845

Journal of Experimental Psychology:
Learning, Memory, and Cognition
1993, Vol. 19, No. 1, 23-33

Phonetic Recoding of Phonologically Ambiguous Printed Words

Ram Frost and Michal Kampf

Speech detection and matching simultaneously presented printed and spoken words were used to examine phonologic and phonetic processing of Hebrew heterophonic homographs. Subjects detected a correspondence between an ambiguous letter string and the amplitude envelopes of both dominant and subordinate phonological alternatives. Similar effects were obtained when the homographs were phonologically disambiguated by adding vowel marks. The matching of the unpointed printed forms of heterophonic homographs to the dominant and subordinate spoken alternatives presented auditorily was as fast as matching the pointed unambiguous forms to the respective spoken words. This outcome was not obtained when print and speech were not presented simultaneously. These results suggest that printed heterophonic homographs activate the two spoken alternatives they represent and provide further confirmation for fast phonetic recoding in reading.

Most studies of lexical ambiguity have examined the processing of printed homophonic homographs embedded in text or presented in isolation (e.g., Onifer & Swinney, 1981; Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Simpson & Burgess, 1985; Swinney, 1979). Homophonic homographs (e.g., *bug*) are characterized by an orthographic structure that has one pronunciation but two different meanings in semantic memory. Research with homophonic homographs has focused on whether the two meanings related to the orthographic structure are activated in parallel or whether one meaning acquires dominance at some stage after the presentation of the ambiguous letter string. Several studies have suggested that, even in a biasing context, all the meanings of a homograph may be automatically activated and retrieved (e.g., Onifer & Swinney, 1981; Seidenberg et al., 1982; Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979). In contrast, it has been shown that biasing contextual information affects lexical processing of homographs at an early stage, selecting only contextually appropriate meanings (e.g., Glucksberg, Kreuz, & Rho, 1986; Schvaneveldt, Meyer, & Becker, 1976). A third approach poses that exhaustive access that does not occur in parallel but is determined by the relative frequency of the two meanings related to the ambiguous word (e.g., Duffy, Morris, & Rayner, 1988; Forster & Bendall, 1976; Hogaboam & Perfetti, 1975; Neill, Hilliard, & Cooper, 1988; Simpson, 1981; and see Simpson, 1984, for a review).

Homophonic homographs are not the only forms of word ambiguity. Ambiguity can also exist in the relationship between the orthographic and the phonologic forms of a word, forming a heterophonic homograph. In contrast with homophonic homographs, heterophonic homographs (e.g., "wind," "bow") are characterized by an orthographic structure that is related to two or more phonological structures. Each of these phonological realizations addresses a different meaning in semantic memory. Because heterophonic homographs form a small and nonrepresentative group of words in English orthography, few studies have examined their processing. Kroll and Schweickert (1978) showed that heterophonic homographs take longer to pronounce than homophonic homographs. Similar results were reported in Serbo-Croatian by Frost, Feldman and Katz (1990), who demonstrated that subjects are slower to match phonologically ambiguous printed words with their spoken forms.

In contrast with English or Serbo-Croatian, the unpointed Hebrew orthography presents an opportunity to explore the processing of heterophonic homographs. In Hebrew, letters represent mostly consonants, whereas most of the vowels can optionally be superimposed on the consonants as diacritical marks. In most printed material (except for poetry and children's literature), the diacritical vowel-marks are usually omitted. Because different vowels may be added to the same string of consonants to form different words or nonwords, the Hebrew unpointed print cannot specify a unique phonological unit. Therefore, a printed letter string is always phonologically ambiguous and often represents more than one word, each with a different meaning (though frequently related). An example of Hebrew homography is presented in Figure 1.

In a recent study, Frost and Bentin (1992) examined the processing of Hebrew heterophonic homographs by using a semantic priming paradigm. Subjects were presented with heterophonic homographs as primes, whereas the targets were related to only one of the primes' possible meanings. The targets followed the primes at different stimulus onset asynchrony (SOAs). It was assumed that if a specific meaning of the prime was accessed, lexical decisions for targets related to that meaning would be facilitated. Frost and Ben-

---

Ram Frost and Michal Kampf, Department of Psychology, Hebrew University, Jerusalem, Israel.

This work was supported in part by a grant awarded to Ram Frost by the Hebrew National Academy of Science and in part by the National Institute of Child Health and Human Development Grant HD-01994 to Haskins Laboratories. We are indebted to Liora Yancovitch for her help in running the experiments, and to Shlomo Bentin, Asher Cohen, Bruno Repp, Derek Besner, Charles Perfetti, and Alexander Pollatsek for their criticism of earlier drafts of this article.

Correspondence concerning this article should be addressed to Ram Frost, Department of Psychology, Hebrew University, Jerusalem, Israel.

Unpointed print	חלב (CH-L-V)	
pointed phonological alternatives	Dominant	Subordinate
	חָלָב	חֵלֶב
	(/chalav/)	(/chelev/)
Semantic meaning	"milk"	"grease"

Figure 1. Example of phonological ambiguity in Hebrew.

tin reported that, in the absence of biasing context, both meanings of heterophonic homographs were active at SOAs ranging from 250 to 750 ms from stimulus onset, whereas at a short SOA of 100 ms, only the dominant meaning was active.

One characteristic of many studies concerned with lexical ambiguity is the use of semantic priming for examining the processing of an ambiguous prime (for a review, see Simpson, 1984). The experimental strategy used in most cases consisted of monitoring lexical decisions or naming latencies for targets that are related to ambiguous primes embedded in text or presented in isolation (Onifer & Swinney, 1981; Seidenberg et al., 1982; Simpson & Burgess, 1985; Swinney, 1979). Several studies used other behavioral measures such as event-related potentials (Van Petten & Kutas, 1987) or eye movements (Duffy et al., 1988). However, in all of these studies the processing of lexically ambiguous letter strings was investigated by examining semantic facilitation. Although semantic priming effects may well indicate how the two meanings of homographs are entertained during lexical access, their interpretation is not always unequivocal. One major problem relates to the possibility of backward semantic priming. Backward semantic priming refers to a situation in which the target word reactivates the meaning of the prime. The lexical decision, in this case, is facilitated by processing the target in the presence of a related reactivated meaning rather than the result of a direct preactivation of the target (Koriat, 1981; see Neely, 1990, for a review). Applied to the disambiguation of homographs presented in isolation, the backward priming hypothesis suggests, for example, that the activation of the subordinate meaning of the prime might be initiated by the presentation of the related target rather than being the result of a context-independent automatic lexical process. Hence, semantic facilitation cannot unequivocally provide evidence in support of an exhaustive or an ordered access model of lexical disambiguation.

Evidence from semantic priming effects is even more problematic when the phonologic processing of heterophonic homographs is investigated. It has been suggested that the orthographic structure of heterophonic homographs is linked with two or more lexical entries in the phonologic lexicon, each of which is unequivocally related to one meaning in semantic memory. (See Frost & Bentin, 1992, for a discussion of this point.) However, it is often assumed that, with the possible exception of very infrequent words, printed words activate orthographic units that are directly related to meanings in semantic memory (e.g. Seidenberg, 1985; Seidenberg, Waters, Barnes, & Tanenhaus, 1984). Recently, Jared and Seidenberg (1991) suggested that the activation of meanings precedes phonologic activation. They used the semantic decision task developed by Van Orden (1987) and reported that phonologically based activation of meanings is limited to low-frequency words and nonwords. Thus, according to this direct access model, the visual presentation of a heterophonic homograph might directly activate its two semantic meanings, or at least its dominant meaning, without a previous activation of the word (phonologic structure) related to it. In a similar manner, if backward priming should occur, the meanings of the primes would be initiated by the disambiguating targets and not necessarily the unequivocal phonological structures that are related to the ambiguous primes. Therefore, the measurement of semantic facilitation does not indicate whether the presentation of the ambiguous letter string has caused the activation of the two phonologic structures related to it, or merely the activation of the two semantic meanings that were accessed directly from the print.

The aim of our study was to investigate whether the two alternative phonemic realizations of heterophonic homographs are activated following the visual presentation of the ambiguous orthographical pattern, yet avoiding the problems inherent in semantic priming methods. For this purpose, two tasks that directly tap phonologic and phonetic activation were used. In Experiments 1 and 2, the speech detection task was used (Frost, 1991; Frost, Repp, & Katz, 1988). In Experiments 3 and 4 the matching task was used (Frost et al., 1990; Frost & Katz, 1989).

The Detection Task

Frost et al. (1988) reported an auditory illusion occurring when printed words and masked spoken words appear simultaneously. In a set of experiments, subjects were presented with speech-plus-noise and noise-only trials and were required to detect the masked speech in a signal detection paradigm. The auditory stimuli were accompanied by print that either matched or did not match the masked speech.

The noise used in their experiment was amplitude modulated (i.e., the spoken word was masked by noise with the same amplitude envelope). A word's amplitude envelope is mainly the variation of its amplitude over time. It represents the dynamic property of the acoustic signal. Amplitude-modulated noise is a stretch of white noise with an amplitude that is correlated with the word's amplitude fluctuations. Thus, amplitude-modulated noise (representing the word's amplitude envelope) does not provide any spectral information and therefore cannot convey the explicit phonemic or syllabic structure of the word. Rather, it retains some speechlike features and conveys mostly prosodic and stress information. Because in the Frost et al. (1988) study the words were masked by their own amplitude envelopes, when a printed word matched the spoken word it also matched the amplitude envelope of the noise generated from it.

The results suggested that subjects automatically detected a correspondence between noise amplitude envelopes and printed stimuli when they matched. The detection of this correspondence made the amplitude-modulated noise sound more speechlike, causing a strong response bias: Whether speech was indeed present in the noise or not, subjects had the illusion of hearing it when the printed stimuli matched the auditory input. To match the visual to the auditory information, subjects had to generate from the print the relevant amplitude envelope. The process of matching the auditorily presented envelopes to the lexically addressed envelope representations derived from the print was probably performed in one single match of the overall acoustic shapes. This is because in the speech detection task the visual presentation occurs at the onset of speech presentation, which unfolds over time. Thus, the subject often retrieved the complete phonetic representation of the printed word before the complete presentation of the auditory stimulus. Regardless of how the matching process occurs, it is the positive matching of the envelope representation derived from the print, with the envelope provided auditorily, that causes the illusion.[1]

Frost (1991) replicated these findings in Hebrew. As in the original study, subjects listened to speech-plus-noise and noise-only trials, accompanied by pointed or unpointed Hebrew print that either matched or did not match the masked speech. The stimuli in the study consisted of high-frequency words, low-frequency words, and nonwords. The results showed that matching print caused a strong bias to report speech in noise for words, regardless of frequency, but not for nonwords. The bias effect was not affected by spelling-to-sound regularity—that is, similar effects were obtained in the pointed and the unpointed conditions. Note that in this and previous studies using the speech detection technique, subjects were not required to respond to the printed information. Moreover, they were informed of the equal distribution of signal and noise trials in the different visual conditions. Nevertheless, the correspondence between the visual stimulus and the speech envelope affected their response criterion. This outcome was interpreted to suggest that the generation of a phonetic representation following the presentation of a printed word occurred automatically. The bias effect did not appear when the printed words and the spoken words from which the amplitude envelopes were generated were merely similar in their syllabic stress pattern or phonologic structure. Frost and his colleagues therefore concluded that the processing of a printed word results not only in a phonologic code but also in a detailed phonetic speech code that includes the word's amplitude envelope.

Amplitude envelopes representations can assist the listener in the process of spoken word recognition. The envelopes cannot identify a specific lexical candidate, however, they do convey prosodic and segmental information (e.g., speech timing, number of syllables, relative stress, and several major classes of consonant manner) that might help in selecting a lexical candidate among a highly constrained set of response alternatives (Van Tasell, Soli, Kirby, & Widin, 1987). Thus, the amplitude envelope might serve as additional information used by the listener to identify spoken words that have several acoustic realizations or for which their phonemic structure is not clearly conveyed (cf. Gordon, 1988). In these cases, a match between the perceived amplitude envelope and the stored template might confirm the identity of a lexical candidate.

The bias to report hearing speech in amplitude-modulated noise when matching print accompanies the auditory presentation was used as the dependent variable in this investigation. This bias occurs only when subjects detect a correspondence between the printed and the spoken information. Therefore, our experiments examined whether subjects detected a correspondence between a printed heterophonic homograph and the masked spoken forms of the two phonologic alternatives it represents. This could easily be monitored by measuring the amount of bias obtained when the amplitude envelopes derived from each of the two phonologic alternatives were presented in the auditory modality.

Experiment 1

In Experiment 1 subjects were presented with printed Hebrew heterophonic homographs in the visual modality. Each homograph could be read as two different words, one with a higher frequency of occurrence (dominant phonological alternative) and the other with a lower frequency of occurrence (subordinate phonological alternative). Simultaneously with the visual presentation, subjects heard over earphones the possible spoken words related to the homographs, each one masked by noise having the same amplitude envelope. In addition, they heard just the amplitude-modulated noises that were derived from the spoken dominant or subordinate alternatives. Thus, in half of the trials the noise was presented by itself, and in the other half it served as a masker for the spoken forms. The subjects' task was to distinguish between those trials.

If, in following the visual presentation, subjects retrieve the amplitude envelopes (as well as other phonetic information) of *both* the dominant and the subordinate phonologic alternatives that are related to the homograph, then the simultaneous auditory presentation of either of these envelopes should produce a bias to detect speech in the noise. If, on the other hand, the visual presentation of the printed homograph does not result in a phonetic activation of the two spoken words related to the letter string, then no effect of bias should be obtained. Alternatively, if only the dom-

---

[1] We cannot account for the specific mechanism responsible for the bias effect. We can only suggest that the convergence of visual and auditory information is responsible for it. The illusion to detect speech in the noise is not restricted to the presentation of print and speech. Repp, Frost, and Zsiga (1992) have shown similar effects with lipreading, when a visual presentation of a speaker's face was used instead of printed words.

inant word is activated following the presentation of the printed letter string, a bias should be revealed only for the dominant alternative.

Method

Subjects. Twenty-four undergraduate students, all native speakers of Hebrew, participated in Experiment 1 for course credit or for payment.

Stimulus preparation. The stimuli were generated from 24 ambiguous consonant strings, each representing two words: one high- and one low-frequency. The two words were not semantically related. In the absence of a reliable frequency count in Hebrew, the subjective frequency of each word was estimated by using the following procedure: From a pool of 100 ambiguous consonant strings, two lists of 100 pointed words each were generated. Each list of disambiguated words contained only one form of the possible realizations of each homograph. Dominant and subordinate meanings were equally distributed between the lists. Both lists were presented to 50 undergraduate students, who rated the frequency of each word on a 7-point scale from 1 (*very infrequent*) to 7 (*very frequent*). The rated frequencies were averaged across all 50 judges. Each of the 24 homographs that were selected for this study represented two words that differed in their rated frequency by at least 1 point on that scale. The validity of this selection was then tested by naming: Twenty-four subjects were presented with the unpointed homographs, and their vocal responses were recorded. The relative dominance of each phonological alternative was assessed by the number of times it was actually pronounced by the subjects. Only those homographs whose frequency judgments coincided with the results obtained in the naming task (i.e., at least 66% of the subjects chose to name the phonological alternative that had a higher frequency rate) were used in Experiment 1.

The auditory stimuli were originally spoken by a male native speaker in an acoustically shielded booth and recorded on an Otari MX5050 tape recorder. The speech was digitized at a 20 kHz sampling rate. From each digitized word, a noise stimulus with the same amplitude envelope was created by randomly reversing the polarity of individual samples with a probability of 0.5 (Schroeder, 1968). This signal-correlated noise retains a certain speechlike quality, even though its spectrum is flat and it cannot be identified as a particular utterance unless the choices are very limited (see Van Tasell et al., 1987). The speech-plus-noise stimuli were created by adding the waveform of each digitized word to that of the matched noise, adjusting their relative intensity to yield a signal-to-noise ratio of −10.7 dB.

Each digitized stimulus was edited by using a waveform editor. The stimulus onset was determined visually on an oscilloscope and verified auditorily through headphones. A mark tone was inserted at the onset of each stimulus on a second channel, inaudible to the subject. The edited stimuli were recorded at 3-s intervals on a two-track audiotape, one track containing the spoken words and the other track containing the mark tones. The purpose of the mark tone was to trigger the presentation of the printed stimuli on a computer screen.

Design. Each of the dominant and subordinate spoken alternatives was presented in two auditory forms: (1) speech-plus-noise trials, in which the spoken stimulus was presented, masked by noise, or (2) noise-only trials, in which the noise was presented by itself without the speech. Each of these auditory presentations was accompanied by two possible visual presentations: (1) matching print (i.e., the same word that was presented auditorily, or that was used to generate the amplitude-modulated noise, was presented in print) or (2) nonmatching print (i.e., the printed stimulus was a different word, having the same number of phonemes and a similar phonologic structure, but without sharing any phoneme in the same location with the word that was presented auditorily or that was used to generate the noise). Thus, there were four combinations of visual/auditory presentations for each of the 48 words, making a total of 192 trials in the experiment.

Procedure and apparatus. Subjects were seated in front of a Macintosh SE computer screen and listened binaurally over Sennheiser headphones. They sat approximately 70 cm from the screen so that the stimuli subtended a horizontal visual angle of 4° on the average. A bold Hebrew font, size 24, was used. The task consisted of pressing a "yes" key if speech was detected in the noise, and a "no" key if it was not. The dominant hand was always used for the "yes" responses. Although the task was introduced as purely auditory, the subjects were requested to attend carefully to the screen as well. They were told in the instructions that, when a word was presented on the screen, it was sometimes similar to the speech or noise presented auditorily, and sometimes not. However, they were informed about the equal proportions of "yes" and "no" trials in each of the different visual conditions.

The tape containing the auditory stimuli was reproduced by a two-channel Otari MX5050 tape recorder. The verbal stimuli were transmitted to the subject's headphones through one channel, and the trigger tones were transmitted through the other channel to an interface that directly connected to the Macintosh, where they triggered the visual presentation.

The experimental session began with 24 practice trials. The practice trials were generated from ambiguous words that were not used in Experiment 1. After the practice, all of the 192 experimental trials were presented in one block. The duration of a whole experimental session was approximately 20 min.

Results and Discussion

The indices of bias in the different experimental conditions were computed by following the procedure suggested by Luce (1963). Results computed according to Luce's procedure tend to be very similar to those produced by the standard signal detection computations (e.g., Wood, 1976). However, Luce's indices do not require any assumptions about the shapes of the underlying signal and noise distributions and are easier to compute relative to the standard measures of signal detection theory. The Luce indices of bias and sensitivity, originally named $\ln b$ and $\ln \eta$, but renamed here for convenience, b and d, are as follows:

$$b = 1/2 \ln [p(\text{yes}/s + n)\, p(\text{yes}/n)/p(\text{no}/s + n)\, p(\text{no}/n)],$$

and

$$d = 1/2 \ln [p(\text{yes}/s + n)\, p(\text{no}/n)/p(\text{yes}/n)\, p(\text{no}/s + n)],$$

where $s + n$ and n stand for speech plus noise and noise only, respectively. The index b assumes positive values for a tendency to say "yes" and negative values for a tendency to say "no." For example, according to the above formula, to obtain an average b of +0.5, the subject must generate, on the average, 60% more positive than negative responses. The index d assumes values in the same general range as the d' of signal detection theory, with zero representing chance performance.

The average values for the bias indices in each experimental condition are shown in Table 1. There was a bias to say "yes" in the matching condition for both the dominant and subordinate alternatives. There was no bias in the nonmatching condition. Similar differences in bias between the matching and the nonmatching conditions were found for the dominant and the subordinate alternatives. The average *d* in the experiment was 0.15.[2]

The bias indices were subjected to a two-way analysis of variance (ANOVA) with the variables of visual condition (matching print or nonmatching print) and dominance (dominant or subordinate).[3] The main effect of visual condition was significant, $F(1, 23) = 21.4$, $MS_e = 0.5$, $p < 0.001$, as was the main effect of dominance, $F(1, 23) = 4.6$, $MS_e = 0.2$, $p < 0.04$. The main effect of dominance, however, is not of great importance because the bias effects for the dominant and subordinate alternatives are measured in reference to the overall differences between the matching and the nonmatching conditions. These differences were similar for the dominant and subordinate alternatives, as reflected by the nonsignificant two-way interaction ($F < 1$). The results of Experiment 1 suggest, therefore, that both the dominant and the subordinate phonological alternatives were activated to the same extent following the presentation of the ambiguous homograph.

Experiment 2

In Experiment 2, subjects were presented with the same set of consonantal strings as in Experiment 1 but in a disambiguated form. Hebrew heterophonic homographs can be disambiguated by adding diacritical dots to the ambiguous letter strings. The vowel marks unequivocally determine the phonemic structure of the consonantal cluster, thereby denoting either its dominant or its subordinate reading. The aim of Experiment 2 was to compare the bias effect obtained with unpointed ambiguous letter strings with that obtained when the print conveyed explicitly the exact phonological alternatives, dominant or subordinate. If, indeed, both phonological alternatives were activated in Experiment 1 with unpointed print, similar bias effects should emerge in Experiment 2, in which the vowels unequivocally denote the dominant and the subordinate readings.

The pointed presentation also allowed the inclusion of an additional experimental control condition. Before speculating about mechanisms of processing heterophonic homographs, it was important to make sure that the dominant and subordinate spoken alternatives in their masked forms were clearly distinguishable from each other. Note that the dominant and the subordinate alternatives of heterophonic homographs have a very similar phonologic structure (identical consonantal cluster) and often differ by only one vowel. It is possible that the amplitude envelopes of the two alternatives were similar to the extent that subjects could not distinguish between them. The presentation of the printed homograph might have resulted in the activation of only one phonological alternative, probably the dominant one, and consequently in the generation of its amplitude envelope alone. If the amplitude envelopes of the dominant and the subordinate alternatives were very similar, even if the subjects had generated the envelope of the dominant alternative only, they would have detected a correspondence between this envelope representation and the envelope of the subordinate alternative that was presented auditorily. By this account, the bias obtained for both dominant and subordinate forms would have resulted merely from the inability of subjects to differentiate between the similar amplitude envelopes and from their falsely detecting a match between the dominant envelope they generated from the ambiguous printed word and the subordinate envelope they heard. Thus, the second aim of Experiment 2 was to test this possibility directly. In addition to the four experimental conditions of Experiment 1, subjects were exposed to a fifth condition in which the phonological alternatives that were presented explicitly in pointed print were accompanied by the amplitude envelopes of the other phonological alternatives that were related to the same homograph, and vice versa. The purpose of these trials was to examine whether such a countermatch can result in a bias to detect speech in the noise.

Table 1
Means of Bias Indices (b) With Unpointed Heterophonic Homographs for Dominant and Subordinate Spoken Alternatives in Two Conditions (Experiment 1)

Condition	Dominant	Subordinate
Match	0.74	0.59
No match	0.09	−0.16

The explicit (pointed) presentation of the dominant or the subordinate phonological alternative presumably would result in the activation of a detailed phonetic representation of that word, including the word's amplitude envelope (Frost, 1991; Frost et al., 1988). If the amplitude envelopes of the dominant and the subordinate alternatives cannot be distinguished from each other, then the countermatch condition should produce a bias effect that is similar to that obtained in the matching conditions; subjects would detect a correspondence between the envelope generated from one printed phonological alternative and the envelope of the other alternative, provided auditorily. If, on the other hand, the amplitude envelopes of the two phonological alternatives are perceptibly different, the pattern of bias obtained in the countermatch condition should be more similar to the pattern obtained in the nonmatching conditions.

---

[2] This almost-chance level of detection is very similar to the detectability scores reported by Frost (1991) with identical signal-to-noise ratio. However, note that the bias for a "yes" response is not affected by the poor level of detection (in fact, effects of bias can emerge only when detection is imperfect). Frost et al. (1988) showed significant bias effects in the speech detection task over a wide range of signal-to-noise ratios.

[3] As in all the previous studies that used the detection task, a stimulus analysis was not carried out. This is because, in this task, the auditory stimuli cannot be identified by the subjects and each stimulus is rotated and repeated in the various auditory forms several times for each subject across all experimental conditions.

Method

Subjects. Twenty-four undergraduate students, all native Hebrew speakers, participated for course credit or for payment. None of the subjects had participated in Experiment 1.

Stimuli, design, and procedure. The stimuli and procedure were identical to those used in Experiment 1, except that all the words were presented in conjunction with vowel marks. Thus, each word was presented in an unequivocal phonological form and had only one meaning.

The design of Experiment 2 included an additional control condition. In this condition for each homograph, subjects were presented with one of the pointed alternatives in print, in conjunction with the masked spoken forms of the other alternatives, and vice versa. Hence, this additional condition (the countermatch condition) served as an experimental control to measure the bias effect caused by the possible phonetic similarity between the dominant and subordinate phonological alternatives related to the same letter string.

Results and Discussion

The average values for the bias indices in each experimental condition are shown in Table 2. There was a bias to say "yes" in the matching condition for both the dominant and the subordinate phonological alternative, whereas there was no bias in the nonmatching condition. The bias effects found for the dominant and the subordinate alternatives were very similar.

The bias indices were subjected to a two-way ANOVA with the variables of visual condition (matching print or nonmatching print) and dominance (dominant or subordinate). The main effect of visual condition was significant, $F(1, 23) = 15.0$, $MS_e = 0.5$, $p < 0.001$. The main effect of dominance and the two-way interaction were not significant, $F(1, 23) = 2.6$, $MS_e = 0.14$, $p < 0.12$; and $F < 1$, respectively.

We compared the effects of bias obtained for the dominant and the subordinate alternatives in the unpointed ambiguous print relative to the pointed unequivocal print. For this analysis, the relevant data from Experiments 1 and 2 were combined in mixed ANOVA designs in which the print form (pointed or unpointed) was introduced as an additional between-subjects variable. The effect of print form was not significant ($F < 1$). Print form did not interact with visual condition or with dominance, nor was the three-way interaction significant (all Fs < 1). This outcome suggests that the unequivocal printed presentation of the dominant or subordinate alternatives in Experiment 2 resulted in bias effects that were very similar to those produced by the ambiguous print in Experiment 1.

Table 2
Means of Bias Indices (b) With Pointed Heterophonic Homographs for Dominant and Subordinate Spoken Alternatives in Three Conditions (Experiment 2)

Condition	Dominant	Subordinate
Match	0.55	0.51
No match	0.07	−0.14
Countermatch	0.16	

Another significant outcome of Experiment 2 was that there was almost no bias effect in the countermatch condition (0.16). To compare directly the effects of bias obtained in the matching and the countermatch conditions, planned comparisons were conducted. These comparisons revealed a significantly greater effect of bias in the matching condition than in the countermatch condition for both the dominant and the subordinate alternatives, $t(23) = 2.88$, $p < 0.008$; and $t(23) = 3.0$, $p < 0.006$, respectively. The difference in bias between the countermatch and the nonmatching condition was significant for the subordinate alternatives, $t(23) = 2.1$, $p < 0.04$, but not for the dominant alternatives, $t(23) = 0.6$, $p < 0.5$. This merely suggests that the countermatch condition was more similar to the nonmatching condition for the dominant than for the subordinate alternatives. Thus, the results of Experiment 2 support the conclusions of Experiment 1.

Experiment 3

Experiments 3 and 4 used the matching task, which directly taps the process of mapping printed words into lexical phonological structures (Frost & Katz, 1989; Frost et al., 1990). In the matching task, subjects are simultaneously presented with a printed word on a computer screen and with a spoken word by headphones. The subjects are asked to decide as fast as possible whether or not the stimuli presented in the visual and the auditory modalities are the same or different. To match the spoken and the printed forms of words, they both have to converge at an identical lexical entry. Because the transformation of speech into an orthographic representation is, by far, less practiced than the transformation of spelling into phonology, the common end result of both print and speech processing in the matching task is presumably a phonological representation in the lexicon. (See Frost et al., 1990, for a detailed discussion of the matching task.)

In Experiment 3, subjects were presented simultaneously with printed heterophonic homographs and with the spoken forms of the dominant and subordinate alternatives. They were instructed to determine whether the printed and spoken words were equivalent. In some of the trials the printed homographs were presented in their pointed form and were therefore disambiguated; that is, the vowel marks depicted unequivocally either the dominant or the subordinate alternatives. In these trials, the matching of the visual printed words to the spoken words did not involve any ambiguity resolution. In other trials the homographs appeared unpointed and, thus, could be read in two ways. In these trials the outcome of matching the visual words to the spoken words was dependent on the specific phonological alternative generated from the ambiguous consonant string. The aim of Experiment 3 was to compare the decision time for pointed and unpointed print.

If only the dominant phonologic alternative is generated from the ambiguous printed homograph, then the vowel marks will not affect the decision time when the dominant spoken word is presented auditorily. The dominant alternative will be generated as a rule from the letter string (pointed or unpointed) and compared with the dominant spoken word presented auditorily, to yield a "yes" response. In contrast, different decision times will be revealed for the pointed and unpointed forms of the subordinate alternatives. This is because with the unpointed ambiguous print, the subject would first generate the dominant alternative and would consequently find a mismatch with the spoken subordinate alternative presented auditorily. This mismatch will slow his or her decision time relatively to the pointed presentation that depicts the subordinate alternative unequivocally. If, on the other hand, both phonologic interpretations are generated from the consonant strings, then no advantage in decision time for pointed presentations will be found for both the dominant and the subordinate alternatives. As both phonological alternatives are computed from the letter string, their matching with the auditory information should not be affected by the explicit presentation of vowel marks.

Method

Subjects. Sixty undergraduate students, native Hebrew speakers, participated in Experiment 3 for course credit or for payment. None of the subjects had participated in the previous experiments.

Stimuli and design. The target stimuli were 40 ambiguous consonant strings that represented both a high- and a low-frequency word. Their selection criteria were identical to those used in Experiments 1 and 2. With different vowel marks, these 40 consonant strings represented 80 words, 40 frequent and 40 nonfrequent. Each trial in Experiment 3 consisted of a visual and an auditory presentation of a word. There were four experimental conditions: An unpointed printed letter string could appear in conjunction with either the dominant or the subordinate alternative; in addition, the spoken dominant and subordinate alternatives appeared in conjunction with their printed pointed forms. All of these trials were "same" trials. In addition, 40 "different" pairs were introduced as fillers to achieve a probability of 0.5 for a "same" response. The "different" trials consisted of ambiguous printed consonant strings that were not used in the "same" trials. These letter strings were half pointed and half unpointed and were paired with spoken words with the same length and vowel-consonant structure but that differed with respect to one or two phonemes. To introduce a higher level of complexity in the experimental task, one third of the "different" trials consisted of a pointed presentation of one phonological alternative of the ambiguous letter string, whereas the spoken words were the other phonological alternative related to that homograph. These trials ensured that the matching process could not be performed by a superficial similarity judgment.

Four lists of words were formed: Each list contained 10 pairs in each of the four experimental conditions and 40 mismatch fillers. Each subject was tested in only one list. The pairs were rotated across lists by a Latin square design, so that each subject was exposed to all experimental conditions, yet avoiding any stimulus repetition effect.

The visual stimuli were presented on a Macintosh II computer screen. They subtended a visual angle of approximately 2.5° on average. The auditory stimuli were originally spoken by a female native speaker in an acoustically shielded booth and digitized at a 20 kHz sampling rate, using Macrecorder. Each digitized stimulus was edited. Its onset was determined visually on an oscilloscope and was verified auditorily through headphones.

Procedure and apparatus. Subjects wore Sennheiser headphones and sat in a semi-darkened room in front of the Macintosh II computer screen. The auditory stimuli were transmitted binaurally to the subject's headphones by the computer. The visual presentation occurred simultaneously and triggered the computer's clock for reaction time (RT) measurements. The experimental task consisted of pressing a "same" key if the visual and the auditory stimuli were the same word, and pressing a "different" key if they were different. The dominant hand was always used for the "same" responses. The experimental session began with 16 practice pairs. After the practice, all 80 test trials were presented in one block.

Results and Discussion

Means and standard deviations of RTs for correct responses were calculated for each subject in each of the four experimental conditions. Within each subject/condition combination, RTs that were outside a range of 2 standard deviations from the respective mean were excluded, and the mean was recalculated. Outliers accounted for less than 5% of all responses. RTs in the different experimental conditions are shown in Table 3. Decision latencies were identical for pointed and unpointed print for both dominant and subordinate alternatives. Hence, no statistical analysis for this effect was needed. Overall, RTs for dominant alternatives were faster than RTs for subordinate alternatives, $F_1(1, 59) = 6.5, MS_e = 7{,}131, p < 0.01$; $F_2(1, 38) = 5.5, MS_e = 6{,}199, p < 0.02$, for the subject and stimuli analyses, respectively. This is a well-documented frequency effect in the matching task (Frost & Katz, 1989; Frost et al., 1990) and merely reflects the slower matching of printed and spoken words that have lower frequency of occurrence.

The results of Experiment 3 strongly support the results of Experiments 1 and 2. The presentation of the spoken subordinate alternative in conjunction with the unpointed heterophonic homograph did not slow the matching process relative to the unequivocal printed presentation. This outcome suggests that *both* phonologic alternatives were generated from the ambiguous letter string. Apparently, when the dominant or subordinate spoken words were presented auditorily (in the matching task, the auditory information effectively lags behind the visual information), they matched one of the phonological representations that had already been generated from the print.

Table 3

Mean Reaction Times and Percentages of Errors for Pointed and Unpointed, Dominant and Subordinate Alternatives in the Matching Task

	Auditory presentation			
	Dominant		Subordinate	
Visual presentation	*M*	%	*M*	%
Unpointed	710	4%	736	4%
Pointed	709	4%	736	6%
No-match fillers	*M* = 685, % = 11%			

Note. Mean reaction times are expressed in milliseconds. Print and speech are presented simultaneously.

Experiment 4

The aim of Experiment 4 was to examine whether the two phonologic alternatives remain active even at a longer SOA so as to test the limits of the dual activation process. For this purpose the design of Experiment 3 was repeated, but the auditory presentation was delayed by 500 ms relative to the onset of the visual word. Because the auditory presentation in itself was distributed over 400 to 500 ms of time on the average, Experiment 4 examined the activation of the two phonologic alternatives at approximately 800 ms from visual stimulus onset.

Method

The subjects were 60 undergraduate students, native Hebrew speakers, who participated in the experiment for course credit or for payment. None of the subjects had participated in the previous experiments. The stimuli, design, and apparatus were identical to those used of Experiment 3.

Results and Discussion

RTs in the different experimental conditions are shown in Table 4. The results with the lagged presentation clearly differ from the results with the simultaneous presentation: Decision latencies with unpointed print were overall slower than decision time with pointed print. This effect was strongest for the subordinate alternatives.[4]

The statistical significance of these results was assessed by an ANOVA across subjects (F_1) and across stimuli (F_2), with the main variables of visual presentation (pointed or unpointed) and dominance of spoken alternatives (dominant or subordinate). Both main effects were significant, $F_1(1, 59) = 53.6$, $MS_e = 1{,}412$, $p < 0.001$, and $F_2(1, 39) = 70.0$, $MS_e = 641$, $p < 0.001$, for visual presentation; and $F_1(1, 59) = 57.2$, $MS_e = 3{,}033$, $p < 0.001$, and $F_2(1, 39) = 27.5$, $MS_e = 4{,}350$, $p < 0.001$, for dominance. The interaction of visual presentation and dominance was significant as well, $F_1(1, 59) = 19.6$, $MS_e = 1{,}247$, $p < 0.001$; $F_2(1, 39) = 25.3$, $MS_e = 664$, $p < 0.001$.

The relatively slower RTs for unpointed as compared with pointed print for subordinate alternatives suggest that they were less activated at 800 ms from stimulus onset, relatively to the dominant alternatives. Consequently, the following presentation of the spoken subordinate alternative presented auditorily often resulted in a mismatch that caused slower RTs in the unpointed presentation relative to the explicit pointed presentation. This suggestion is further supported by the somewhat slower RTs for unpointed relative to pointed print when the dominant alternatives were presented auditorily. Because the subjective dominance ratings were not always unanimously accepted, these slower RTs were probably due to several trials in which, for some subjects, the subordinate alternatives were, in fact, considered as the dominant ones and vice versa. In these few cases, the following auditory presentation of the dominant spoken alternatives resulted in mismatches that caused the overall slower latencies in the unpointed condition.

Table 4
Mean Reaction Times and Percentages of Errors for Pointed and Unpointed, Dominant and Subordinate Alternatives in the Matching Task (Experiment 4)

	Auditory presentation			
	Dominant		Subordinate	
Visual presentation	*M*	%	*M*	%
Unpointed	612	5%	687	4%
Pointed	600	4%	633	7%
No-match fillers	*M* = 638, % = 11%			

Note. Mean reaction times are expressed in milliseconds. Auditory presentation occurred 500 ms after visual presentation.

General Discussion

In our study we examined the processing of Hebrew heterophonic homographs by using two experimental tasks that directly tap phonetic and phonologic processing. In Experiments 1 and 2, the detection of speech in amplitude-modulated noise served as a tool for directly measuring the amount of phonetic activation that developed following the visual presentation of the printed homograph. The extent of phonetic activation was reflected in a response bias to report speech in the noise when the masked speech was accompanied by matching print. In Experiments 3 and 4, RTs for matching the pointed and unpointed printed forms of heterophonic homographs to the dominant and subordinate spoken alternatives reflected the relative activation of the two phonologic structures represented by the ambiguous letter string.

The results of Experiment 1 demonstrated that the pairing of a printed heterophonic homograph with an auditory presentation of both dominant and subordinate masked spoken alternatives led to a similar bias toward a "yes" response. This outcome suggests that subjects derived from the ambiguous letter string two phonetic representations that were subsequently matched to the dominant and subordinate amplitude envelopes presented auditorily. In Experiment 2, the explicit presentation of the dominant and subordinate phonological alternatives by using the vowel marks produced bias effects that were very similar to the effects obtained in the unpointed presentation. Moreover, the inclusion of the countermatch condition clarified that (a) the two phonetic representations that were derived from the letter string were clearly distinct, and (b) the bias obtained for both dominant and subordinate alternatives did not result from a possible acoustic similarity between the amplitude envelopes of the two spoken alternatives.

The results of Experiments 3 and 4 using the matching task, supported the conclusions of Experiments 1 and 2. If in Experiments 1 and 2 the activation of both phonologic al-

---

[4] Because reaction times (RTs) were measured from the onset of the auditory presentation, the faster RTs in Experiment 4 relative to Experiment 3 reflect the trivial fact that subjects have already processed the visual stimulus for 500 ms before the onset of RT measurement.

ternatives was inferred from responses to amplitude-modulated noises that could not be consciously recognized as words by the subjects, in Experiments 3 and 4 the two spoken forms of the ambiguous letter strings were explicitly and clearly presented. The identical matching latencies of pointed and unpointed print to both dominant and subordinate spoken alternatives in Experiment 3 suggest that both alternatives were, indeed, generated from the ambiguous consonant cluster. This conclusion is further supported by the contrasting results of Experiment 4, which revealed a much larger activation of the dominant alternatives relative to the subordinate alternatives, some 800 ms from visual stimulus onset.

The results of our study thus suggest that both phonological alternatives were activated following the presentation of the printed homographs. This outcome converges with previous studies that examined the activation of dominant and subordinate meanings of homophonic homographs (e.g., Simpson & Burgess, 1985) and of heterophonic homographs (Frost & Bentin, 1992). Using a semantic priming paradigm, Simpson and Burgess (1985) demonstrated that the dominant and subordinate meanings of heterophonic homographs are both active at SOAs ranging from 100 to 250 ms from stimulus onset. However, more relevant to our study are the recent results reported by Frost and Bentin (1992), who used a semantic priming paradigm similar to that used by Simpson and Burgess (1985), but with Hebrew heterophonic homographs. Isolated ambiguous consonant strings were presented as primes, and the visual targets, which were related to only one of their possible meanings, followed the ambiguous primes at 100 ms, 250 ms, and 750 ms SOA. The results demonstrated that, at SOAs of 250 ms or longer, lexical decisions for targets that were related either to the dominant or to the subordinate phonological alternative were facilitated.

The strong bias effect obtained for both dominant and subordinate phonological alternatives in Experiment 1 suggests that the visual presentation of heterophonic homographs resulted not only in the activation of the two meanings related to it, as reported by Frost and Bentin (1992), but also in the activation of the two phonetic alternatives that the letter string represents. Whether this activation reflects a mandatory and automatic process of phonologic recoding of the ambiguous printed word cannot be unequivocally determined by our results. It is possible that the presentation of auditory stimuli served to elicit phonological processing of the printed stimuli. Although we cannot rule out this possible interpretation, we find it less probable. In Experiments 1 and 2, subjects were explicitly instructed not to base their auditory judgments on the visual information and were informed of the equal distribution of "yes" and "no" trials in the different visual conditions. Nevertheless, the large numbers of false alarms in the matching condition suggests that they could not avoid being influenced by the visual information.

The findings that both phonetic alternatives were activated following the printed presentation provides further confirmation for the notion of fast phonetic recoding in reading offered by a large literature in visual word perception (e.g., Perfetti, Bell, & Delaney, 1988; Van Orden, Johnston, & Hale, 1988) but is often challenged by those who find evidence suggesting that printed words activate orthographic units that are directly related to meanings in semantic memory (see Van Orden, Pennington, & Stone, 1990, for a review). What the findings of Experiments 1 and 2 teach is that subjects generate the two phonetic representations related to a phonologically ambiguous letter string, even when the experimental task (speech detection in noise) does not require any processing of the printed stimulus. This conclusion is in accordance with the claim put forward by Frost and Bentin (1992), who suggested that the activation of the two phonological entries of heterophonic homographs precedes the activation of their meanings. Frost and Bentin based their conclusions on findings showing a different onset of meaning activation for heterophonic than for homophonic homographs, and on more robust priming effects observed when the primes were heterophonic homographs than when they were homophonic homographs. Because both homophonic and heterophonic homographs address two meanings in semantic memory, models of direct access from print to meaning could not account for the differences in meaning activation obtained for these two types of letter strings. These differences can be accounted for only by assuming that the processing of heterophonic homographs first involves phonological disambiguation. Our results confirm that the phonological processing of heterophonic homographs is characterized by the generation of both of the phonetic representations that the letter string represents.

One important question related to the activation of the two phonological alternatives refers to their relative level of activation with simultaneous and delayed presentation. Note that, in contrast with semantic priming experiments, in which the SOA between visual primes and targets can be explicitly manipulated and monitored, the matching task cannot provide evidence for the exact onset of activation of the two phonologic alternatives. Moreover, unlike the study reported by Frost and Bentin (1992), in which SOA was systematically manipulated, Experiments 3 and 4 examined the activation of the two phonologic alternatives with simultaneous and delayed presentations only. However, the overall range of onset activation can be estimated. The stimuli used in our experiments consisted mainly of two-syllable words, and the duration of the auditory presentation ranged from 400 to 500 ms on the average. Assuming that some of the responses were given as soon as the auditory presentation reached the word's recognition point (see Marslen-Wilson, 1987), an overall estimate of the time course of activation of the two phonological alternatives in Experiments 1 and 3 suggests that they were both active at 200 to 500 ms SOA. This estimation, however, cannot rule out the possibility that the two alternatives were available before 250 ms and remained active later than 500 ms from stimulus onset. The results of Experiment 4 suggest that, at approximately 800 ms from stimulus onset, the activation of subordinate alternatives decayed relatively to the activation of the dominant alternatives.

Another finding of the present study was the very small bias effect obtained in the countermatch condition of Experiment 2. This result suggests that the envelope representations generated from the print were very detailed. The ability of subjects to automatically generate detailed amplitude envelopes from verbal information presented in the visual modality was shown previously in studies that used printed words (Frost, 1991; Frost et al., 1988) and in a study that used speech reading (Repp et al. 1992). In these studies the words in the matching and nonmatching condition had the same phonologic structure and stress pattern but did not share phonemes in the same location. The subjects were shown to be able to discriminate between a representation they generated from a word presented visually and the envelope of a nonmatching word presented auditorily. This discrimination was reflected by a lower effect of bias in the nonmatching condition relative to the matching condition. The words in the countermatch condition in our study were the two different realizations of heterophonic homographs. Thus, although in some pairs there were differences in stress patterns, they shared the same consonants and, in many cases, they differed only by a single vowel. Nevertheless, it appears that the envelope representation generated from the printed dominant alternative was not confused with the envelope of the subordinate alternative presented auditorily, and vice versa. This outcome suggests a surprising ability of subjects to generate a detailed and specific phonetic representation from printed words.

In conclusion, our study suggests a novel tool for examining phonetic processing of print. The task of detecting speech embedded in amplitude-modulated noise, when matching or nonmatching print is presented simultaneously in the visual modality, has been shown to be able to monitor the generation of phonetic representations from the printed stimuli (Frost, 1991; Frost et al., 1988; but see also Repp et al., 1992). The advantage of the speech detection task is that phonetic processing is not inferred from responses to printed words following orthographic or semantic experimental manipulations but is measured indirectly in a task that does not explicitly require any response to the printed word. The results from this task converge with the results of the matching task that taps the conversion of printed words into phonologic structures.

References

Duffy, S. A., Morris, R. K., & Rayner, K. (1988). Lexical ambiguity and fixation time in reading. *Journal of Memory and Language, 27,* 429–446.

Forster, K. I., & Bendall, E. S. (1976). Terminating and exhaustive search in lexical access. *Memory & Cognition, 4,* 53–61.

Frost, R. (1991). Phonetic recoding of print and its effect on the detection of concurrent speech in amplitude modulated noise. *Cognition, 39,* 195–214.

Frost, R., & Bentin, S. (1992). Processing phonological and semantic ambiguity: Evidence from semantic priming at different SOAs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 58–68.

Frost, R., Feldman, L. B., & Katz, L. (1990). Phonological ambiguity and lexical ambiguity: Effects on visual and auditory word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 569–580.

Frost, R., & Katz, L. (1989). Orthographic depth and the interaction of visual and auditory processing in word recognition. *Memory & Cognition, 17,* 302–311.

Frost, R., Repp, B. H., & Katz, L. (1988). Can speech perception be influenced by a simultaneous presentation of print? *Journal of Memory and Language, 27,* 741–755.

Glucksberg, S., Kreuz, R. J., & Rho, S. H. (1986). Context can constrain lexical access: Implications for models of language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12,* 323–335.

Gordon, P. C. (1988). Induction of rate-dependent processing by coarse-grained aspects of speech. *Perception & Psychophysics, 43,* 137–146.

Hogaboam, T. W., & Perfetti, C. A. (1975). Lexical ambiguity and sentence comprehension. *Journal of Verbal Learning and Verbal Behavior, 14,* 265–274.

Jared, D., & Seidenberg, M. S. (1991). Does word identification proceed from spelling to sound to meaning? *Journal of Experimental Psychology: General, 120,* 358–394.

Koriat, A. (1981). Semantic facilitation in lexical decision as a function of prime-target association. *Memory & Cognition, 9,* 587–598.

Kroll, J. F., & Schweickert, J. M. (1978). Syntactic disambiguation of homographs. Paper presented at the Nineteenth Annual Meeting of the Psychonomic Society, San Antonio, Texas.

Luce, R. D. (1963). *Response times: Their role in inferring elementary mental organization.* New York: Oxford University Press.

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition, 25,* 71–102.

Neely, J. H. (1990). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner & G. Humphreys (Eds.), *Basic processes in reading: Visual word recognition.* Hillsdale, NJ: Erlbaum.

Neill, W. T., Hilliard, D. V., & Cooper, E. (1988). The detection of lexical ambiguity: Evidence for context-sensitive parallel access. *Journal of Memory and Language, 27,* 279–287.

Onifer, W., & Swinney, D. A. (1981). Accessing lexical ambiguities during sentence comprehension: Effects of frequency of meaning and contextual bias. *Memory & Cognition, 9,* 225–236.

Perfetti, C. A., Bell, L. C., & Delaney, S. M. (1988). Automatic (prelexical) phonetic activation in silent word reading: Evidence from backward masking. *Journal of Memory and Language, 27,* 59–70.

Repp, B. H., Frost, R., & Zsiga, E. (1992). Lexical mediation between sight and sound in speech reading. *Quarterly Journal of Experimental Psychology, 45A,* 1–20.

Schroeder, M. R. (1968). Reference signal for signal quality studies. *Journal of the Acoustical Society of America, 43,* 1735–1736.

Schvaneveldt, R. W., Meyer, D. E., & Becker, C. A. (1976). Lexical ambiguity, semantic context, and visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 243–256.

Seidenberg, M. S. (1985). The time course of phonological code activation in two writing systems. *Cognition, 19,* 1–30.

Seidenberg, M. S., Tanenhaus, M. K., Leiman, J. M., & Bienkowski, M. (1982). Automatic access of the meaning of ambiguous words in context: Some limitations of knowledge-based processing. *Cognitive Psychology, 14,* 489–537.

Seidenberg, M. S., Waters, G. S., Barnes, M., & Tanenhaus, M. K. (1984). When does irregular spelling or pronunciation influence word recognition? *Journal of Verbal Learning and Verbal Behavior, 23,* 383–404.

Simpson, G. B. (1981). Meaning dominance and semantic context in the processing of lexical ambiguity. *Journal of Verbal Learn-*

ing and Verbal Behavior, 20, 120–136.

Simpson, G. B. (1984). Lexical ambiguity and its role in models of word recognition. *Psychological Bulletin, 96,* 316–340.

Simpson, G. B., & Burgess, C. (1985). Activation and selection processes in the recognition of ambiguous words. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 28–39.

Swinney, D. A. (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning and Verbal Behavior, 18,* 645–660.

Tanenhaus, M. K., Leiman, J. M., & Seidenberg, M. S. (1979). Evidence for multiple stages in the processing of ambiguous words in syntactic contexts. *Journal of Verbal Learning and Verbal Behavior, 18,* 427–440.

Van Orden, G. C. (1987). A ROWS is a ROSE: Spelling, sound, and reading. *Memory & Cognition, 10,* 434–442.

Van Orden, G. C., Johnston, J. C., & Hale, B. L. (1988). Word identification in reading proceeds from spelling to sound to meaning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 371–386.

Van Orden, G. C., Pennington, B. F., & Stone, G. O. (1990). Word identification in reading and the promise of subsymbolic psycholinguistics. *Psychological Review, 97,* 488–522.

Van Petten, C., & Kutas, M. (1987). Ambiguous words in context: An event-related potential analysis of the time course of meaning activation. *Journal of Memory and Language, 26,* 188–208.

Van Tasell, D. J., Soli, S. D., Kirby, V. M., & Widin, G. P. (1987). Speech waveform envelope cues for consonant recognition. *Journal of the Acoustical Society of America, 82,* 1152–1161.

Wood, C. C. (1976). Discriminability, response bias, and phoneme categories in discrimination of voice onset time. *Journal of the Acoustical Society of America, 60,* 1381–1389.

Received December 18, 1991
Revision received April 14, 1992
Accepted April 17, 1992 ■