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The Enhancement Effect in Letter Detection: Further Evidence for the Structural Model of Reading

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According to the structural model of reading (A. Koriat & S. N. Greenberg, 1994), the extraction of structure leads the way to the analysis of meaning. Consistent with this model, previous letter-detection studies have documented an inordinately high rate of letter omissions in function morphemes, suggesting that the cognitive representation of function morphemes is diminished once they have been utilized to set phrase structure. The present study revealed a new and complementary enhancement effect: Letter detection in content morphemes that immediately followed functors was superior to that of content morphemes positioned elsewhere in the text. Together these effects suggest an on-line figure–ground representation of text in which structural elements recede as semantic elements are pushed to the foreground.

There has been a growing interest in recent years in the role played by linguistic structure in both speech production and speech comprehension. The study of naturally occurring errors in language production has given rise to frame-and-slot models of speech production (Bock, 1990; Dell, 1986; Garrett, 1975), according to which lexical items are selected and then assigned to syntactic slots within independently created structural frames. Bock and Loebell (1990) have provided evidence that syntactic structure can be activated independent of meaning.

A similar emphasis on structural processing can also be found in some of the recent work on speech comprehension. Apparently, prosodic patterns help disclose to the listener the structure of the spoken message and the syntactic class of its individual units (e.g., Gee & Grosjean, 1983; Kelly, 1992; Sorensen, Cooper, & Paccia, 1978). Indeed, the elimination or alteration of prosodic patterns has been found to impair speech comprehension (Carroll & Slowiaczek, 1987).

In line with this emphasis on the critical role of structure in speech, we proposed that structural processing might also play a similarly important role in reading (Koriat & Greenberg, 1994). According to the structural model of reading, the processing of structure leads the way to the processing of meaning. Thus, readers attempt to quickly extract a structural frame for the sentence to help the on-line integration of accessed representations. Function morphemes are important cues for structure (Kimball, 1973) and are monitored early in reading. However, after the functors have served their purpose and the structural frame has been established, their representations in memory recede to give prominence to the semantically loaded content morphemes (see, e.g., Kintsch, 1974; Kintsch & Van Dijk, 1978). The logic for such an assumption is made clear by Jacoby and Kelley's (1987) distinction between tool and object. Function units serve essentially as tools that help convey the structure of the semantic units within a sentence and hence receive little attention. It is the semantically loaded elements that are the object of attention and therefore remain available for processing both later and longer than do the companion functors.

Evidence supporting this structural position comes from several lines of research represented in our work with the letter detection task (Greenberg & Koriat, 1991; Greenberg, Koriat, & Shapiro, 1992; Koriat & Greenberg, 1991, 1993, 1994; Koriat, Greenberg, & Goldshmid, 1991). This task had been originally exploited by Healy and her associates to test the unitization model of reading (e.g., Healy, 1976; Healy & Drewnowski, 1983; see Healy, 1994, for a review). Their basic finding, widely replicated in many experiments, is referred to as the *missing-letter effect:* Letter detection in connected text is more difficult in frequent words, such as *the, and,* and *for,* than in less common words (e.g., Corcoran, 1966; Healy, 1976; Healy & Drewnowski, 1983; Healy, Oliver, & McNamara, 1987; Proctor & Healy, 1985). Healy and her colleagues interpret this finding as supporting the hypothesis that familiar orthographic units tend to be processed as whole-word, unitized representations that conceal their constituent letters. Our results, however, favor an alternative interpretation that attributes the missing-letter effect to the structural role played by these common words within the sentence. Although it is noteworthy that Healy (e.g., Healy, 1976) found a higher rate of letter omissions for more frequent content words than for less frequent content words (in disconnected text), the most impressive results have been obtained when function words have been contrasted with content words. Our work has consistently demonstrated that the missing-letter effect for function words is intimately tied to their function in disclosing the structure of the sentence. Moreover, consistent with the structural view of reading, the results suggest that letters in functors are missed at a postaccess stage, after these functors have been utilized to set a tentative frame for the sentence.

A brief review of the pertinent evidence is in order. In one series of experiments, we took advantage of a particular property of Hebrew to disentangle the contributions of fre-

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quency and function to the missing-letter effect (Koriat et al., 1991). Hebrew provides alternate forms for several of its function morphemes. For example, the word *to* can appear either as the high-frequency word *el* or as the single-letter prefix *l* appended to word stems (e.g., *to Haifa* may be translated as either *el haifa* or *lhaifa*). Because both forms have nearly identical functions and meanings, two equivalent phrases can be constructed, a function-word phrase and a function-prefix phrase. Letter detection was poorer in function words than in matched content words, replicating the missing-letter effect. However, it was also significantly poorer in function prefixes despite the fact that prefix words (e.g., *lhaifa*) are not more common than their matched unprefixed content words. Clearly, then, function morphemes are lost because of their role within the sentence, not because of their higher orthographic frequency.

Subsequent experiments confirmed that the missing-letter effect for a Hebrew prefix word is confined only to the letter representing the function morpheme, implying that prefix words, if anything, are *less* unitized than their matched content words for which letter detection is more uniform across positions. Furthermore, when Hebrew homographic strings were used, more omission errors were found for the initial letter of a string (e.g., *s* in *smr*) when preceding context biased interpretation of that string as a function prefix + stem combination (*s* + *mr*, meaning "that mister. . .") than when it biased its interpretation as an unprefixed content word (meaning "kept"). These results indicate that letter detection in an orthographic unit depends on the function of that unit within the sentence. The results also place the locus of the missing-letter effect at a postlexical stage, after the word has been parsed into its proper constituent morphemes. Apparently, function units recede to the background of the cognitive representation once they have been utilized to define a syntactic frame for the phrase.

In another series of experiments, inspired by Lewis Carroll's (1900) poem "Jabberwocky," we demonstrated that the missing-letter effect can be obtained even with nonwords (Koriat & Greenberg, 1991). "Jabberwocky" appears to convey a great deal of information about the structure of sentences but little semantic content. We reasoned that if such structural information is extracted prior to complete semantic analysis, then the missing-letter effect should be observed even with nonsense strings embedded within a sentence. Several experiments confirmed this possibility. Nonsense strings yielded more detection errors when they appeared in English text in locations that would normally require function words than when they appeared in positions calling for content words. Furthermore, similar results were obtained with Hebrew when comparing function prefixes that were attached to word or to nonword stems. Thus, when a nonword (e.g., *lbgn*) was placed in a slot in which the initial letter (*l*) was likely to be interpreted as a function prefix (*to bgn*, *bgn* being a nonword), detection of the initial letter was worse than when it was likely to be interpreted as part of the stem of a content word (e.g., *he ate lbgn*). In fact, in this experiment, the size of the missing-letter effect was similar for words and nonwords. These results indicate that the missing-letter effect can be obtained with low-frequency nonsense strings that are devoid of semantic content; thus, the results help further tie this effect to the structural organization of the sentence.

Additional results indicate that the rate of detection errors for function words in English is delicately tuned to their specific structural role within the sentence (Greenberg & Koriat, 1991). For example, the detection of *f* in *for* is better in the expression *for or against* than in *for better or worse*. In the former expression, *for*'s role is more like that of a noun, and, in fact, the error rate here was no higher than in matched content words. Similarly, detection of the letter *n* was better in *on* when *on* was used in the role of a modifier (e.g., *on switch*) than when it was used as a preposition (e.g., *on his way*). It is important that the structural role of a functor affected letter detection even when that role was revealed only by the words that immediately followed the functor in text.

Taken together, the results summarized above are consistent with the structural view of reading according to which function morphemes are initially utilized to define the structural frame of the sentence but then recede to the background in favor of the meaning-laden content words. This view assumes a dynamic change in the relative prominence of different sentential units as the cognitive representation of the sentence evolves. One prediction that follows from this view is that the diminished prominence of function units should be accompanied by a greater accentuation of the neighboring content units. To be specific, if the missing-letter effect reflects the evolving figure–ground organization of the sentence in which structural units recede to the background while pushing content units into the foreground, then we may expect this organization to affect letter detection in content units as well: Content units that are preceded by function morphemes should enjoy enhanced detectability in comparison with those not preceded by functors. Thus, the fading of functors should be accompanied by an enhancement of the content morphemes that follow them.

Consistent with this proposition is an observation in Koriat and Greenberg (1993). In that study, we examined letter omissions for a series of functors that appeared in sequence (e.g., in *and for the* ____). The missing-letter effect was found to hold only or mostly for the leading functor. This was true for several function words in both English (with the notable exception of *the*) and Hebrew (Koriat & Greenberg, 1993, Experiments 3 and 4). Furthermore, the leading-functor effect was also found for sequences of Hebrew function prefixes (Koriat & Greenberg, 1993, Experiments 1 and 2). Multiprefix sequences in Hebrew consist of several one-letter prefixes that are strung together and attached to a word stem (e.g., *vmhgn*, meaning "and from the garden," with *gn* standing for "garden" and *v*, *m*, and *h* standing for "and," "from," and "the," respectively). When such multiprefix words were used, only the initial prefix was found to yield more omission errors than comparable letters in similar positions in unprefixed content words. In contrast, function letters occupying later positions in the sequence actually evidenced a function *advantage:* Letter detection was better for such letters than for those that were part of the stem of a content word. Possibly the importance of a leading functor as the primary contributor to structure resulted in an offsetting beneficial effect for the function elements that followed (see Koriat & Greenberg,

Table 1
Means and Standard Errors (SEs) of Percentage of Omission Errors for Function-Preceding and Content-Preceding Sentences as a Function of Target Letter and (for the Function-Preceding Sentences) Function Word (Experiment 1)

Target letter	Function word for function-preceding sentences								Content-preceding sentences	
	and		*for*		*the*		Total			
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
c	0.9	0.5	0.3	0.3	2.2	1.1	1.0	0.4	2.8	0.6
m	2.8	0.8	1.6	0.7	3.4	1.3	2.5	0.7	4.0	0.9
w	6.3	1.5	1.9	0.8	3.1	1.0	3.8	0.8	5.2	0.9
Total	3.3	0.7	1.3	0.4	2.9	0.8	2.4	0.4	4.0	0.6

1993). Perhaps, then, content words that follow immediately on the heels of a function word will likewise demonstrate enhanced letter detection. This possibility was examined in the present experiments for both English and Hebrew.

In all of our previous experiments, letter-detection errors in function words and function prefixes were compared with those in matched content words. In the present experiments, in contrast, we confine ourselves to content words and compare letter detection for these words when they are preceded by a function morpheme and when they are not. Note that detection of letters in content words in connected text is generally quite good, and so any benefit enjoyed from a preceding function word is expected to be modest.

Experiment 1

Most of the evidence in support of the missing-letter effect comes from studies with English text (e.g., Greenberg & Koriat, 1991; Proctor & Healy, 1985), and therefore Experiment 1 used English. In this experiment, we contrasted letter detection in content words when these were preceded by a function word and when they were preceded by a content word. Three function words were used, *and, for,* and *the,* and three target letters were used, *c, m,* and *w.*

Method

Participants. Thirty-two University of Haifa students whose native language was English were paid for participating in the experiment.

Design. The target letter was always the initial letter of a critical content word. The design involved all combinations of two factors: target letter (*c, m,* and *w*) and whether or not the word preceding the critical word was a function word or a content word (preceding function vs. preceding content). The function sentences were divided equally according to the function word used in front of the critical words *the, for,* and *and.*

Stimulus materials. Thirty pairs of sentences were prepared for each of the three target letters, *c, m,* and *w.* Each contained a critical content word with the target letter occupying the initial position. The same word appeared in each pair of matched sentences, but it was preceded by a function word in one member of each pair and by another content word in the other member. The two members of each pair were matched for the number of words and for the ordinal position of the critical word within the sentence. Sentences contained between 6 and 23 words each.

In addition, for each target letter, 10 of the function sentences used *and* as the preceding functor, 10 used *for,* and 10 used *the.* Also, in some sentences the target letter appeared in one other word in the sentence. These noncritical targets appeared in words that occupied the same position across matched sentences. They never appeared in the word immediately preceding or following the critical word. In none of the sentences did a function word immediately follow the critical word, and in none of the function sentences did a function word immediately precede the critical function word.

All sentences representing each target letter were printed on two pages, 30 sentences on each page. The order of the sentences was random, except that matched sentences never appeared on the same page. Each page contained exactly half of the sentences corresponding to each condition. A page appeared as one long paragraph of continuous text composed of unrelated sentences. The critical word never appeared at the beginning or end of a sentence or a line. Two warm-up sentences were added at the beginning of each page, so that each page contained 32 sentences.

Participants' booklets contained one page of instructions and practice, followed by six experimental pages arranged in two blocks of three pages each. Within a block, one page was devoted to each target letter. The order of the three targets (pages) remained the same across the two blocks but was counterbalanced across subjects.

Procedure. Participants were told to read the passages at their normal reading speed, but whenever they came to the letter designated at the top of the page (the target letter), they were to circle it. They were further instructed not to slow down their reading speed to catch all target letters and not to go back to circle a letter they had missed. They began by reading through a practice paragraph and circling the target letter *n.*

Results

Table 1 presents the means and standard errors of the percentage of omission errors for the preceding-content and preceding-function sentences for each of the three target letters. The results for the function sentences are also broken down by type of function word used: *and, for,* and *the.*

Overall, the percentage of omission errors was very low, averaging 3.2%. Nevertheless, it was smaller for the preceding-function sentences (2.4%) than for the preceding-content sentences (4.0%), consistent with the proposition that function words help accentuate the content words that follow. Thus, a two-way analysis of variance (ANOVA), Sentence Type × Target Letter, yielded significant effects for sentence type, $F(1, 31) = 17.88, p < .0002$, and for target letter, $F(2, 62) = 5.37$,

$p < .01$, but not for the interaction, $F < 1$. One-way ANOVAs for each of the target letters indicated significant effects of sentence type for the letters *c*, $F(1, 31) = 11.68, p < .002$, and *m*, $F(1, 31) = 5.01, p < .05$, and a near-significant effect for *w*, $F(1, 31) = 3.07, p < .10$.

The results were somewhat less consistent when analyzed separately for each of the three function words. Although for each of these words the percentage of detection errors was smaller than for the content condition, one-way ANOVAs indicated a significant effect of sentence type only for *for*, $F(1, 31) = 24.19, p < .0001$, and a near-significant effect for *the*, $F(1, 31) = 3.22, p < .10$. The effect for *and* was not significant, $F(1, 31) = 1.21$.

Discussion

The results are generally consistent with the prediction that letters in content words are more detectable when these words are preceded by functors than when they are not. The expected enhancement effect was obtained despite the fact that the rate of detection errors for the preceding-content condition was very low overall: only 4.0%. Although the results for some combinations of function word and target letter deviated from this pattern (see Table 1), these deviations do not appear to be systematic and may be due to the small number of observations representing each combination. Indeed, in previous studies too there were spurious differences in the size of the missing-letter effect for different functors, and these differences were not generally consistent across different experiments (see, e.g., Koriat et al., 1991).

Nevertheless, future research must take into account the possibility of systematic differences between different types of functors in the extent to which they provide reliable cues for structure. A case in point is the word *the*. Unlike most other functors, which carry ambiguous structural information, the word *the* always opens a noun phrase. Indeed, *the* yielded a different pattern of results in a previous letter-detection study (Koriat & Greenberg, 1993): Although for other functors letter detection was better when these followed another functor than when they followed a content word, *the* continued to produce a high rate of omission errors regardless of its position. Nevertheless, *the* itself is expected to yield an enhancement effect for the content words that follow it. The results of Experiment 1 suggest that this may indeed be the case.

What is the process responsible for the enhancement effect observed in Experiment 1? According to the structural model, both the missing-letter effect for function words and the enhancement effect for content words reveal the figure–ground organization of the phrase that is established on-line while the structural frame of the phrase is extracted. In this organization, the elements that convey the structural organization of the phrase assume the role of a cognitive skeleton that supports and organizes the semantically rich content elements.

An alternative interpretation, however, that is more in line with the unitization model of reading may be derived from Hadley and Healy's (1991) parafoveal-processing hypothesis. According to this hypothesis, the disproportionally large number of detection errors in familiar words like *the* results from a reading process in which the eyes often skip over parafoveally identified words. Thus, whole-word processing of familiar words takes place only when these words are identified in the parafovea. Such identification allows familiar words to be skipped, whereas words that precede or follow these words are fixated and therefore are identified at the letter level. In support of this hypothesis, Hadley and Healy reported evidence indicating that manipulations that presumably impede the parafoveal identification of familiar words (e.g., a narrow, five-letter viewing window or a large interword space preceding or following the target word) reduce the size of the missing-letter effect.

The parafoveal-processing hypothesis can account for the results of Experiment 1: The skipping of familiar function words may be expected to increase the likelihood that a reader processes the trailing content word foveally in comparison with a content word that follows other content words.

Although we agree with Hadley and Healy (1991) that the missing-letter effect may depend on parafoveal processing (see Greenberg & Koriat, 1991; Koriat & Greenberg, 1991), we attribute the higher error rate observed for function words to their syntactic role rather than to their visual familiarity. In fact, according to the structural model, the poorer letter detection in function words derives precisely from the critical role of these words in defining the structure of the sentence and occurs after these words have been interpreted and utilized in setting structure. Therefore, the enhancement effect should be found even in conditions that do not permit fast identification of functors on the basis of their familiar visual shape. This possibility was tested in Experiment 2 by taking advantage of the Hebrew language.

Experiment 2

Experiment 2 contrasted unprefixed Hebrew content words with content words to which a single-letter function prefix is appended. Participants always searched for the letter occupying the *second* position of the critical word (i.e., the first letter of the stem in the case of the prefixed words, and the second letter of the stem in the case of the unprefixed words). For example, detection of the letter *n* in the unprefixed content word *mnhgim* (pronounced "minhagim," meaning "customs") was contrasted with that in the prefix word *bnmlim* (pronounced *benemalim*, meaning "in ports," with *b* and *nmlim* signifying "in" and "ports," respectively). In all, four target letters were used: *a*, *m*, *n*, and *p*. In the case of the prefixed words, three function prefixes were used (see Koriat et al., 1991; Koriat & Greenberg, 1991): *b* (signifying "in"), *k* ("as"/"like") and *l* ("to").

Given that the prefix words require readers to parse the orthographic strings to distinguish between their function and content components, the occurrence of an enhancement effect for these strings should imply that the improvement in letter detection due to the attached function prefix occurs at a postparsing, postlexical stage and is not due to parafoveal identification and skipping of familiar orthographic patterns (see Hadley & Healy, 1991). Such an effect would also support the view of the reading process as involving a dynamic shift in the relative prominence of syntactic and semantic morphemes in the course of text processing.

Table 2
Means and Standard Errors (SEs) of Percentage of Omission Errors for Prefixed and Unprefixed Content Words as a Function of Target Letter and (for the Prefixed Words) Function Prefix (Experiment 2)

Target letter	Function prefix								Unprefixed words	
	b ("in")		*k* ("as")		*l* ("to")		Total			
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
a	14.1	4.3	14.6	3.7	7.8	2.5	12.2	3.1	8.5	2.5
m	10.4	3.0	9.4	2.4	15.6	3.1	11.8	2.4	22.9	4.4
n	10.9	2.5	4.2	1.8	6.8	2.0	7.3	1.8	14.9	3.0
p	9.9	2.7	3.6	1.4	6.3	1.8	6.6	1.7	9.2	2.5
Total	11.3	1.6	7.9	1.3	9.1	1.2	9.5	1.2	13.9	1.7

Method

Participants. Twenty-four University of Haifa students whose native language was Hebrew participated in the study: 5 were given course credit, and 19 were paid for their participation.

Design. The design involved all combinations of two factors: word type (prefixed vs. unprefixed) and target letter (*a, m, n, p*).[1] In addition, the prefixed words used three different function-prefix letters, *b, k,* and *l,* and these were equally represented for each target letter.[2]

Stimulus materials. A total of 192 Hebrew sentences were constructed, each including one critical content word. These represented 96 pairs of matched sentences, so that in one member of each pair the critical word was unprefixed, whereas the other began with single-letter function prefix. Both critical words contained the same target letter (*a, m, n,* or *p*) only once, always in the second position.[3] The two sentences in each pair were matched for the number of words, for the location of the critical word within the sentence, and for the size (number of letters) of the critical word. Experimental sentences contained between 6 and 16 words each.

Each of the target letters (*a, m, n,* and *p*) was represented in 24 pairs of matched sentences. (All four target letters are relatively frequent in Hebrew, and none of them contain ascenders or descenders.) In addition, the three function prefixes (*b, k,* and *l*) were equally represented across the function sentences, so that each was associated with each target letter in 8 function sentences.

The target letter appeared only once in each of the critical words. Target letters appeared in noncritical words in the sentence as well. No attempt was made to control their occurrence except for the fact that they never appeared in the word immediately preceding or following the critical word. Moreover, the critical word never appeared at the beginning or end of a sentence or a line and was never preceded or followed by a function word.

The 48 sentences representing each target letter were printed on two pages. The various types of sentences were equally represented on each page, and matched sentences never appeared on the same page. The order of the sentences was random, so that a page appeared as one long paragraph of continuous text composed of unrelated sentences. Two warm-up sentences were added at the beginning of each page, so that altogether each page contained 26 sentences.

Each participant's booklet contained two pages of instructions and practice followed by eight experimental pages arranged in two blocks of four pages each. Within a block, one page was devoted to each target letter. The order of the four targets was counterbalanced across subjects, but for each participant it remained the same across the two blocks.

Procedure. Participants were told to read passages at their normal reading speed, but whenever they came to the letter designated at the top of the page (the target letter), they were to circle it. They were further instructed not to slow down their reading speed to catch all target letters and not to go back to circle a letter they had missed. They were then given practice with one paragraph. The order of presentation of target letters was counterbalanced across subjects.

Results

Table 2 presents the means and standard errors of the percentage of omission errors for prefixed and unprefixed words for each of the four target letters. For the prefixed words, the results reported in this table also include a subdivision according to the function prefix used.

Overall, mean error rate was indeed smaller for the prefixed words (9.5%) than for the unprefixed words (13.9%), consistent with the proposition that function morphemes help accentuate the content words to which they are attached. This pattern, however, was not consistently observed across all four target letters used. Thus, a two-way ANOVA, Word Type × Target Letter, yielded significant effects for word type, $F(1, 23) = 17.42, p < .0005$; for target letter, $F(3, 69) = 10.98$, $p < .0001$; and for the interaction, $F(3, 69) = 7.61, p < .0005$.

[1] Note that the letter *a* (Aleph) in Hebrew is one of the four "mothers of reading," and therefore can represent both a consonant (pronounced /ʔ/, a glottal stop) and a vowel (see Navon & Shimron, 1984). In Experiment 2, *a* was always pronounced as a consonant in all of the critical words where it served as a target.

[2] In Hebrew, the definite article is always expressed by the letter *h* prefixed to a content word (see Koriat & Greenberg, 1991). Where the prefix *h* appears, the first letter in the content word is stressed. Thus, in the present design we did not use *h* as a prefix. We also should point out that in certain contexts, other function prefixes could be interpreted as containing implicit definite articles, so that *in* could be read as *in the.* Under those conditions, the first letter in the content stem would also be emphasized. Thus, in the present study we were also careful to avoid sentences where the reader could interpret the prefix construction as one which implied *the.*

[3] It was not possible to equate the exact frequencies of the prefixed and unprefixed matched words, because the available Hebrew frequency norms do not list separately the frequencies of the various function prefix + stem combinations. However, all of the critical words were of a relatively high frequency of usage according to the authors' intuitive judgments (and see Experiment 3).

The enhanced letter detectability for prefixed words was observed for all target letters except *a*, perhaps because of the special status of this letter (Aleph) in Hebrew (see footnote 1). One-way ANOVAs for each of the target letters yielded a significant enhancement effect for *m*, $F(1, 23) = 17.27$, $p < .0005$, and for *n*, $F(1, 23) = 16.66$, $p < .0005$, but not for *a*, $F(1, 23) = 2.77$, or *p*, $F(1, 23) = 1.29$.

The results were more consistent when examined across the three function prefixes used. Separate one-way ANOVAs indicated that the enhancement effect was significant for each of the function prefixes used: *b* ("in"), $F(1, 23) = 6.29$, $p < .05$, *k* ("as/like"), $F(1, 23) = 12.97$, $p < .005$, and *l* ("to"), $F(1, 23) = 14.43$, $p < .001$.

Discussion

The results of Experiment 2 replicate the enhancement effect observed in Experiment 1, indicating that letters in content morphemes are more available when these morphemes are preceded by a function morpheme than when they are not. These results, then, extend the enhancement effect to a different language—Hebrew—and a different type of functor—function prefix.

Of importance, the results of Experiment 2 help place the enhancement effect at a postlexical, postparsing stage. Although Hebrew function prefixes cannot be identified on the basis of their visual shape, they were found to facilitate letter detection in the content words to which they were attached. This effect, then, cannot be accounted for in terms of processes concerned with the recognition of highly familiar orthographic units, as might be the case for the results obtained with English (Experiment 1). The results of Experiment 1 could be explained, perhaps, in terms of the skipping of familiar function units assumed by the parafoveal-processing hypothesis of Hadley and Healy (1991). The enhancement effect observed in Experiment 2, in contrast, must depend on the prior parsing of the prefixed Hebrew word into its constituent morphemes and on the utilization of the function prefix in its structural role. This effect presumably reflects the figure–ground organization of the sentence that occurs after a function morpheme has been interpreted in its structure-supporting role. As this morpheme is used on-line to define the structural frame of the phrase, it pushes to the foreground the semantically loaded content unit that follows and enhances the detectability of its letters.

Experiment 3

Experiment 3 examined the possibility that the enhancement effect can also be obtained with nonwords. This should be the case if this effect reflects the structural organization of the sentence and is relatively independent of semantics. As described earlier, our previous work has demonstrated that the missing-letter effect can be obtained even with nonwords: Letter detection in nonwords was found to depend on the nonword's presumed role in sentential context (Koriat & Greenberg, 1991). When context endowed a nonword with a structural role, letter detection was poorer than when the context imparted a content role onto that nonword. Thus, in Experiment 3 we examined whether the enhancement effect too is obtained with nonwords. Experiment 3, then, was similar to Experiment 2 except that it also included Hebrew sentences in which the critical string was a nonword. This nonword was placed either in a context that biased its interpretation as an unprefixed content word or in one that biased its interpretation as a function prefix + stem combination. The question is whether the detectability of letters in the nonsense "content" morpheme would be improved in the latter condition relative to the former condition.

As in Experiment 2, participants always searched for the letter occupying the second position of the critical string (i.e., the first letter of the stem in the case of the prefixed strings, and the second letter of the stem in the case of the unprefixed strings). Three target letters were used, *m*, *n*, and *p*, and three function prefixes were used in the function condition, *b* (signifying "in"), *k* ("as/like") and *l* ("to").

Method

Participants. Twenty-four University of Haifa students whose native language was Hebrew participated in the study for course credit.

Design. There were four conditions, defined by whether the critical string was a word or a nonword (lexicality) and by whether the sentential frame favored interpretation of the initial letter of that string as a function prefix or as part of the content stem (favored interpretation). Three letters served as the target letters, *m*, *n*, and *p*. In addition, as in Experiment 2, there were three function prefixes, *b*, *k*, and *l*, which were equally represented for each target letter.

Stimulus materials. A total of 144 Hebrew sentences were constructed, each including one critical content word. These represented 72 pairs of matched sentences, so that in one member of each pair the critical string was an unprefixed content string, whereas in the other it was a prefixed content string with the initial prefix representing a function morpheme. In half of the prefixed and unprefixed sentences, the critical word was replaced by a nonword. The nonword had the same second letter as the matched word, and in the case of the prefixed nonwords, it also had the same initial letter. The nonwords were constructed by replacing the root morpheme with a nonword, but retaining the same derivational and inflectional pattern as in the parent word (see below). Thus, the syntactic structure of the sentence favored interpretation of the initial letter of the critical nonword either as a function prefix or as part of the stem morpheme.

In addition, in each of the word sentences, one content word (other than the critical word) was transformed into a nonword, leaving intact affixes. This nonword preceded the critical word in half of the prefix and stem sentences and followed the critical word in the remaining sentences, but at least one word separated that nonword from the critical word. In this manner, each of the sentences used in the experiment included one nonword.

The substitution scheme for creating the nonwords was the same as that used in Koriat and Greenberg (1991, Experiment 2). In general, most Hebrew words consist of two discontinuous morphemes: a consonantal root and a construction pattern that combines a derivational and inflectional affixation (as in English, *grow–growing*) with a vowel pattern of the root consonants (somewhat similar to *drive–drove* in English; see Frost & Bentin, 1992). Thus, in transforming words into nonwords, the consonantal root was replaced by a nonword root, but the construction–affixation pattern of the original word was left intact, as was the initial letter in the case of the critical prefixed nonwords. In general, the nonword root had no letters in common with the parent word root (thus, by analogy, *growing* would be replaced by *dloking*), so that the nonword could not be confused with the original parent word. It should be noted that vowels are normally not explicitly expressed in Hebrew unpointed orthography, so we may only presume that the

Table 3
Means and Standard Errors (SEs) of Percentage of Omission Errors for Prefixed and Unprefixed Content Words as a Function of Target Letter and (for the Prefixed Words) Function Prefix (Experiment 3)

Target letter	Function prefix								Unprefixed words	
	b ("in")		*k* ("as")		*l* ("to")		Total			
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
	Words									
m	10.4	4.0	4.2	3.3	14.6	4.1	9.7	3.0	13.9	3.2
n	4.2	2.5	10.4	3.7	6.3	2.3	6.9	1.9	12.2	2.4
p	6.3	3.1	7.3	3.5	6.3	2.7	6.6	2.7	6.9	1.6
Total	6.9	2.2	7.3	3.0	9.0	2.3	7.8	1.4	11.0	1.9
	Nonwords									
m	3.1	1.7	5.2	3.0	3.1	2.3	3.8	1.5	8.3	2.5
n	3.1	1.7	0.0	0.0	5.2	3.4	2.8	1.6	5.9	1.6
p	1.0	1.0	5.2	2.6	2.1	1.4	2.8	1.6	2.8	1.0
Total	2.4	0.9	3.5	1.6	3.5	1.7	3.1	1.7	5.7	1.3

nonwords were often read according to the vowel pattern of the parent word, because they mimicked the affixation pattern of the word they replaced (see Koriat, 1984).

The two sentences in each pair were matched for the number of words, for the location of the critical word within the sentence, and for the size (number of letters) of the critical word. Experimental sentences contained between 7 and 15 words each. There was only one critical word in each sentence, and it contained the target letter only once, always in the second position. Each of the three target letters was represented in 12 word and 12 nonword prefix sentences, and in 12 word and 12 nonword nonprefix sentences. In addition, in the prefix sentences, each of the three function prefixes (*b*, *k*, and *l*) was used in conjunction with each of the target letters in 4 word and 4 nonword sentences. In other respects, the stimuli resembled those used in Experiment 2.

All sentences representing each target letter were printed on two pages with two sentences on each page. The order of the various types of sentences was random, except that matched sentences never appeared on the same page and that each page contained exactly half of the sentences corresponding to each condition. A page appeared as one long paragraph of continuous text composed of unrelated sentences. The critical word never appeared at the beginning or end of a sentence or a line. Three warm-up sentences were added at the beginning of each page.

Each participant's booklet contained two pages of instruction and practice followed by eight experimental pages arranged in two blocks of four pages each. Within a block, one page was devoted to each target letter. The order of the four targets remained the same across the two blocks but was counterbalanced across subjects.

Procedure. The instructions were similar to those of Experiment 2, except that participants were warned that the sentences might include unfamiliar letter strings but that they should attempt to read the text continuously despite the presence of such strings. Participants were then given practice with a paragraph that contained sentences of a similar structure to the experimental sentences. The order of presentation of target letters was counterbalanced across subjects.

Results

Table 3 presents the means and standard errors of the percentage of omission errors for prefixed and unprefixed strings for each of the four target letters. The results are presented separately for words (top) and nonwords (bottom). For the prefixed words and prefixed nonwords, the results reported in this table also include a subdivision according to the type of function prefix used.

Overall, the error rate was lower for nonwords (4.4%) than for words (9.4%). More important, it was also lower for the prefixed strings than for the unprefixed strings for both words (7.8% vs. 11.0%) and nonwords (3.1% vs. 5.7%). A two-way, Lexicality (words vs. nonwords) × Favored Interpretation (function vs. content) ANOVA yielded $F(1, 23) = 14.77, p < .001$, for lexicality, $F(1, 23) = 16.66, p < .0005$, for favored interpretation, and $F < 1$ for the interaction. The effects of favored interpretation were significant for both words, $F(1, 23) = 8.60, p < .01$, and nonwords, $F(1, 23) = 8.02, p < .01$. Thus, function morphemes help to improve letter detection in the content strings to which they are attached, and, of importance, this effect is equally observed for words and nonwords.

As in Experiment 2, the results were not entirely consistent across all target letters. Thus, the effects of favored interpretation were observed only for the target letters *m* and *n*, but not for *p*: For the letter *m*, a Lexicality × Favored Interpretation ANOVA yielded $F(1, 23) = 5.28, p < .05$, for lexicality; $F(1, 23) = 8.69, p < .01$, for favored interpretation; and $F < 1$ for the interaction. The respective ANOVA for the letter *n* yielded $F(1, 23) = 13.37, p < .005$, for lexicality; $F(1, 23) = 11.04, p < .005$, for favored interpretation; and $F < 1$ for the interaction. In contrast, for the letter *p*, the results indicated $F(1, 23) = 13.72, p < .005$, for lexicality, but $F < 1$ for both favored interpretation and the interaction.

The effect of favored interpretation, however, was consistently observed for each of the function prefixes studied. Thus, separate two-way ANOVAs, Lexicality × Favored Interpretation for the function prefix *b* ("in") yielded $F(1, 23) = 12.92, p < .005$, for lexicality; $F(1, 23) = 14.43, p < .001$, for favored interpretation; and $F < 1$ for the interaction. For the function prefix *k* ("as/like"), the same analysis yielded $F(1, 23) = 10.93$, $p < .01$, for lexicality; $F(1, 23) = 5.74$, $p < .05$, for favored interpretation; and $F < 1$ for the interaction. For the function prefix *l* ("to"), the results indicated $F(1, 23) = 11.06$, $p < .005$, for lexicality; $F(1, 23) = 4.31$, $p < .05$, for favored interpretation; and $F < 1$ for the interaction. Thus, the enhancement effect was found for each of the function morphemes tested, and it is important that for each of these morphemes the size of the enhancement effect was equally strong for words and nonwords.

Discussion

The results of Experiment 3 lend further support for the structural view of reading in demonstrating an enhancement effect even for nonwords. Furthermore, this effect was as strong as that found for words. These results clearly indicate that the enhancement effect reflects structural contributions that are relatively independent of semantic factors.

Once again, we note that the enhancement effect, although significant overall, was not found when *p* was a target. Given that the effect is based on target detection in content words, where letter detection performance is already quite good, it is perhaps not surprising that letter-detection improvement was not observed in all cases, and particularly in letters such as *p* (in Hebrew) that exhibit good detectability overall.

General Discussion

The work presented in this article provides further support for the structural view of reading. According to this view, the reading process recapitulates the general architecture inherent in speech production as specified by frame-and-slot models (Bock, 1990; Dell, 1986; Garrett, 1975): Frames are first established, and slots within these frames are then filled in by lexical units. We proposed that in text processing too the coding of structure leads the way to the coding of meaning (see Aaronson & Ferres, 1984; Bock, 1990; Forster & Ryder, 1971; Garrett, 1980): Early in text processing, an attempt is made to establish a rudimentary structural frame for the phrase or the sentence that can help guide the interpretation of individual units and their integration within the encompassing phrasal structure. The on-line extraction of structure rests on expectations generated by context, as well as on various syntactic cues present in the text, particularly function morphemes. Functors inform the reader about which elements are most likely to be significant in the text and thus direct the reader's attention toward these elements. Functors are therefore monitored early in text processing, but once they have been utilized to set structure, they slip into the background, yielding to the semantically rich content units.

Support for this view has come so far from the function-disadvantage effect: Letter detection is poorer in morphemes that carry structural information than in those that carry semantic information. Several results summarized earlier clearly indicate that the function-disadvantage effect occurs after the stage at which orthographic strings are parsed into their constituent morphemes and after these morphemes have been assigned their syntactic roles (see Koriat & Greenberg, 1994). The function-disadvantage effect, then, appears to reveal the figure–ground relationship between content and function elements that results from the rapid on-line identification of the phrase's rudimentary structure.

In the present experiments, we explored the additional hypothesis that the reduced prominence of structural elements (ground) is accompanied by the enhanced accentuation of the content (figure) elements that follow. The enhancement effect documented in these experiments is assumed to reflect the gradual, dynamic shift to a sentential representation dominated by content units. Thus, content morphemes that followed functors evidenced a higher rate of letter detection than those that followed other content words. It is important that this pattern was obtained across two languages, English and Hebrew, and across two types of functors, function words and function prefixes.

The enhancement effect could be explained by assuming that functors are skipped over during reading because of their high redundancy or high familiarity (Haber & Schindler, 1981; Hadley & Healy, 1991). Such skipping might result in a greater likelihood of fixating a content word that follows a functor, and can thus explain the improved letter detection in content words that followed function words in Experiment 1 with English. The results with the Hebrew prefixed words (Experiments 2 and 3), however, pose a problem for this interpretation, because here the function and content units are part of the same string, and the function morpheme cannot be identified on the basis of its visual familiarity. Presumably, then, the enhancement effect stems from a process that occurs after the prefixed word has been parsed into its function + content constituents. What is more, this effect was obtained even with nonwords (Experiment 3), whose parsing cannot be aided by the familiarity of the content constituents. This latter result suggests that the enhancement effect reflects the structural organization of the sentence and, moreover, that this organization can be extracted relatively independently of meaning.

Figure 1 nicely captures the independent contribution of structural processing as revealed by the contrast between the missing-letter effect observed for functors (left), and the enhancement effect found for content words and nonwords that follow such functors (right). The data for the missing-letter effect come from Experiment 2 in Koriat and Greenberg (1991), whereas those for the enhancement effect come from Experiment 3 of the present study. Although the two experiments differ in many details, they share the same Lexicality × Favored Interpretation factorial design: In both experiments, the critical Hebrew string housing the target letter was either a word or a nonword (lexicality), and the initial letter of that string was likely to be interpreted either as a function prefix or as part of the stem of a content word (favored interpretation). The main difference was that the earlier experiment focused on the missing-letter effect and hence tested detection of the initial letter of the critical string (which sometimes represented a functor). Experiment 3 of the present study, in contrast, focused on the enhancement effect and hence examined detection of the second letter of the string (which was always part of the stem of the content morpheme).

According to the structural view of reading, both the missing-letter effect and the enhancement effect are different

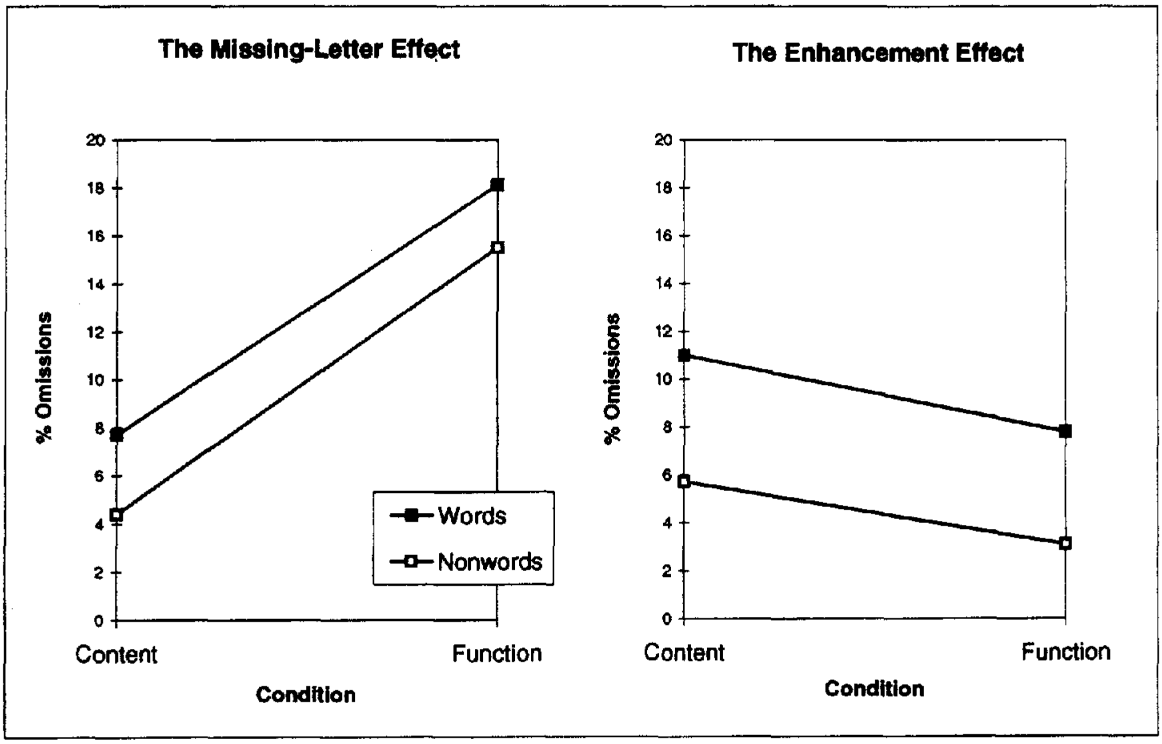

Figure 1. A comparison of the missing-letter effect (left) and the enhancement effect (right) in letter detection. The data for the missing-letter effect are based on Experiment 2 in Koriat and Greenberg (1991), whereas those for the enhancement effect are based on Experiment 3 of the present study.

manifestations of the same phenomenon: the figure–ground articulation of the sentence's structure, in which the structure-supporting units recede to the background while pushing to the foreground the content units that follow. Figure 1, then, depicts the ensuing trade-off pattern between the fading of the structural elements and the enhancement of the succeeding semantic elements. Indeed, the figure discloses a remarkable parallel: In both experiments, letter detection was better for nonwords than for words, but both types of strings yielded divergent effects of favored interpretation in the two experiments. For the initial letter of the string, more errors were made when that letter represented a function prefix than when it was part of the stem of a content string. For the second letter, in contrast, the opposite trend was found, indicating fewer errors in the content part of the string when the initial letter was interpreted as a function prefix than when it was interpreted as part of the stem.

Of importance, as can be seen in Figure 1, both effects were perfectly additive with lexicality. In fact, in both experiments the Lexicality × Favored Interpretation interaction yielded $F < 1$. This pattern supports the claim that both of these effects disclose structural contributions that can be activated independent of meaning (see Bock & Loebell, 1990).

Note that although both the missing-letter effect and the enhancement effect reflect the same process—the structural articulation of the sentence—we have assumed that the fading of functors precedes the enhanced detectability of the following content units. This should be the case if the coding of structure leads the way to the coding of meaning and if structure is cued better by function words than by content words. Of course, a more parsimonious account is that text processing is guided from the start by a focus on the semantically rich content units and that this focus is what makes function elements less prominent. This account, however, would not explain why it is precisely the content words that are introduced by functors that enjoy better detectability than those located a few words ahead.

How is the structure of a sentence or a phrase extracted and articulated on-line during reading? In discussing the missing-letter effect, we proposed that the extraction of tentative frames is determined by a collaborative interaction among syntactic, semantic–lexical, and visual factors (see Koriat & Greenberg, 1991, 1993, 1994). Thus, readers presumably monitor the text for function morphemes that can help disclose local structures. Such morphemes can be utilized even with Jaberwocky-type sentences that are deprived of meaning. As noted above, both the function-disadvantage effect and the enhancement effect are obtained even with nonwords (see Koriat & Greenberg, 1991). In addition, however, the expectancies generated by syntactic–semantic constraints also guide the establishment of structural frames. Indeed, manipulations that impair phrase structure have been found to reduce the size of the missing-letter effect. Thus, letter detection in functors improves when word order is scrambled (Drewnowski & Healy, 1977; Healy, 1976) or when words are placed in a syntactically inappropriate slot (Koriat et al., 1991).

In fact, contextual constraints also help specify the syntactic status of words. Thus, letter detection in *on* is more difficult in *he sat on the chair* than in *he pushed the on switch* (Greenberg & Koriat, 1991). Also, Moravcsik and Healy (1995) reported fewer errors in *the* when it was used as a content word (e.g., when *the* referred to a type of Thai spice) than when it was used as an article, suggesting that letter detection in function words is affected by semantic–syntactic constraints. In the case of Hebrew prefixed words (and nonwords), contextual constraints also guide the parsing of the string into its constituent morphemes and the interpretation of the prefix letter as representing a functor (Koriat & Greenberg, 1991).

This analysis perhaps helps explain the improved letter detection in nonwords compared with words (see Koriat & Greenberg, 1991). Healy and her associates also observed a similar effect in comparing letter detection in correctly spelled and misspelled words (e.g., Healy, 1976; Healy & Drewnowski, 1983; Healy et al., 1987) and attributed this effect to the greater familiarity of words. Although this might be the case, an alternative explanation that is more in line with the structural model has been proposed by Koriat and Greenberg (1991). According to that explanation, the structural role of words in normal text is revealed by both lexical and contextual factors. That of nonwords, in contrast, is disclosed only by context. Perhaps the specification of a nonword's role may delay its processing relative to that of a word, resulting in improved letter detection.

Finally, the establishment of tentative structural frames seems to be aided by a preliminary parafoveal preview of the text. For example, we found that letter detection in a function word (e.g., *for*) is affected by the words that follow it even when the preceding context is held constant (Greenberg & Koriat, 1991). Perhaps because of this reliance on the low-resolution, parafoveal scanning of text, visual factors also play a role in the specification of structure. Thus, nonwords placed in function slots engender more detection errors the greater their visual similarity to the functors that they replace (Koriat & Greenberg, 1991).

In summary, the on-line extraction and articulation of phrase structure appears to take advantage of a variety of cues that operate in collaboration. Essentially, a fast-moving, shallow analysis allows the reader to specify rudimentary, local frames that can serve as building blocks in constructing the meaning representation of the sentence. The letter-detection task apparently captures these local frames, reflecting the dynamic shift of focus from structure to meaning that occurs on-line. Although readers may establish structural frames of different sizes (story, passage, sentence, phrase), the letter-detection task is most sensitive to local frames, possibly at the phrase level only. Indeed, the missing-letter effect for function words is affected by the immediately surrounding context (see Drewnowski & Healy, 1977; Greenberg & Koriat, 1991; Healy et al., 1987; Koriat & Greenberg, 1993) but not by a trailing context that is several words ahead (Koriat et al., 1991). This may explain why letter detection is better for a content word that immediately follows a functor than for one that does not.

It has been argued that the letter-detection task may distort the normal process of reading because of the superimposed requirement to cancel letters while reading (e.g., Rayner & Pollatsek, 1989). However, it seems that participants do read for comprehension during the letter-detection task (e.g., in a recently completed study by Alter & Greenberg, 1996, participants who cancelled letters in a coherent passage correctly answered more than five out of six questions about the passage; see also Healy, 1994). Furthermore, it has been observed that the size of the missing-letter effect, if anything, increases when participants are warned of a subsequent comprehension test (Smith & Groat, 1979). Nevertheless, it is important to examine the generality of our results to other methods that may be less likely to alter the processing units used by the reader. Thus, we are currently exploring two additional vehicles for studying the on-line establishment of phrase structure: eye movements and prosody.

With regard to eye movements, there is evidence that function words are often identified without a direct fixation (see Inhoff, Topolski, Vitu, & O'Regan, 1993; O'Regan, 1979; Rayner & Pollatsek, 1989; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989), suggesting that these words are apprehended in the parafovea and utilized to set structure. However, in some preliminary work evaluating the structural hypothesis,[4] we found that the likelihood of fixating at the short, familiar function word *for* depends on whether or not *for* is leading a prepositional phrase. In cases in which *for* plays less of a structural role (e.g., *Are you for or against?*), readers are more likely to fixate on it than when it is fulfilling its more typical function role. Furthermore, our eye-movement results also indicate that readers are more likely to fixate on a content word that follows *the* than on one that does not, and this effect is maintained even when the word *the* was only implicit (i.e., removed from the text). These results parallel those found with the letter-detection task and suggest that eye fixations during reading are symptomatic of the structural frames established.

We are currently exploring the possibility that these structural frames are also disclosed by the prosodic patterns assigned by readers on-line when they are asked to read a sentence for the first time. Previous studies that examined the relationship between phonetic factors and visual letter detection have focused primarily on phonetic aspects of letters or syllables. Thus, Drewnowski and Healy (1982) found that letter-detection errors did not depend on whether a letter was voiced or unvoiced, but more errors were made in unstressed than in stressed syllables. (The latter effect occurred only for frequent words and for targets occurring in the last syllable.) In any case, phonological factors do not seem to be responsible for the missing-letter effect because articulatory suppression was found to reduce the effect of stress but did not influence the size of the missing-letter effect (Goldman & Healy, 1985). In our own work, we focus on the pause durations in reading a sentence. Initial results suggest that prosodic pause patterns are heavily influenced by syntactic cues and are derived relatively independently of semantics. If the results with prosody are found to parallel those obtained with the letter-detection task, it would remain to be seen whether letter-detection errors simply mirror the relative prosodic prominence of different units in silent reading, or whether both

[4] This work was carried out in collaboration with Albrecht Inhoff.

prosodic patterns and letter-detection patterns (as well as eye-movement patterns) are direct manifestations of structural processing. Furthermore, such results would raise the question of whether the structural frames established early in reading are more closely aligned with prosodic or with syntactic structures. This question becomes important in view of the claim that although prosodic structure is highly correlated with syntactic structure, it is still distinct from it (Ferreira, 1993). Thus, if we are correct that reading recapitulates the general architecture inherent in speech production, it is important to examine whether the letter-detection pattern discloses the architecture of syntax or perhaps that of prosody. (So far, we have left this question open; hence, our preference for the term *structural frame* over *syntactic frame.*)

What is the function of the structural articulation of text that is disclosed by the function-disadvantage and the enhancement effects? We can only speculate that it has the same function as that of figure–ground organization in perception: to make the more important entities stand out so that they can be submitted to further processing (see Palmer & Rock, 1994). In the case of reading, structural articulation presumably brings to the fore the meaning-loaded content elements within their embedding structural constellation so that they are given prominence in the generation of meaning representations. Syntactic elements convey the overall structure of the sentence and specify the role of the individual elements within that structure. However, they serve primarily as a vehicle for accessing meaning. In terms of Jacoby and Kelley's (1987) distinction, the structure of the sentence is treated by the reader as a tool, whereas it is the meaning that serves as the object of attention and memory. In fact, the structure of a sentence remains largely transparent when reading for meaning. Nevertheless, this structure helps accentuate some of the content elements relative to others, thereby preserving some of the structural information in the meaning representation of the sentence. A good example for this process is provided in a study by McKoon, Ratcliff, Ward, and Sproat (1993), which showed that concepts placed in syntactically prominent slots have increased accessibility in both short-term and long-term memory. They proposed that syntactic information influences the relative salience of different text segments, and thereby helps guide the allocation of attention to different units. More attention to "foregrounded" units translates into more processing for a longer period of time. Perhaps, similarly, the introduction of a content morpheme by a functor gives that morpheme a higher priority in subsequent processing and a greater salience in memory.

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