
Age × Prime type	0.004	0.004	1	4784.7	0.594	0.441
Age group × Condition	0.055	0.018	3	4811.8	2.654	0.047
Prime type × Condition	0.169	0.056	3	4787.8	8.153	<0.001
Age group × Prime type × Condition	0.068	0.023	3	4784.8	3.280	0.020

Fixed effects	Sum Sq	Mean Sq	Num DF	*F*-value	Pr(>F)
Accuracy					
Age group	25.085	25.085	1	25.085	<0.001
Prime type	3.379	3.379	1	3.379	0.102
Condition	6.798	2.266	3	2.266	0.083
Prime type × Condition	12.412	4.37	3	4.137	0.005
Age group × Condition	9.119	3.039	3	3.039	0.024

Age group = sixth graders vs. adults. Prime type = related vs. unrelated. Condition = -M-S+O vs. +M-S+O vs. +M+S+O vs. -M+S-O.

EXPERIMENT 3

Participants

Thirty-two grade 6 children ($M_{\text{age}} = 12.0$, $SD = 0.5$, 14 boys) and 32 adults ($M_{\text{age}} = 24.1$, $SD = 2.8$, 15 males) were recruited from the same participants pool as that in Experiments 1 and 2.

Design, Materials and Procedure

The same design, materials and procedure were used as those in Experiments 1 and 2, except that the prime duration was changed to 57 ms.

Results and Discussion

The loss of RT data due to incorrect responses was 4.7% and there was an additional 3.5% loss after removal of RT data that were below 400 ms and 2.5 standard deviations above the individual means. The most parsimonious model with the best fit to the RT data (4,935 data points, **Table 7**, upper part) included effects of age group, prime type, condition, a two-way interaction between prime type and condition, a two-way interaction between age and condition, a three-way interaction among age group, prime type, and condition, and two random intercepts for subjects and items. The most parsimonious model with the best fit to the accuracy data (5,364 data points, **Table 7**, lower part) included effects of age group, prime type, condition, a two-way interaction between age and condition, and a two-way interaction between prime type and condition, and random intercepts for subjects and items.

At 57 ms prime duration, for RT data, grade 6 children showed a marginally significant facilitative priming effect (67 ms) in +M-S+O ($p = 0.073$) (**Figure 3**). Adults showed a significant inhibitive priming effect (−32 ms) in -M-S+O ($p = 0.006$) and a significant facilitative priming effect (31 ms) in +M+S+O ($p = 0.009$). For accuracy data, only adults showed a significant inhibitive priming effect in -M-S+O (−3.9%, $p = 0.018$). Similar to Experiment 2, the activation of orthographic information continued to play a role in adult readers' word recognition at 57 ms. In addition, morphological decomposition of semantically and orthographically primes occurred at 57 ms for adult readers, which is at a later stage compared children who showed significant priming effect in +M+S+O at 36 ms in Experiment 1.

EXPERIMENT 4

Participants

Twenty-eight grade 6 children ($M_{\text{age}} = 12.0$, $SD = 0.5$, 14 boys) and 32 adults ($M_{\text{age}} = 24.6$, $SD = 4.9$, 14 males) were recruited from the same participants pool as that in Experiments 1, 2, and 3.

Design, Materials and Procedure

The same design, materials and procedure were used as those in Experiments 1, 2, and 3, except that the prime duration was changed to 72 ms.

Results and Discussion

The loss of RT data due to incorrect responses was 3.9% and there was an additional 3.9% loss after removal of RT data that were below 400 ms and 2.5 standard deviations above the individual means. The most parsimonious model with the best fit to the RT data (4,563 data points, **Table 8** upper part) included effects of age group, prime type, condition, a two-way interaction between prime type and condition, a two-way interaction between age and condition, a by-subject random slope and a random intercepts for items. The most parsimonious model with the best fit to the accuracy data (4,935 data points, **Table 8** lower part) included effects of age group, prime type, condition, a two-way interaction between prime type and condition, and random intercepts for subjects and items.

At 72 ms prime duration, none of the planned comparisons for RT data was statistically significant (all $ps > 0.3$) for grade 6 children (**Figure 4**). In contrast, for adults, there were

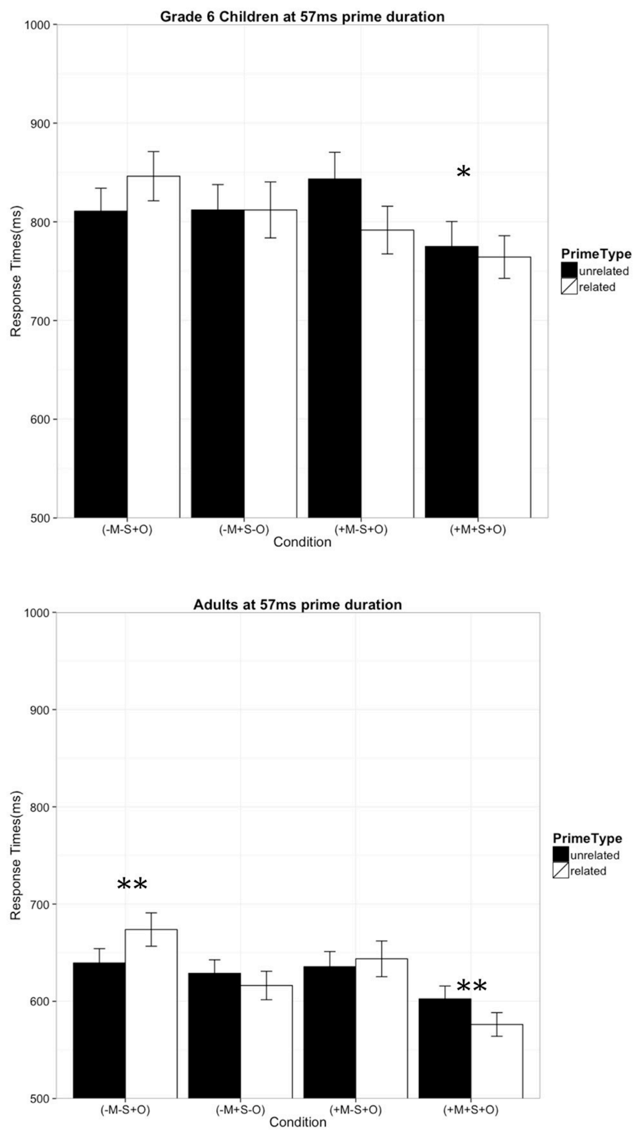

FIGURE 3 | Priming effects in reaction times in Experiment 3 (*$p < 0.05$, **$p < 0.01$).

significant facilitative priming effects in both +M-S+O (19 ms, $p = 0.045$) and +M+S+O (31 ms, $p = 0.038$). For accuracy data, the only significant finding was an inhibitive effect in -M-S+O (−8.5%, $p < 0.001$) for children. These results suggest that morphological decomposition independent of semantic information (e.g., 구두쇠-구두, *archer-arch*) occurred at 72 ms for adult readers while orthographic information was activated at this stage of word recognition for developing readers.

GENERAL DISCUSSION

The current study aimed to investigate the influence of morphological, orthographic, and semantic information at the early stage of visual word recognition in developing and adult readers of Korean. Using the masked priming paradigm with four prime durations between 36 and 72 ms, we manipulated morphological decomposability, semantic relatedness, and orthographic overlap between prime-target pairs. The following discussion only focuses on the significant findings. First, adult readers showed a significant facilitative priming effect at 57 ms prime duration only in the +M+S+O condition while significant facilitation was observed in both +M+S+O (e.g., *bravely-BRAVE*) and +M-S+O (e.g., *archer-ARCH*) at 72 ms. The finding that "archer" could lead to faster response of "arch" suggests that Korean adult readers decompose derived words into stem and suffix (i.e., arch + er) on the basis of morpho-orthographic analysis even though the prime-target pair had a semantically opaque relationship. The second key finding is that Korean sixth graders showed significant facilitation in +M+S+O at 36 ms prime duration, suggesting that morphological decomposition occurs rapidly for less skilled readers of a non-Roman alphabetic writing system. Third, sixth graders showed a significant facilitative priming effect in -M+S-O at 48 ms, suggesting that semantic information was activated relatively early in Korean children's visual word recognition. Finally, both adults and grade 6 children showed significant inhibitory priming effects in -M-S+O across different prime durations. These results suggest that orthographic information was activated early in both developing and skilled readers and the inhibition may stem from lexical competition among orthographically similar candidates.

Morpho-Orthographic Decomposition in Korean

The first key finding of significant facilitation in both +M+S+O and +M-S+O at 72 ms prime duration in adult readers provides evidence for morpho-orthographic decomposition in Korean. This adds to a growing body of research focusing on Roman and Cyrillic alphabets (e.g., English: Rastle et al., 2000; 2004, Marslen-Wilson et al., 2008; French: Longtin et al., 2003; Russian: Kazanina et al., 2008). This result demonstrated that the early visual word recognition of Korean Hangul, an orthography written in a non-linear spatial layout with clear syllable boundaries, is based on morphological structure and independent of meaning.

On the other hand, a significant priming effect in +M+S+O at 57 ms prime duration suggests that meaning-dependent morphological decomposition also occurs at the early stage of word recognition. This finding is generally consistent with previous masked morphological priming studies involving Korean. For example, Kim et al. (2015) found a facilitative priming effect for derived real words at 47 ms for monolingual Korean-speaking adults. Similarly, Kim and Wang (2014) observed a significant priming effect at 36 ms for Korean-English bilingual adults using Korean primes and English target words. It appears that morpho-orthographic decomposition in Korean occurs at a slightly later time course (i.e., 72 ms) compared to the results from English speakers [i.e., 42 ms in Rastle et al. (2004) and 36 ms in Marslen-Wilson et al.

TABLE 8 | Results from the ANOVA approach to linear mixed-effects model analysis of log RT and accuracy rates in Experiment 4 with 72 ms prime duration.

Fixed effects	Sum Sq	Mean Sq	Num DF	Den DF	*F*-value	Pr(>F)
Log RT						
Age group	0.451	0.451	1	31.7	73.225	<0.001
Prime type	0.076	0.076	1	4418.1	12.396	<0.001
Condition	0.173	0.058	3	82.9	9.350	<0.001
Prime type × Condition	0.047	0.016	3	4418.5	2.557	0.053
Age group × Condition	0.064	0.022	3	4451.3	3.500	0.015

Fixed effects	Sum Sq	Mean Sq	Num DF	*F*-value	Pr(>F)
Accuracy					
Age group	29.344	29.344	1	29.344	<0.001
Prime type	14.282	14.282	1	14.282	<0.001
Condition	12.2198	4.073	3	4.073	0.008
Prime type × Condition	7.396	2.465	3	2.465	0.051

Age group = sixth graders vs. adults. Prime type = related vs. unrelated. Condition = -M-S+O vs. +M-S+O vs. +M+S+O vs. -M+S-O.

(2008)]. One possible explanation for these different findings is the need to integrate semantic information in morphological decomposition due to the large number of homographs in the Korean orthography. Homographs refer to words with the same spelling (but not necessarily the same pronunciation) but having different meanings and origins. In the current study, 91% of the derived words across the three +O conditions have monosyllabic suffixes and syllables with more than one meaning (Yi, 2009). For example, 음악가 [musician] is decomposed into 음악 [music] + 가 [-ian]; 가 is a homograph with several different meanings, such as [edge], [approval], [man], and [street], and all of them may be activated. It takes time to resolve the semantic ambiguity for the target suffix 가, which should be [man] in the current example. Prime durations <72 ms may not be sufficient for Korean adults to select the correct meaning for the suffix in the prime word, resulting in null priming effects for 36, 48, and 57 ms prime durations. In contrast to Korean, most English derivational suffixes only have one meaning (except for *-er* which can mean [more] or [person]). For example, *-ful* means [full of] as in *joyful* while *-less* means [without] as in *careless*. Therefore, activation of the semantic representation for the suffix may be much quicker for English readers. These cross-linguistic variations in writing systems may help partially explain the differences in the time course of morpho-orthographic decomposition between readers of Korean and readers of English.

Morphological Effects in Developing Readers

The second key finding is the significant facilitation in +M+S+O observed in sixth grade children at 36 ms prime duration. To the best of our knowledge, the shortest prime duration used in previous research with children was 57 ms by Castles et al. (1999) with English-speaking children in grades 2–6. Our results with Korean-speaking children demonstrated that 36 ms prime duration was sufficient to produce robust effects in a masked priming paradigm for developing readers in upper grades. More importantly, these results suggest that Korean developing readers decompose derived words into stem and suffix as early as 36 ms. A possible explanation for the early occurrence of the morphological priming effect is the clear-cut syllable boundary of the Korean orthography (e.g., 안녕하십니까). This visually prominent syllable boundary makes the morpheme boundary in Korean Hangul more salient, thus, encouraging morphological decomposition to a greater degree than English in which the morpheme boundary can be blurred (e.g., *writer*).

In contrast to adults who showed significant facilitation in +M+S+O at 57 ms prime duration, this significant priming effect was observed in sixth grade children at 36 ms. One possible explanation for the different time course between developing and adult readers is that less skilled readers have a smaller mental lexicon, hence, they may not know or be able to activate all of the different meanings of the monosyllabic suffix, a homograph in nature, within a short amount of time. For example, children may be slower to access the different meanings of 가 (e.g., [edge], [approval], [man], and [street]), resulting in less semantic competition and faster activation of the intended semantic representation (e.g., [man]) of the target word (e.g., 음악가 [musician]) which facilitates word recognition. Therefore, sixth graders showed earlier morphological priming effects in +M+S+O compared to adults.

Semantic and Orthographic Effects in Adult and Developing Readers

The third key finding is that grade 6 children showed significant facilitation for -M+S-O primes at 48 ms prime duration, suggesting the relatively early activation of semantic information in visual word recognition of developing readers of Korean. This finding is different from previous studies with French-speaking children (Bonnotte and Casalis, 2009; e.g., Quémart et al., 2011) in which semantic related primes did not speed up lexical decision of target words at 60 ms prime duration but did facilitate lexical judgment at 250 and 800 ms. We speculate

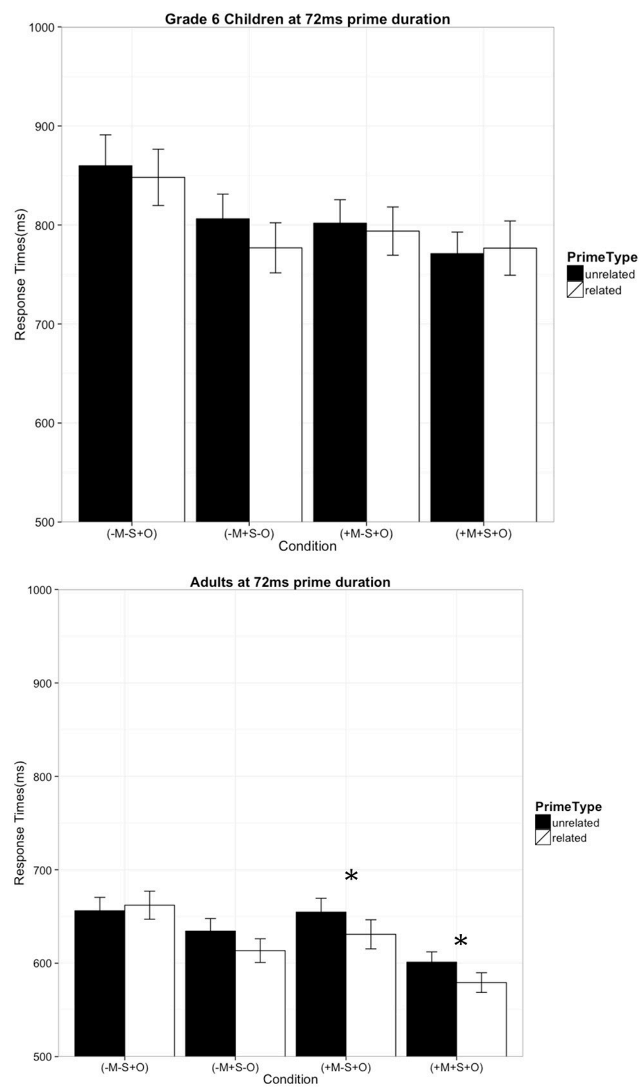

FIGURE 4 | Priming effects in reaction times in Experiment 4 (*$p < 0.05$).

that one potential reason for the difference in the time course of semantic activation may be the saliency of semantic information in the Korean language. There are three types of words in the Korean vocabulary: native words (∼35%), Sino-Korean words (about 60%), and loan words (about 5%). Sino-Korean words were originated from or influenced by *hanja* (i.e., Chinese characters). In contrast to alphabetic writing systems in which each grapheme maps onto a phoneme, each Chinese character maps onto a morpheme. In fact, previous research with Chinese adult readers showed significant semantic priming effects as early as 57 ms (Zhou and Marslen-Wilson, 2000) when reading single characters as well as Chinese compound words. Considering that two-thirds of the Korean vocabulary is loaned from Chinese or words coined using *hanja*, semantic information may be particularly salient to Korean readers compared to readers of alphabetic writing systems. It is common practice in South Korea for children to receive private tutoring in learning to read Hanja, whereas adults may be much more exposed to Hangul only (Pae, 2017, personal communication). In the current study, we did not have a report from the parents on whether their children were receiving *hanja* tutoring or the amount of *hanja* exposure. Future research can collect information about Korean readers' *hanja* exposure and compare semantic priming effects between those with extensive exposure to *hanja* and those with limited exposure. If experiences with *hanja* indeed play a role in the activation of semantic information in word recognition, children with more *hanja* exposure should have greater or earlier semantic priming effect than children with less *hanja* exposure.

The fourth key finding is the robust significant inhibition in -M-S+O observed in both skilled and less skilled readers. Specifically, this inhibitory effect occurred as early as 36 ms prime duration for developing readers and at 48 ms for adult readers. These results are consistent with previous research with adult English readers (Bijeljac-Babic et al., 1997; Brysbaert et al., 2000; Davis and Lupker, 2006). These lexical inhibition effects can be explained by the Interactive Activation (IA) model (McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982), which assumes that there are three levels of representations including a feature level, a letter level, and a word level. The representational units at lower levels feed activation and inhibition to higher levels. For example, when the unit representing the letter "도" at the first letter position receives activation from the feature level, it sends activation to all word level units in which the word has "도" as an onset while simultaneously sends inhibition to all word level units in which the word has other letters at the onset position. In addition, when the target word (e.g., 도시 *city*) is presented and its corresponding word unit is activated, it sends inhibition to all other word-level units which have received some activation from the letter-level units (e.g., 도시락 *lunch box*). To the best of our knowledge, the current study is one of the first to observe lexical inhibition in Korean adult and developing readers. It appears that the IA model can be extended to explain word recognition in a non-Roman alphabetic orthography, such as Korean and this lexical selection processes is also present in developing readers with a smaller lexicon.

Limitations and Future Directions

One of the few noteworthy limitations in the current study was that prime durations longer than 72 ms were not included in the masked priming lexical decision task. Presenting the prime for 200 ms or longer may increase the probability of finding significant semantic effects in adult readers. Besides making methodological modifications, future research should replicate the masked priming paradigm with other non-Indo-European agglutinative languages, such as Japanese to examine the generalizability of the current findings.

The current study showed significant morphological priming effects at 36 ms prime duration for sixth graders. In addition, Quémart et al. (2011) showed significant facilitation with +M+S+O and +M-S+O primes at 60 ms prime duration for third graders. Future research should consider adapting the masked priming lexical decision task with shorter prime durations for younger children (i.e., fourth graders) to examine the earliest time course of morphological decomposition among children with less advanced reading abilities.

A number of studies have demonstrated that children rely on their knowledge of morphological information when they read morphologically complex words across a variety of languages (e.g., English: Deacon et al., 2011; Dutch: Verhoeven and Schreuder, 2011; Italian: Marcolini et al., 2011; Angelelli et al., 2014; Spanish: Lázaro et al., 2013). Particularly, children were faster to read aloud and make lexical judgment for words with high-frequency root morphemes than those with low-frequency root morphemes. Moreover, the ability to apply this morpheme-based strategy appears to be a function of reading skills since dyslexic children were less sensitive to the frequency effect (Lázaro et al., 2013). However, since these studies were conducted with developing readers of Roman alphabets, it is not clear whether their findings can be generalized to readers of other types of alphabets or orthography. It would be worthwhile for future studies to include measures of word reading and reading comprehension abilities to examine the relationship between reading acquisition and morphological processing in developing readers of other alphabetic systems.

The current study recruited only a small sample size of children in each experiment ($N = 28$ in 36 ms, 28 in 48 ms, 32 in 57 ms, and 28 in 72 ms prime duration, respectively). Future research needs to be creative and to use a simpler design with more trials in each condition and with a larger sample size. Another limitation is that we did not collect information about children's reading levels, thus we were unable to match it across prime durations. Since prime duration was treated as a between-participants variable, it is important for future research to closely match children participants' reading level across prime durations. Finally, future research should allow the participants to use their dominant hands for "yes" responses.

Conclusion

The current study made several important theoretical contributions to the literature. First, the current study is one of the first to examine the involvement of semantic and orthographic information in the processing of derived words for both skilled and less skilled readers of a non-Roman alphabetic orthography. Second, the current study is one of the first to vary four prime durations (e.g., 36–72 ms) in a masked priming lexical decision task for developing readers. Results showed significant morphological priming effects for sixth graders at 36 ms and for skilled readers at 57 ms, suggesting that morphological decomposition arises earlier for less skilled readers, probably due to their smaller lexicon and less competition for semantic activation for the monosyllabic suffix, which is a homograph in the Hangul orthography. Third, the current study showed that semantic-based morphological decomposition occurs earlier than orthographic-based decomposition for Korean skilled readers and semantic priming effect arises early for sixth grade children at 48 ms prime duration. Korean readers may be particularly sensitive to semantic information due to the large number of words originated from Hanja or Chinese characters. Finally, both adults and children showed significant inhibition for orthographically overlapped primes with non-morphological endings across the four prime durations, suggesting that orthographic information plays an important role throughout the early to later stage of Korean visual word recognition. The current study extends previous research with readers of Roman and Cyrillic alphabets to readers of an alpha-syllabary orthography written in a non-linear spatial layout, showing that the involvement of semantic and orthographic information in morphological processing may vary depending on characteristics of the orthography. While semantic activation may occur later in the time course of English word recognition, it appears to occur earlier and plays a more important role in Korean word recognition.

AUTHOR CONTRIBUTIONS

MW and IK conceived and designed the experiments. IK performed the experiments. CL analyzed the data. CL and MW wrote the paper.

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Conflict of Interest Statement: 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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APPENDIX A

TABLE A1 | Stimuli used in the masked priming lexical decision task.

Condition	Prime	Target	Condition	Prime	Target
-M-S+O	아가미 gill	아가 baby	**+M-S+O**	구두쇠 miser	구두 shoes
	달걀 egg	달 moon		곰보 pockmarked person	곰 bear
	씨름 wrestling	씨 seed		방정식 equation	방정 a rash act
	고사리 bracken	고사 exam		고무적 encouraging	고무 rubber
	방울 bell	방 room		가시적 visibility	가시 thorn
	도시락 lunch box	도시 city		귀퉁이 corner	귀 ear
	다리미 iron	다리 leg		사랑채 detached house	사랑 love
	자격 qualification	자 ruler		고리짝 a wicker trunk	고리 ring
	사투리 dialect	사투 desperate struggle		배우자 spouse	배우 actor
	잠수 diving	잠 sleep		지구력 spadework	지구 phlegm
	하마터면 almost	하마 hippo		이유기 the weaning period	이유 reason
	비밀 secret	비 rain		손님 gueset	손 hand
	주사위 dice	주사 injection		개성 individuality	개 dog
	피곤 fatigue	피 blood		유리식 a rational expression	유리 glass
	버스럭 rustle	버스 bus		피로연 reception	피로 fatigue
	빵긋 with a smile	빵 bread		토박이 natives	토 postposition
	거리끼다 stand in the way	거리 distance		야유회 picnic	야유 banter
	별명 nickname	별 star		지진아 retarded child	지진 earthquake
	부리나케 in a hurry	부리 beak		무용담 heroic episode	무용 dance
	실신 faint	실 thread		돌쇠 servant	돌 stone
	목축 farming	목 neck		철학 philosophy	철 iron
	색출 track down	색 color		조리개 aperture	조리 cook
+M+S+O	가위질 scissoring	가위 scissor	**-M+S-O**	반대 opposite	이의 objection
	정치가 politics	정치 politician		사탕 candy	과자 cookie

(Continued)

TABLE A1 | Continued

Condition	Prime	Target	Condition	Prime	Target
	매력적	매력		학업	공부
	attractive	attract		learning	study
	문화적	문화		삭제	제거
	cultural	culture		deletion	removal
	장난감	장난		동그라미	원
	toy	game		circle	circle
	멋쟁이	멋		가난	빈곤
	dandy	stylishness		poverty	poverty
	음악가	음악		요괴	괴물
	musician	music		goblin	monster
	개인용	개인		소원	희망
	personal	individual		wish	hope
	기대감	기대		결핍	부족
	expectation	expect		insufficiency	lack
	영화관	영화		식사	밥
	movie theater	movie		meal	rice
	맛깔	맛		부엌	주방
	taste	taste		kitchen	kitchen
	미술품	미술		뚜껑	마개
	art work	art		lid	cork
	동물원	동물		부탁	요구
	zoo	animal		asking	request
	수영복	수영		누나	언니
	swimwuit	swimming		sister	sister
	응원단	응원		가게	상점
	cheer group	cheering		store	store
	일기장	일기		열매	과일
	diary	diary		fruit	fruit
	음식점	음식		안정	평화
	restaurant	food		stability	peace
	요리사	요리		아우성	소란
	chef	cooking		shout	disturbance
	선생님	선생		도서	책
	teacher	teacher		book	book
	연락처	연락		천사	요정
	contact address	contact		angel	fairy
	사냥꾼	사냥		불평	원망
	hunter	hunting		complaint	blame
	치료제	치료		머저리	바보
	medicine	cure		jerk	fool