Semantic Processing of Previews Within Compound Words

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Previous studies have suggested that previews of words prior to fixation can be processed orthographically, but not semantically, during reading of sentences (K. Rayner, D. A. Balota, & A. Pollatsek, 1986). The present study tested whether semantic processing of previews can occur within words. The preview of the second constituent of 2-constituent Finnish compound nouns was manipulated. The previews were either identical to the 2nd constituent or they were incorrect in the form of a semantically related word, a semantically unrelated word, or a semantically meaningless nonword. The results indicate that previews of 2nd constituents within compound words can be semantically processed. The results have important implications for understanding the nature of preview and compound word processing. These issues are crucial to developing comprehensive models of eye-movement control and word recognition during reading.

Keywords: reading, eye movements, word recognition, parafoveal processing

A critical issue for understanding word recognition as well as eye-movement control during reading is determining when processing of the meaning of words takes place. The time course of semantic processing is of special interest in regard to compound words within which morphemic semantic information is spatially localized to separate constituents (e.g., *black* and *board* in *black-board*). The present study tests two important theoretical issues: (a) whether within-word previews prior to fixation can be processed semantically and (b) whether the lexical or semantic characteristics of compound word constituents are initially processed separately or together.

The issue of whether text previewed prior to fixation can be semantically processed is a fundamental issue for understanding eye-movement behavior during reading (Rayner, 1998). For adjacent words, orthographic (e.g., Lima & Inhoff, 1985) and phonological (Pollatsek, Lesch, Morris, & Rayner, 1992) information can be extracted from the word to the right of the fixated word. However, several studies have shown no evidence for semantic processing of word previews that are subsequently fixated (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Hyönä & Häikiö, 2005; Rayner, Balota, & Pollatsek, 1986; for a review see Rayner, White, Kambe, Miller, & Liversedge, 2003).[1]

A recent study by Hyönä, Bertram, and Pollatsek (2004) suggests that considerably more processing of previewed text is undertaken within compound words, compared with between two adjacent words. Consequently, if semantic processing of previews occurs anywhere, then perhaps it is most likely to occur within compound words. Therefore, the present study tested whether the preview of the second constituent of two-constituent Finnish noun compounds can be semantically processed. We used the saccade contingent change boundary technique (Rayner, 1975) such that there was an invisible boundary just before the second constituent. Prior to the eye crossing the boundary, the preview of the second constituent was (a) identical to the correct form, (b) a semantically related word to the second constituent, (c) a semantically unrelated word to the second constituent, or (d) a pronounceable nonword. When the eye crossed the boundary, the preview always changed to the correct second constituent. If the preview was semantically processed, then reading times should have been shorter when the preview was semantically related compared with when it was semantically unrelated to the second constituent.

The study also has implications for whether the lexical characteristics of compound noun constituents are processed separately or together, which is a critical issue for both models of eye-movement control during reading and models of word recognition. Some models of eye-movement control suggest that lexical processing can be undertaken only one word at a time (Reichle, Rayner, & Pollatsek, 2003), whereas other accounts hold that lexical processing can be undertaken in parallel across multiple words (Engbert, Nuthmann, Richter, & Kliegl, 2005; Kennedy, 2000). Similarly, a critical question for the nature of word recognition for compound words is whether the individual constituents are identified separately or pro-

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[1] Although some studies have claimed to show semantic preview effects, there is doubt over whether these really demonstrate semantic preprocessing. Rayner and Morris (1992) failed to replicate Underwood, Clews, and Everatt's (1990) finding that informativeness can influence where words are first fixated. See also White and Liversedge (2004) and Rayner, Warren, Juhasz, and Liversedge (2004).

cessed together (Andrews, Miller, & Rayner, 2004; Bertram & Hyönä, 2003; Hyönä & Pollatsek, 1998; Juhasz, Starr, Inhoff, & Placke, 2003; Pollatsek, Hyönä, & Bertram, 2000). In the present study, if the visual-orthographic, lexical, or semantic characteristics of the second constituent are processed in parallel with the first constituent, then the second constituent preview may influence first-pass fixations on the first constituent.

Method

Participants

Analyses are presented for 28 students from the University of Turku with normal or corrected-to-normal vision who participated in the experiment for course credit. All were native speakers of Finnish and were naïve in relation to the purpose of the experiment.

Apparatus

Eye movements were monitored using an EyeLink II eye tracker (SR Research, Ontario, Canada). Pupil location was sampled at a rate of 500 Hz. Viewing was binocular, although only monocular eye movements were recorded. Spatial accuracy was better than 0.5°. The sentences were presented on a ViewSonic P225f monitor with a refresh rate of 7 ms (150 Hz). Given data processing delays and refresh rates, display changes occurred within approximately 8–13 ms of the boundary being crossed.

Materials and Design

The parafoveal preview of the second constituent of Finnish compound nouns was manipulated. There were four preview conditions: (a) identical to the correct form, (b) a semantically related word to the second constituent, (c) a semantically unrelated word to the second constituent, or (d) a pronounceable nonword. Table 1 shows examples of the stimuli for each of the conditions.

The critical compound words were composed of two noun constituents that were directly adjacent (no spaces or hyphens) to one another. Previous research indicates that there may be more processing of the second constituent previews if they are predictable (constrained) on the basis of the first constituent (Hyönä et al., 2004). Therefore, critical words were selected in which the correct second constituents were strongly constrained by the first constituent. The semantically related previews were related to the second constituents such that they were associated (e.g., chair–table) or had common semantic characteristics (e.g., mustard–sauce). Note that the first constituent and the incorrect word previews of the second constituent never produced a real compound. The semantic relatedness of the second constituent nouns and their word previews was assessed by a pretest. Twelve participants were asked to rate on a scale of 1 to 7 the semantic relatedness between the two words. The previews in the semantically related condition were rated as being significantly more related to the second constituent ($M = 5.8$, $SD = 0.5$, $Min = 4.5$) compared to the previews in the semantically unrelated condition ($M = 1.4$, $SD = 0.3$, $Max = 2.5$), $t_2(55) = 53.14$, $p < .001$. The three word-preview conditions (but naturally not the nonword condition) were matched on a number of relevant factors (see Table 2), extracted from the unpublished 22.7 million-word newspaper corpus *Turun Sanomat* (Laine & Virtanen, 1999). Overall, we took great care to

Table 1

Example Experimental Sentence

Preview condition	Sentence
Identical	
Finnish	Lauran mielestä *vaniljakastike* kuuluu yhteen omenapiirakan kanssa.
English translation	According to Laura *vanillasauce* goes well together with apple pie.
Semantically related	
Finnish	Lauran mielestä *vaniljasinappi* kuuluu yhteen omenapiirakan kanssa.
English translation	According to Laura *vanillamustard* goes well together with apple pie.
Semantically unrelated	
Finnish	Lauran mielestä *vaniljarovasti* kuuluu yhteen omenapiirakan kanssa.
English translation	According to Laura *vanillapriest* goes well together with apple pie.
Pronounceable nonword	
Finnish	Lauran mielestä *vaniljaseoklii* kuuluu yhteen omenapiirakan kanssa.
English translation	According to Laura *vanillanonword* goes well together with apple pie.

Note. The critical word is in italics.

provide the strongest possible manipulation of semantic relatedness using compounds in which the second constituent was highly constrained and controlling for variables such as word length and frequency. The nonwords were constructed by changing two to four letters in existing Finnish words (apart from two items wherein one letter was changed).

In total there were 56 critical words, and each critical word was embedded approximately in the middle of a sentence frame. Each of the sentences was no longer than one line of text (76 characters). The four conditions were manipulated within participants, and items followed a Latin square design. Four lists of 84 sentences were constructed, and 7 participants were randomly allocated to each list. Twenty-eight of these sentences were filler items in which there was no saccade contingent change. The sentences were presented in a fixed pseudorandom order. Twelve experimental sentences and six filler sentences were followed by a question to test for comprehension. The sentences were presented in Courier (proportional) font in black on a white background. The sentences were displayed at a viewing distance of 60 cm and 2.3 characters subtended 1° of the visual angle.

Procedure

An invisible boundary was set between the penultimate and final letters of the first constituent. For example, in the compound *vaniljakastike* in which *vanilja* is the first constituent, the boundary was between *vanilj* and *akastike*. The second constituent was presented according to the four experimental conditions before the eye crossed the boundary. After the boundary was crossed, the second constituent changed to the correct form for all of the conditions.

The eye tracker was calibrated with a three-point horizontal calibration. The calibration was checked prior to each sentence by presenting a fixation point to the left of the start of the sentence. The calibration was automatically corrected or recalibrated if nec-

Table 2
Lexical Statistical Properties for the Four Preview Conditions for the Critical Compound Word

Stimulus characteristics	Identical	Semantically related	Semantically unrelated	Pronounceable nonword
Freq. whole word[a]	6	0	0	0
Freq. 1st [a]	13.9	13.9	13.9	13.9
Freq. 2nd[a]	182.6	249.4	236.6	0.0
Length[b] of whole word	12.9	12.9	12.9	12.9
Length of 1st	7.5	7.5	7.5	7.5
Length of 2nd	5.4	5.4	5.4	5.4
Mean bigram freq.[c]	7.1	7.7	7.4	3.9
Mean initial trigram freq.[c]	0.54	0.88	0.84	0.21
Mean final trigram freq.[c]	1.04	1.23	1.15	0.27

Note. Freq. = frequency; 1st = first constituent; 2nd = second constituent.
[a] All values are scaled to counts per 1 million.   [b] Length is given in characters.   [c] For second constituents all values are second constituents scaled to counts per one thousand.

essary. Participants were instructed to read the sentences for comprehension, and they responded "true" or "false" to question statements using a button response pad. Participants first read five practice sentences. On completion of the experiment, participants were asked if they had noticed anything odd about the appearance of the text during the experiment. If the participants had noticed any display changes they were asked to estimate how many they saw. Half of the 28 participants included here did not notice any of the changes, and half estimated that they noticed five or fewer changes. The experiment lasted approximately 30 min.

Analyses

Following standard practice for boundary-contingent change experiments, for each trial, regardless of the experimental condition, the time at which the display change occurred was compared to the time at which the first fixation after the boundary began. Some trials (7.3%) were excluded because the display change was triggered too early (before the eye crossed the boundary). Seven and a half percent of trials were excluded because the display change occurred more than 9 ms into the start of the subsequent fixation.[2] In addition, trials were excluded due to (a) blinks during first pass reading of the compound (0.4%), (b) the first constituent not being fixated on first pass (1.4%), and (c) the initial first-pass fixation on the first constituent of the compound word being on the final letter of the first constituent after the boundary (2.4%).[3] Six additional participants for whom more than 25% of data were excluded and 10 additional participants who noticed more than five changes[4] were not included in the analyses.

Results

The mean error rate on the comprehension questions was 6.2% ($SD = 5.6\%$). In order to examine early processing of the compound constituents, first fixation duration and gaze duration (the sum of fixations on a constituent before leaving it on first pass) were calculated for both the first (first fixation$_1$, gaze$_1$) and second (first fixation$_2$, gaze$_2$) constituents. Analyses of the probability of skipping the second constituent on first pass were also undertaken. Later measures for the whole compound word include gaze duration, total time (the sum of all fixations on the word), and regression path duration within the word (see below).

Repeated measures analyses of variance on the basis of participant (F_1) and item (F_2) variability were calculated across the four experimental conditions. If these analyses of variance were significant, then paired sample *t* tests were undertaken between the preview conditions. To be clear, an orthographic (or visual) preview effect is established when the identical condition differs from the other three conditions; a sublexical or lexical effect is established when the nonword condition differs from the unrelated- and related-word conditions; a semantic effect is established when the semantically related condition differs from the semantically unrelated condition.

Early Measures for the Two Constituents

Table 3 shows early measures of processing the two constituents for each condition. There was no effect of the preview of the second constituent on processing of the first constituent as shown by both first fixation$_1$ durations ($Fs < 1$) and gaze$_1$ durations,

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[2] Due to the position of the boundary within the word, participants frequently fixated very close to the right of the boundary after it had been crossed. Consequently, there was often very little time remaining within the saccade that crossed the boundary for the display change to occur. Trials were excluded if the display change occurred more than 9 ms into the start of the subsequent fixation. It is important to note that Sereno and Rayner (1992) showed no differences in reading times when a 21 ms prime at the beginning of a fixation was a string of random letters, a semantically related word, or a semantically unrelated word. Therefore, it is highly unlikely that a brief presentation of a preview with a maximum of 9 ms and averaging 2.7 ms ($SD = 2.9$) at the beginning of fixations could have produced differences between the word and nonword preview conditions in the present study. The arbitrary 9 ms cutoff enabled 47.4% of the overall data set to be included in the analyses, which would otherwise have been excluded if the cutoff had been 0 ms.

[3] Note that 11.4% of trials were included in which the first constituent was first fixated before the boundary (hence receiving previews of the second constituent as a function of condition) and subsequently on the final letter after the boundary (during which the preview was always identical). Analyses of the data with these trials excluded yielded the same patterns of effects as reported here, although it is possible that preview benefit may have been reduced for these trials.

[4] Inclusion of participants who are aware of display changes can substantially increase measures of preview benefit and therefore distort the pattern of results (White, Rayner, & Liversedge, 2005).

Table 3
Early Measures for the Compound Constituents

Constituent measure	Identical		Semantically related		Semantically unrelated		Pronounceable nonword	
	M	SD	M	SD	M	SD	M	SD
First								
First$_1$ fixation	219	75	217	75	217	71	218	74
Gaze$_1$ duration	325	175	350	215	329	191	357	262
Fixation prior to 2nd constituent	217	64	211	66	221	72	218	65
Second								
Skipping probability	.25		.17		.14		.13	
First$_2$ fixation	204	80	231	87	236	101	233	93
Gaze$_2$ duration	226	103	262	114	274	126	266	111

Note. Fixation prior to second constituent = fixation duration on the first constituent prior to fixating the second constituent, for cases in which a total of one or two first pass fixations were made on the first constituent and for which there were no regressions out of the first constituent on first pass. All measures are in ms except for skipping probability. Skipping prob. = probability of skipping the second constituent on first pass.

$F_1(3, 81) = 1.95$, $MSE = 6,938$, $p = .153$; $F_2(3, 165) = 1.83$, $MSE = 10,493$, $p = .154$. There was also no effect of the second constituent preview on the duration of the fixation on the first constituent prior to fixating the second constituent for cases in which there were no regressions out of the first constituent on first pass and in which a total of one or two first-pass fixations were made on the first constituent ($Fs < 1$). These results indicate that there was no influence of the lexical characteristics of the second constituent on first-pass fixations on the first constituent. That is, at least initially, the first constituent was processed independently of the lexical characteristics of the second constituent.

In contrast to the results for the first constituent, there were significant effects of preview on early reading measures for the second constituent for first fixation$_2$ duration, $F_1(3, 81) = 9.74$, $MSE = 783$, $p < .001$; $F_2(3, 165) = 7.71$, $MSE = 2,262$, $p < .001$; for gaze$_2$ duration, $F_1(3, 81) = 13.44$, $MSE = 1,192$, $p < .001$; $F_2(3, 165) = 9.77$, $MSE = 3,973$, $p < .001$; and for the probability of skipping the second constituent on first pass, $F_1(3, 81) = 7.66$, $MSE = 0.01$, $p < .001$; $F_2(3, 165) = 5.78$, $MSE = 0.03$, $p < .01$. First fixation$_2$ and gaze$_2$ durations were significantly shorter—and the skipping probability was significantly higher—when the previews of the second constituent were identical compared to all three of the incorrect preview conditions ($ts > 2$, $ps < .05$). These results indicate that previews of the second constituent can be at least visually or orthographically processed such that this influences the probability of skipping the second constituent, and processing of the second constituent is facilitated when it is sub-

sequently fixated. There was no significant difference between the semantically related and the semantically unrelated condition for gaze$_2$ duration, $t_1(27) = 1.64$, $p = .112$; $t_2 < 1.10$, and there were no other differences between the incorrect preview conditions for either first fixation$_2$ or gaze$_2$ duration ($ts < 1$). There were no significant differences between the probabilities of skipping the second constituent for any of the incorrect previews ($ts < 2$, $ps > .06$). Therefore, if there is semantic or lexical processing of the second constituent preview, then this does not significantly influence initial reading of the second constituent.

Measures for the Entire Compound Word

Table 4 shows reading measures for the whole compound word for each condition. There were significant effects of preview on both gaze duration, $F_1(3, 81) = 27.45$, $MSE = 7,066$, $p < .001$; $F_2(3, 165) = 19.16$, $MSE = 20,799$, $p < .001$; and total time, $F_1(3, 81) = 39.47$, $MSE = 9,586$, $p < .001$; $F_2(3, 165) = 25.20$, $MSE = 47,145$, $p < .001$, for the entire compound word. Similar to the measures of first-fixation$_2$ duration and gaze$_2$ duration, both gaze durations and total time for the entire word were longer when the preview was incorrect compared with the identical preview condition for all three of the incorrect preview types ($ts > 4.6$, $ps < .001$). The large visual or orthographic preview effect for gaze durations on the whole word was similar to that of Hyönä et al. (2004). Such large effects indicate that processing of the preview

Table 4
Measures for the Whole Compound in ms

Measure	Identical		Semantically related		Semantically unrelated		Pronounceable nonword	
	M	SD	M	SD	M	SD	M	SD
Gaze duration	519	211	638	305	658	297	710	354
Total time	662	300	860	392	891	383	907	380
Reg. path duration	268	146	381	225	414	215	446	212

Note. Reg. = regression.

of the second constituent has a crucial role in efficient processing of the whole compound.

The pronounceable nonword previews produced the numerically longest reading times for the whole compound word. Gaze durations for the nonword preview were not only significantly longer than for the identical preview condition but also significantly longer than the semantically related previews, $t_1(27) = 3.30$, $p < .01$; $t_2(55) = 3.85$, $p < .001$, and there was a similar trend for total time, $t_1(27) = 1.95$, $p = .062$; $t_2(55) = 2.29$, $p < .05$. The nonword preview also produced numerically longer gaze durations than the semantically unrelated preview, $t_1(27) = 2.43$, $p < .05$; $t_2(55) = 1.73$, $p = .09$, though there was no significant difference for total time ($ts < 1$). Furthermore, the semantically related condition produced numerically shorter reading times than the semantically unrelated condition, though these differences were not significant for gaze durations, $t_1(27) = 1.38$, $p = .18$; $t_2 < 1$; or total time ($ts < 1$).

In order to examine late processing of the compound word more carefully, we calculated regression path duration within the compound word. Regression path duration within the compound is the sum of fixations on both the first and second constituents from when the second constituent is first fixated on first pass until the eyes leave the whole compound to the right. This analysis excludes cases in which regressions are made out of the whole compound word after first fixating on the second constituent.[5] To clarify, if there are no first-pass regressions out of the first constituent or from the second constituent to the first constituent, then the regression path duration is equal to gaze$_2$ duration. However, for example, if there is a regression back to the first constituent, then these fixations—and any subsequent fixations on either constituent—are included in regression path duration before the eyes pass to the right of the compound.

There was a main effect of preview on regression path duration, $F_1(3, 81) = 46.88$, $MSE = 3,965$, $p < .001$; $F_2(3,165) = 43.58$, $MSE = 9,324$, $p < .001$, and regression path durations were longer when the previews were incorrect compared with the identical preview condition ($ts > 6.2$, $ps < .001$). Regression path durations were also longer when the preview was a nonword compared with when it was either a semantically related word, $t_1(27) = 4.85$, $p < .001$; $t_2(55) = 3.72$, $p < .001$, or a semantically unrelated word, $t_1(27) = 2.19$, $p < .05$; $t_2(55) = 2.10$, $p < .05$. These results suggest that aspects of processing associated with word constituents, which cannot be undertaken on pronounceable nonword constituents, were undertaken on the second constituent previews. Aspects of processing that can be undertaken on word, but not pronounceable nonword, constituent previews include sublexical and lexical processes. To be clear, these results suggest that sublexical or lexical processing of the preview of the second constituent can influence late processing of the compound word.

Importantly, regression path duration was also shorter when the preview was semantically related compared to when it was semantically unrelated to the second constituent, $t_1(27) = 2.60$, $p < .05$; $t_2(55) = 2.00$, $p = .05$. These results are consistent with the numerical effects for gaze duration and total time for the entire compound. Critically, these findings suggest that the preview of the second constituent can be semantically processed.[6]

Discussion

The results demonstrate that semantic processing of text previewed prior to fixation can occur when that information is within a word.

These findings contrast with previous studies showing that words are not processed at a semantic level prior to fixation (Altarriba et al., 2001; Hyönä, & Häikiö, 2005; Rayner et al., 1986).

Interestingly, the semantic preview effect occurred relatively late.[7] In contrast, visual or orthographic effects in the present study and in previous studies (Lima & Inhoff, 1985) can already be observed in the initial fixation duration on the previewed lexeme, indicating that the orthography of the second constituent is processed prior to fixation.

Despite its relatively late manifestation in the processing stream, it is possible that semantic processing of the second constituent preview within compound words occurs prior to fixating the second constituent. Semantic activation of the preview may then be maintained until it facilitates the late stages of word processing. The numerically shorter gaze$_2$ durations for the semantically related compared with the semantically unrelated previews may be taken to indicate that semantic activation of the preview might facilitate compound processing even earlier. Another possibility is that processing of the second constituent preview may only reach an orthographic or phonological level prior to fixating the second constituent. During subsequent fixations, the semantic characteristics of the preview may become activated and hence facilitate only the later stages of word processing.

A further important finding in the present study is that initial processing of the first constituent of the compound words was not influenced by the preview of the second constituent. These results indicate that, at least initially, the first constituent is processed separately to lexical processing of the second constituent. These results provide evidence of serial lexical processing during reading of compounds (Pollatsek, Reichle, & Rayner, 2003) and contrast with the suggestion that multiple lexical units may be processed in parallel (Engbert et al., 2005; Kennedy, 2000). The findings do not preclude the possibility that orthographic characteristics may be processed in parallel or that there may be lexical parallel processing under some circumstances (e.g., within shorter words or when

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[5] The measure of regression path duration is very similar to that labeled *subgaze*$_2$ in Hyönä et al. (2004). Note that the same pattern of results and statistical significance were found for regression path duration when cases were included in which regressions were made out of the whole word after fixating on the second constituent.

[6] Given the considerable importance of the semantic preview results, further analyses were undertaken to ensure that the semantic preview effects could not have been due to the inclusion of trials in which the preview was still present ≤9 ms into the first fixation on the second constituent. There was no difference in the proportion of trials that included such a delay between the four conditions for this measure ($Fs < 1$). Furthermore, when cases in which there was any delay were excluded, the semantically unrelated preview condition still produced longer regression path durations ($M = 433$, $SD = 236$) compared with the semantically related preview condition ($M = 391$, $SD = 248$), $t_1(26) = 1.81$, $p = .083$, (t test for 27 participants with data for each condition; there were insufficient data for items analyses).

[7] There may have been stronger and earlier effects of semantic preview had it been possible to select semantically related second constituents that produced a legal compound (e.g. *vanillapudding*). However, it would not have been feasible to produce semantically related and unrelated legal compound previews that were also controlled for the variables detailed in Table 1. Therefore, it is possible that semantic preview effects within compounds appear earlier and are stronger than our study implies.

the compound is a legal word). However, the results at least indicate that there is no strong lexical parallel processing of constituents on first pass of the first constituent of long compound words. Furthermore, given that the two constituents are in such close proximity and within the same linguistic word unit, the findings also indicate that there may be little capacity for lexical parallel processing between words during reading in general (Reichle et al., 2003).

The results have important implications for models of word recognition and eye-movement control. The findings are consistent with the suggestion that constituents can be processed separately within compound words, at least for long compounds (Bertram & Hyönä, 2003), which is in line with Pollatsek et al.'s (2000) race model in which it is assumed that compounds are processed both in terms of their component lexemes and also as whole words. The relatively late semantic effect observed for long compounds would then reflect the final stage of the former route, during which the meaning of the two constituents is integrated.

More generally, models of word recognition have traditionally focused on accounting for processing of individual fixated words; however, there is now mounting evidence that suggests that yet-to-be-fixated text is also linguistically processed (Rayner, 1998). Ultimately models of word recognition and eye-movement control may combine to produce a more comprehensive account of word processing during reading (Grainger, 2003). More specifically, the results presented here suggest that, in order to be comprehensive, models of eye-movement control in reading (e.g., Engbert et al., 2005; Reichle et al., 2003) would need to incorporate a mechanism to account for semantic preview within compound words.

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