Journal of Experimental Psychology:
Learning, Memory, and Cognition
1992, Vol. 18, No. 1, 58–68

0278-7393/92/$3.00

Processing Phonological and Semantic Ambiguity: Evidence From Semantic Priming at Different SOAs

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Disambiguation of heterophonic and homophonic homographs was investigated in Hebrew using semantic priming. Ambiguous primes were followed by unambiguous targets at 100 ms, 250 ms, and 750 ms stimulus onset asynchrony (SOA). Lexical decision for targets related to the dominant phonological alternatives of heterophonic homographs were facilitated at all SOAs. Targets related to subordinate alternatives were facilitated only at SOAs of 250 ms or longer. When the primes were homophonic homographs, semantic relationship facilitated lexical decision to targets at all SOAs regardless of the dominance of the meaning to which the targets were related. These data can be accounted for by assuming multiple lexical entries for heterophonic homographs, single lexical entries for homophonic homographs, and phonological mediation of accessing meanings. Language-specific factors probably account for the long-lasting activation of subordinate meanings.

Several studies of lexical disambiguation suggested that all the meanings of a homograph may be automatically activated. One experimental procedure used to demonstrate access to multiple meanings is semantic priming. It has been reported that homographs embedded in sentences facilitate lexical decisions for related targets even if these targets are related to meanings that are different than those implied by the sentence context (e.g., Onifer & Swinney, 1981; Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979). These results were interpreted as supporting an exhaustive, context-independent model of lexical access for homographs according to which all possible meanings of one homograph are retrieved in parallel. An alternative view is that contextual information affects lexical processing of homographs at an early stage, selecting only meanings that are contextually appropriate (e.g., Glucksberg, Kreuz, & Rho, 1986; Schvaneveldt, Meyer, & Becker, 1976).

A third approach combines features of both previous views into an ordered access model. This model posits exhaustive access that does not occur in parallel but that is determined by the relative frequency of the two meanings related to the ambiguous word (e.g., Duffy, Morris, & Rayner, 1988; Forster & Bednall, 1976; Hogaboam & Perfetti, 1975; Neill, Hilliard, & Cooper, 1988; Simpson, 1981; see Simpson, 1984, for a review). Hogaboam and Perfetti (1975) demonstrated that, whatever the biasing context, the dominant meaning of a homograph is retrieved first. Evidence for an ordered access was also presented by Simpson (1981), who showed that in a nonbiasing context only targets that were related to the dominant meaning of an ambiguous word were primed. Similarly, differential activation of high- and low-frequency meanings of ambiguous homographs was also demonstrated with event-related potentials (Van Petten & Kutas, 1987) and by monitoring eye movements (Duffy et al., 1988; Rayner & Frazier, 1989).

If more than one meaning of a homograph can be retrieved, even if it appears in a biasing-sentence context, multiple-meaning access should be the rule for homographs presented in isolation. This hypothesis was confirmed by Holley-Wilcox and Blank (1980), who found that polysemous primes (e.g., *bank*) facilitated lexical decisions to targets related to all of their meanings. Holley-Wilcox and Blank (1980) interpreted their results as supporting the parallel-access model. More recently, however, Simpson and Burgess (1985) reported evidence for an ordered-access model for isolated homographs. They showed that in the case of isolated homographs the most frequently used (dominant) meaning is accessed first, whereas the less frequently used (subordinate) meaning is accessed relatively later.

Most studies of lexical ambiguity focused on homophonic homographs (i.e., letter strings that have a single pronunciation but two or more meanings, e.g., *bank*). However, homophonic homographs are not the only forms of word ambiguity. Ambiguity can exist also in the relationship between the orthographical and the phonological forms of a word. For example, in contrast to *bank*, the printed letter string *wind* has two different pronunciations, each of which has a different meaning. Frost, Feldman, and Katz (1990) examined the effect of phonological ambiguity in Serbo-Croatian. Subjects were presented simultaneously with printed and spoken words and were required to determine whether the words matched. Phonological ambiguity was produced using letters that represented different phonemes in the Cyrillic and Roman alphabets. The results showed that matching phonologically ambiguous printed words with their spoken realizations was

This work was supported by a Basic Research Foundation grant administered by the Israel Academy of Science and Humanities to Ram Frost and by National Institute of Child Health and Human Development Grant HD-01994 to Haskins Laboratories. We are indebted to Pazit Mey-Raz and Michal Kampf for their help in conducting the experiments and to Cyma Van Petten, Greg Simpson, Charles Perfetti, and three anonymous reviewers for their criticism on earlier drafts of this article.

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delayed relative to the matching of unambiguous printed patterns in which only letters unique to one alphabet were used. This delay was significantly larger when the ambiguous print was matched with the less frequent spoken alternatives than when it was matched with the more frequent spoken alternative. Frost et al. (1990) suggested that these results support a multiple-access model in which dominant alternatives reach a higher level of activation. The effect of phonological ambiguity was examined in English as well. Carpenter and Daneman (1981) demonstrated that the duration of eye fixations on heterophonic homographs was longer when the phonological alternative implied by the semantic context was a low-frequency word than when it was a high-frequency word. In a direct comparison between heterophonic and homophonic homographs, Kroll and Schweickert (1978) found that heterophonic homographs like *wind* take longer to name than homophonic homographs. These results suggest that in English, as in Serbo-Croatian, heterophonic homographs are processed differently than homophonic homographs. However, in both English and Serbo-Croatian, heterophonic homographs form a small and perhaps nonrepresentative group of words.

The unvoweled Hebrew orthography presents an opportunity to examine the process of disambiguating the meaning of heterophonic homographs. In Hebrew, letters represent mostly consonants, and vowels can optionally be superimposed on consonants as diacritical marks. In most printed material (except for poetry, holy scriptures, and children's literature), the vowel marks are usually omitted. Because different vowels may be added to the same string of consonants to form different words, the Hebrew unvoweled print cannot specify a unique phonological unit. Therefore, a printed letter string is very frequently phonologically ambiguous, representing more than one word, each with a different meaning.

In a previous study (Bentin & Frost, 1987), we examined the influence of semantic and phonological ambiguity on lexical decision and on naming isolated Hebrew words. We found that lexical decisions for unvoweled ambiguous consonant strings were faster than for any of the high- or low-frequency voweled (and therefore disambiguated) meanings of the same strings. In contrast, naming ambiguous unvoweled words was as fast as naming the high-frequency voweled alternative, whereas naming the low-frequency alternative was significantly slower. On the basis of these and previous results (Bentin, Bargai, & Katz, 1984), we suggested that lexical decisions for unvoweled Hebrew words are generated before the process of phonological disambiguation probably on the basis of orthographic familiarity (cf. Balota & Chumbley, 1984; Chumbley & Balota, 1984; Seidenberg, 1985). This suggestion also accommodates previous data demonstrating that orthographic information is used for lexical decisions and naming more extensively in Hebrew than in other languages (Frost, Katz, & Bentin, 1987).

In contrast to lexical decision, naming necessarily requires the selection of one phonological alternative of the ambiguous letter string. The significant delay in naming the low-frequency voweled alternative relative to the unvoweled and the high-frequency forms of the same letter string led us to support the ordered-access model for the retrieval of phonological information. Consequently, we suggested that when confronted with phonologically ambiguous letter strings readers retrieve the high-frequency phonological structure first. The naming task, however, cannot disclose covert phonological selection processes. In particular, naming does not reveal whether phonological alternatives, other than the reader's final choice, had been accessed during the process of disambiguation. For example, in our previous study, subjects overtly expressed only one phonological structure: more often the high-frequency alternative. However, we could not determine whether alternative words were generated but discarded during the output process or whether only one word was generated from the print. Moreover, although each phonological form was related to a different meaning, naming does not necessarily imply access to semantic information. Therefore, although our previous results supported a frequency-ordered retrieval of phonological alternatives, a more direct measure was necessary to examine whether more than one meaning of a heterophonic homograph is automatically activated and whether this access is ordered by the relative frequency of each meaning.

In the present article, we addressed this question using a semantic priming paradigm similar to that used by Simpson and Burgess (1985). Isolated ambiguous consonant strings were presented as primes, and the targets were related to only one of their possible meanings. We assumed that if a specific meaning of the prime is initially accessed, lexical decision for targets that are related to that meaning should be facilitated.

A second question addressed in the present study refers to the time course of activation of dominant and subordinate (i.e., high- and low-frequency) meanings of phonologically ambiguous letter strings. Several studies in English showed that in a sentence context the subordinate meaning is active only during a limited period of time (Seidenberg et al., 1982; Van Petten & Kutas, 1987). Similar results were found also for isolated homographs (Kellas, Ferraro, & Simpson, 1988; Simpson & Burgess, 1985). In particular, Simpson and Burgess (1985) found that a stimulus onset asynchrony (SOA) of 16 ms between prime and target was sufficient to facilitate lexical decisions for targets related to the dominant meaning but not for targets related to the subordinate meanings. Relatedness to the subordinate meaning facilitated lexical decisions only when the SOA between prime and target ranged from 100 to 300 ms. The fast decay of the subordinate meaning was explained in that study by assuming that the limited-capacity attention system (Neely, 1977) must focus on only one meaning and, in the absence of disambiguating context, the dominant alternative is usually chosen (see also Kellas et al., 1988). However, because in Hebrew several phonological units are activated in addition to several semantic nodes, it is possible that the activation of both dominant and subordinate alternatives lasts longer. This might happen, for example, if the retrieval of different phonological units results in more extensive lexical processing. In the present study, we examined this possibility by manipulating the SOA between the ambiguous primes and the targets.

Experiment 1a

In Experiment 1a, we presented subjects with unvoweled heterophonic homographs as primes. By applying different vowel patterns, each prime could be read both as a high- and as a low-frequency word. In each trial, the prime was followed by a word or by a nonword target at 100-ms or 250-ms SOA. Subjects were instructed to read the primes silently and to make lexical decisions to the targets. Across subjects, each target was either unrelated to its prime or related to the dominant or to the subordinate meaning of the ambiguous prime. Facilitation of lexical decisions in any related condition (relative to the unrelated condition) was considered evidence for accessing the related meaning of the prime.

Method

Subjects. Forty undergraduate students, native Hebrew speakers, participated in the experiment for course credit or for payment.

Stimuli. The primes were 40 ambiguous consonant strings, which represented both high- and low-frequency words. In the absence of a reliable frequency count in Hebrew, we estimated the subjective frequency of each word using the following procedure: From a pool of 100 ambiguous consonant strings, we generated two lists of 100 voweled words each. 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 ranging from *very infrequent* (1) to *very frequent* (7). The rated frequencies were averaged across all 50 judges. Each of the 40 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 unvoweled homographs, and their vocal responses were recorded. We measured the relative dominance of each phonological alternative as reflected by the number of times it was actually chosen and 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 the experiment.

Two targets were associated to each selected homograph. One target was semantically related to its dominant meaning and the other to its subordinate meaning. The targets were all unambiguous (i.e., even without vowel marks they represented only one word). To ensure similar semantic relatedness for the dominant and the subordinate meanings, the semantic relation of primes and targets was rated by the same 50 judges on a 7-point scale ranging from *unrelated* (1) to *highly related* (7). The means of those ratings were 5.2 for the dominant meanings and 5.3 for the subordinate meanings. Each of the 80 targets was also paired with an unrelated prime. The unrelated primes were 40 heterophonic homographs selected from the original pool and different than those used in the related conditions. Because none of their possible readings was related to the targets, and because dominance is irrelevant in the unrelated condition, the same prime preceded the targets used in the dominant and the subordinate related conditions. Hence, there were only 40 different ambiguous primes in the unrelated conditions, which were rotated across subjects. In addition to the word–word pairs, 80 word–nonword pairs were introduced as fillers. The words were heterophonic homographs different than those contained in the original pool. The nonwords were consonant strings that have no meaning in Hebrew regardless of vowel configuration. An example of related and unrelated prime–target pairs is presented in Figure 1.

Design. There were eight experimental conditions: Different targets were related to the dominant or to the subordinate meanings of the ambiguous primes; each of the related targets was also presented in an unrelated condition. In each of these four possible pairings, the SOA between primes and targets was either 100 or 250 ms. Four lists

Unvoweled prime מלח

(MLCH)

Phonological alternatives	Dominant		Subordinate	
	MELACH		MALACH	
semantic meaning	"salt"		"sailor"	
Condition	Related	Unrelated	Related	Unrelated
Prime	MLCH	KLV ("dog")	MLCH	KLV ("dog")
Target	"sugar"	"sugar"	"ship"	"ship"

Figure 1. Example of related and unrelated prime–target pairs in unvoweled Hebrew.

Table 1
Reaction Times and Percentage of Errors to Related and Unrelated Targets in the Different Experimental Conditions with Phonologically Ambiguous (Unvoweled) Primes (Experiments 1a and 1b)

Variable	Dominant primes			Subordinate primes			Nonwords	
SOA	100	250	750	100	250	750	Exps. 1a	1b
Unrelated	715	678	692	718	701	714	754	778
% of errors	9%	8%	8%	12%	12%	10%	11%	8%
Related	684	639	658	739	669	692		
% of errors	10%	7%	8%	10%	13%	11%		
Priming effect	31	39	34	−21	32	22		

Note. SOA = stimulus onset asynchrony.

of words were formed: Each list contained 10 prime–target pairs in each of the eight experimental conditions and 80 word–nonword fillers. The prime–target pairs were rotated across lists by a Latin-square design: Related pairs in one list were unrelated in another list; pairs that appeared with a prime–target SOA of 100 ms in one list appeared with SOA of 250 ms in another list, and so on. The purpose of this rotation was to present the targets that were related to the dominant meanings of the primes and the targets that were related to the subordinate meanings of the primes in both the related and the unrelated conditions at all SOAs while avoiding repetitions within a list. Hence, each target word served as its own control for the measurement of semantic facilitation in an across-subjects design (see Figure 1).

Procedure and apparatus. The subjects were tested individually. They were instructed to read the primes and to make lexical decisions only for the targets by pressing a "word" or a "nonword" response key. The dominant hand was always used for "word" responses. All stimuli were presented at the center of a Macintosh computer screen (bold Hebrew font size 24). The subjects sat approximately 70 cm from the screen so that the stimuli subtended a horizontal visual angle of 4 degrees on the average. A trial began with the presentation of the prime, which was replaced by the target at the end of the respective SOA period. The target was continuously exposed until a response was recorded. The interstimulus interval was 2,500 ms from subject's response to the onset of the following prime. Each session started with 16 practice trials. The 160 test trials were presented in one block.

Results

Means and standard deviations of reaction times (RTs) for correct responses were calculated for each subject in each of the eight 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 then 5% of all responses. This procedure was repeated in all six experiments in the present study.

Reaction times (RTs) and errors in the different experimental conditions are presented in Table 1. Lexical decisions to targets related to the dominant meanings of the ambiguous primes were faster than to unrelated targets at both 100-ms and 250-ms SOA. In contrast, lexical decisions to targets related to the subordinate meanings were faster than responses to unrelated targets only at 250-ms SOA. At 100-ms SOA, lexical decisions to related targets were apparently slower than lexical decisions to unrelated targets.

The statistical significance of those differences was assessed by an analysis of variance (ANOVA) across subjects ($F1$) and across stimuli ($F2$); the main factors were semantic relatedness (related, unrelated), dominance of prime meaning (dominant, subordinate), and SOA (100 ms, 250 ms). The main effects of relatedness, dominance, and SOA were significant: RTs to related targets were faster than to unrelated targets, $F1(1, 39) = 22.0$, $p < .001$, $MS_e = 1789$, $F2(1, 39) = 15.7$, $p < .001$, $MS_e = 2655$; RTs to targets that referred to the dominant meaning of the prime in the related condition were faster than RTs to targets that referred to the subordinate meaning of the prime, $F1(1, 39) = 14.6$, $p < .001$, $MS_e = 2373$, $F2(1, 39) = 5.75$, $p < .02$, $MS_e = 7509$; and RTs at 250-ms SOA were faster than at 100-ms SOA, $F1(1, 39) = 63.9$, $p < .001$, $MS_e = 2315$, $F2(1, 39) = 27$, $p < .001$, $MS_e = 5319$.[1] Relatedness interacted with dominance, $F1(1, 39) = 5.62$, $p < .001$, $MS_e = 2119$, $F2(1, 39) = 3.16$, $p < .08$, $MS_e = 3594$, and with SOA, $F1(1, 39) = 14$, $p < .001$, $MS_e = 1256$, $F2(1, 39) = 10.5$, $p < .002$, $MS_e = 2332$. The interaction of SOA and dominance was not significant ($F1$ and $F2 < 1$). The three-way interaction was significant in the subject analysis, $F1(1, 39) = 4.0$, $p < .05$, $MS_e = 2191$, but only approached significance in the stimulus analysis, $F2(1, 39) = 2.7$, $p < .10$, $MS_e = 4868$. The three-way interaction seems to have resulted in part from greater RT differences between SOAs for unrelated dominant primes (37 ms) than for unrelated subordinate primes (17 ms). We do not have an explanation for this difference.

To elaborate the three-way interaction, and because we were concerned with the different patterns of facilitation for the dominant and the subordinate meanings at the short and the longer SOAs, we conducted separate analyses of the relatedness and dominance effects at each SOA. These respective ANOVAs showed that relatedness interacted with dominance at 100-ms SOA, $F1(1, 39) = 13.6$, $p < .001$, $MS_e = 1502$,

[1] Simpson and Burgess (1985) found no difference in RTs between SOAs of 100 and 300 ms. However, throughout the present study, the main effect of SOA was quite reliable and robust (including in the replication of Experiment 1a), suggesting that, unlike Simpson and Burgess, in the present study the 100-ms SOA condition was more difficult than the other SOA conditions. A possible explanation of this difference is that our procedure did not include an initial fixation point.

$F2(1, 39) = 8.4$, $p < .006$, $MS_e = 2905$, but not at 250-ms SOA, $F1, F2(1, 39) < 1$. A Tukey-A post hoc analysis of the interaction at 100-ms SOA revealed that the difference between unrelated targets and targets related to the subordinate meanings of the homographs was not significant, whereas lexical decisions for targets related to the dominant meaning of the homographs were faster than to unrelated targets.

The differences in error rates between the various experimental conditions did not produce significant effects.

Experiment 1b

A more complete description of the time course of activating the dominant and subordinate meanings of heterophonic homographs required examination of the semantic priming effects at an SOA longer than 250 ms. This condition could not be included in the first part of the experiment because the total number of stimuli used in our rotated within-subjects design did not permit an additional division.[2] Therefore, this condition was examined in a second group of 40 subjects sampled from the same population of undergraduates as in Experiment 1a.

Method

The stimuli, design, and procedure were similar to those used in Experiment 1a except that the SOA between primes and targets was 750 ms. To make the structure of the stimulus lists as similar as possible to the previous experiment, we introduced as fillers an identical number of heterophonic homographs with a shorter SOA of 250 ms. Moreover, because subjects encountering only long delays between primes and targets might actively invoke the two phonological alternatives whereas subjects encountering both long and short delays might not, a second purpose of the fillers with the shorter SOAs was to prevent subjects from developing this search strategy.

Results

RTs were faster for related targets than for unrelated targets and for targets related to the dominant meaning of the prime than for targets related to the subordinate meaning (Table 1). The statistical significance was assessed in a two-way ANOVA across subjects ($F1$) and across stimuli ($F2$). The main factors were semantic relatedness (related, unrelated) and dominance of prime meaning (dominant, subordinate). The ANOVA showed that both main effects were significant, $F1(1, 39) = 24.3$, $p < .001$, $MS_e = 1286$ and $F2(1, 39) = 14.6$, $p < .001$, $MS_e = 1765$ for semantic relatedness and $F1(1, 39) = 10.3$, $p < .002$, $MS_e = 3123$ and $F2(1, 39) = 11.6$, $p < .002$, $MS_e = 3378$ for dominance of the prime meaning. The interaction of the two factors was not significant, $F1$ and $F2$ $(1, 39) < 1$. Planned comparisons revealed that RTs to targets related to the subordinate alternatives of the prime meanings were significantly faster than in the unrelated condition, $t(1, 39) = 2.54$, $p < .01$. The pattern of semantic facilitation obtained for the fillers with 250-ms SOA was similar to that obtained with the identical SOA in Experiment 1a (33-ms facilitation for targets related to the dominant meaning and 20 ms for targets related to the subordinate meanings).

Discussion

The results of Experiments 1a and 1b suggest that meanings of isolated heterophonic homographs were retrieved as predicted by an ordered-access model. The meaning of the dominant phonological alternative was accessed faster than that of the subordinate phonological alternative. However, the time course of activating the subordinate meanings was different from that found with English homophonic homographs (Simpson & Burgess, 1985) in several ways. The subordinate meanings in Simpson and Burgess's study had been already activated at 100 ms and decayed after 300 ms from stimulus onset. In contrast, the meanings of subordinate phonological alternatives in the present study were not available at 100 ms.

The subordinate alternatives were active at 250 ms and, in contrast to English, they were still available as late as 750 ms from stimulus onset. Hence, the present data suggest that subordinate meanings of heterophonic homographs are accessed slower than the subordinate meaning of polysemous words, but they remain active for a longer time.

The divergence between the time course of disambiguating Hebrew heterophonic homographs and English homophonic homographs might reflect language-related differences or alternatively basic differences in processing heterophonic and homophonic homographs. However, before speculating further about mechanisms of disambiguation of homographs, it was important to make sure that the dominant and subordinate forms of the present stimuli were equivalent in their efficiency to prime their respective targets. To control for differences in accessing dominant and subordinate meanings in absence of phonological ambiguity and to understand better the independent relationship between the dominant and the subordinate phonological alternatives of one letter string and their respective meanings, a second experiment was conducted. In the second experiment, we examined the pattern of semantic facilitation of targets related to each meaning when the phonological units to which they were related were presented in a disambiguated form.

Experiments 2a and 2b

The interpretation of the apparently ordered retrieval of the subordinate and the dominant meanings of the phonologically ambiguous letter strings presented in Experiments 1a and 1b was based on the relative magnitude of priming effects. This interpretation assumed that the observed difference between dominant and subordinate meanings of the primes is accounted for by their phonological ambiguity. In other words, it was assumed that in a disambiguated form the subordinate and the dominant primes would have primed

[2] Although phonological ambiguity is very common in the Hebrew orthography, the set of stimuli used in the experiments was constrained by many experimental controls such as mean rated frequencies, dominance as reflected by naming performance, syntactic classes, rated semantic relatedness, and so on. This set of stimuli did not permit a within-subjects design across all SOAs. A similar problem was raised and solved similarly by Simpson and Burgess (1985).

their respective targets equally. The purpose of Experiments 2a and 2b was to test this assumption.

Hebrew provides a unique opportunity to compare semantic priming effects involving alternative meanings of homographs with the semantic priming effects involving the same words presented explicitly (i.e., in a nonambiguous form). In contrast to homophonic homographs that can be disambiguated only by semantic context (e.g., by embedding the homograph in a sentence), Hebrew heterophonic homographs can be disambiguated and still be presented as isolated words. This can be achieved by adding the diacritical dots to the ambiguous letter strings. The advantage of this procedure is that the experimental structure and the priming conditions remain constant for the ambiguous and unambiguous presentations.

Method

Subjects. Eighty undergraduate students, all native Hebrew speakers, participated for course credit or for payment. None of the subjects participated in the previous experiments. As in the previous experiments, 40 subjects were tested with prime–target SOAs of 100 ms and 250 ms (Experiment 2a) and the other 40 with 750-ms SOA (Experiment 2b).

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

Results

At all SOAs and with both dominant and subordinate primes, RTs to related targets were faster than RTs to unrelated targets (Table 2).

The statistical significance of the priming effects at 100-ms and 250-ms SOAs in Experiment 2a was assessed by ANOVA across subjects ($F1$) and across stimuli ($F2$). The main factors were semantic relatedness (related, unrelated), dominance of prime (dominant, subordinate), and SOA (100 ms, 250 ms).

The ANOVA showed that across SOAs RTs to targets in the related condition were faster than in the unrelated condition, $F1(1, 39) = 68.8$, $p < .001$, $MS_e = 1852$, $F2(1, 39) = 55.5$, $p < .001$, $MS_e = 2194$; RTs to targets related to dominant primes were faster than to targets related to subordinate primes, $F1(1, 39) = 18.6$, $p < .001$, $MS_e = 2013$, $F2(1, 39) = 6.3$, $p < .01$, $MS_e = 5491$; and RTs were faster at 250-ms SOA than at 100-ms SOA, $F1(1, 39) = 37.9$, $p < .001$, $MS_e = 4223$, $F2(1, 39) = 158$, $p < .001$, $MS_e = 1123$. However, in contrast to Experiment 1a, none of the interactions were statistically significant, $F1$ and $F2 < 1$ for relatedness by frequency; $F1 < 1.0$, $F2 = 1.3$ for relatedness by SOA; $F1$ and $F2 < 1$ for frequency by SOA; and $F1 = 1.2$, $F2 = 1.0$ for the three-way interaction.

The analysis of the priming effects at 750-ms SOA in Experiment 2b revealed a significant effect of semantic relatedness, $F1(1, 39) = 44.3$, $p < .001$, $MS_e = 1689$, $F2(1, 39) = 50.1$, $p < .001$, $MS_e = 1539$, and no main effect of frequency of the prime, $F1(1, 39) = 2.8$, $p > .09$, $MS_e = 1432$, $F2(1, 39) = 1.4$, $p > .19$, $MS_e = 2692$. The interaction between the two factors was not significant ($F1$ and $F2 < 1$). The effects of semantic facilitation obtained with the fillers at 250-ms SOA in Experiment 2b were similar to those obtained with targets at the same SOA in Experiment 2a (49 ms for targets related to the dominant alternatives and 47 ms for targets related to the subordinate alternatives).

Discussion

The absence of an interaction between semantic priming and the frequency of the prime revealed that, in disambiguated form, the dominant and the subordinate phonological alternatives of the heterophonic homographs were equally effective in facilitating lexical decisions to related targets. In addition, the results of Experiments 2a and 2b showed that the time course of processing high- and low-frequency unambiguous Hebrew words was similar. Hence, Experiments 2a and 2b suggest that the difference in processing dominant and subordinate alternative meanings of heterophonic homographs observed in Experiments 1a and 1b was indeed caused by the ambiguous nature of the primes that were both phonologically and semantically equivocal.

Although the primes in Experiments 2a and 2b were unambiguous, an effect of dominance was obtained. Targets related to the dominant phonological alternatives incurred faster RTs than targets related to the subordinate phonological alternatives. Because in Experiments 2a and 2b the primes were unequivocal, this effect should be considered as a pseudodominance effect. This outcome might have resulted from our design in which different targets followed identical ambiguous primes. Consequently, the comparison across

Table 2
Reaction Times and Percentage of Errors to Related and Unrelated Targets in the Different Experimental Conditions with Phonologically Unambiguous (Voweled) Primes (Experiments 2a and 2b)

Variable	Dominant primes			Subordinate primes			Nonwords	
SOA	100	250	750	100	250	750	Exps. 2a	2b
Unrelated	722	681	716	746	702	725	767	765
% of errors	8%	10%	7%	9%	12%	8%	9%	8%
Related	690	634	672	703	664	683		
% of errors	8%	8%	8%	8%	8%	6%		
Priming effect	32	47	44	43	38	42		

Note. SOA = stimulus onset asynchrony.

dominant and subordinate categories involved different target words. It is possible that there were intrinsic decision time differences between the target words such that targets that happened to be related to the dominant alternatives were accessed faster than targets related to the subordinate alternatives. However, because the conclusions concerning semantic facilitation depend on the interaction within prime categories (i.e., comparing RTs to the same target in related vs. unrelated conditions), the pseudodominance effect has no theoretical importance.

In Experiments 3a and 3b, we sought to examine the possible sources of the differences between the time course of activation found with English homophonic homographs (e.g., Simpson & Burgess, 1985) and between our present results with Hebrew heterophonic homographs. We endeavored to isolate the effects of semantic and phonological ambiguity and to control for possible language-specific factors. For this purpose, we used the design of Experiment 1 with a new set of stimuli. These were Hebrew homophonic homographs (i.e., words like *bank* that have two meanings but only one pronunciation).

Experiments 3a and 3b

Experiments 3a and 3b examined the time course of activation of dominant and subordinate meanings of Hebrew homophonic homographs. Each stimulus was a pattern of letters representing only one word (one phonological unit); that word, however, had two meanings: One was more frequent than the other. Consequently, like most English homographs, these stimuli were semantically ambiguous but phonologically unequivocal. Using exactly the same design as in the previous experiments, the present experiments allowed comparison of homophonic and heterophonic homographs within one language: Hebrew.

Method

Subjects. The subjects were 120 undergraduates who were native Hebrew speakers. They participated in the experiments for credits or payment. Sixty subjects participated in Experiment 3a, and 60 participated in Experiment 3b.

Stimuli. The primes were 36 ambiguous homophonic homographs that were selected from a pool of 120 homographs. Each selected word had a dominant meaning and a subordinate meaning. Dominance was determined empirically by the following procedure: 50 subjects rated the frequency of the meanings of all homographs on a 7-point scale ranging from *very infrequent* (1) to *very frequent* (7). Because naming could not distinguish between meanings of homophonic homographs, the rated frequencies were validated differently than in Experiment 1. Thirty-two subjects were read a list containing only homophonic homographs, the meanings of which were rated at least 1 point apart on the frequency scale. These words were read one at a time. The subjects responded verbally with their first association to each word. The meaning that the subjects had in mind was inferred from their response. Dominant meanings were produced by at least 66% of the subjects, and subordinate meanings were not produced by more than 33% of the subjects. Each prime was paired with two target words: One was semantically related to the dominant meaning and the other to the subordinate meaning. Thirty-six additional homophonic homographs from the same pool were used to form semantically unrelated pairs. In addition to the word–word pairs, 72 word–nonword pairs were again introduced as fillers. The words were homophonic homographs taken from the original pool. The 72 nonwords were taken from Experiment 1a.

Design and procedure. The design of Experiments 3a and 3b was identical to that of Experiments 1a and 1b. One group of 60 subjects was tested using SOAs of 100 ms and 250 ms between primes and targets. Fifteen subjects were assigned to each of four lists structured exactly as in Experiment 1a (except that in each list there were 9 targets rather than 10 in each condition). Across lists, each target appeared in both related and unrelated conditions and at both SOAs.

The second group of 60 subjects was tested using the same stimulus lists with a design identical to Experiment 1b (i.e., with the longer SOA of 750 ms). Although separate analyses were conducted in each group, we report all the results in one section.

Results and Discussion

The RTs in the related condition were faster than in the unrelated condition at all SOAs for dominant as well as for subordinate targets (Table 3).

Separate ANOVAs were conducted to assess the reliability of the priming effects across subjects ($F1$) and across stimuli ($F2$) at 100-ms and 250-ms SOAs (Experiment 3a). These ANOVAs showed that across SOAs RTs to targets in the related condition were faster than in the unrelated condition, $F1(1, 59) = 19.7$, $p < .001$, $MS_e = 1957$, $F2(1, 35) = 15.6$, $p < .001$, $MS_e = 1690$; RTs to targets related to dominant primes were faster than RTs to targets related to subordinate primes, $F1(1, 59) = 14.6$, $p < .001$, $MS_e = 1675$, $F2(1, 35) = 4.5$, $p < .04$, $MS_e = 5166$; and RTs were faster at 250-ms SOA than at 100-ms SOA, $F1(1, 59) = 145$, $p < .001$, $MS_e = 2035$, $F2(1, 35) = 250$, $p < .001$, $MS_e = 675$. As with

Table 3
Reaction Times and Percentage of Errors to Related and Unrelated Targets in the Different Experimental Conditions with Homophonic Homographs as Primes (Experiments 3a and 3b)

Variable	Dominant primes			Subordinate primes			Nonwords	
SOA	100	250	750	100	250	750	Exps. 3a	3b
Unrelated	591	545	567	606	561	580	680	653
% of errors	6%	8%	6%	7%	8%	7%	9%	8%
Related	580	522	553	588	540	570		
% of errors	6%	6%	6%	6%	8%	8%		
Priming effect	11	23	14	18	21	10		

Note. SOA = stimulus onset asynchrony.

unambiguous primes in Experiments 2a and 2b and in contrast to Experiments 1a and 1b, semantic relatedness did not reliably interact with any other factor.

The analysis of the priming effects at 750-ms SOA (Experiment 3b) showed that the semantic relatedness effect was reliable, $F1(1, 59) = 7.9$, $p < .007$, $MS_e = 1098$, $F2(1, 35) = 7.6$, $p < .009$, $MS_e = 694$; and RTs to targets were faster following dominant primes than following subordinate primes, $F1(1, 59) = 10.6$, $p < .002$, $MS_e = 1265$, $F2(1, 35) = 3.9$, $p < .05$, $MS_e = 3323$. As with the shorter SOAs, the interaction between the two factors was not reliable ($F1$ and $F2 < 1$).

The most important finding in Experiments 3a and 3b was that, in the absence of phonological ambiguity, both the dominant and the subordinate meanings of Hebrew polysemous words were already available at 100 ms from stimulus onset. Similar to heterophonic homographs, they remained active at least during the first 750 ms. These results suggest that the distinct pattern of activation observed for low-frequency phonological alternatives of heterophonic homographs (in Experiment 1a) was caused by phonological rather than semantic ambiguity.

Because our study did not include a condition of very short SOA (16 ms) between primes and targets, the onset of activating dominant and subordinate meanings of Hebrew homophonic homographs cannot be directly compared with the pattern of activation reported by Simpson and Burgess (1985) with English materials. However, the persistent activation of subordinate meanings at the longer SOA of 750 ms in the present experiment clearly differs from the pattern of activation observed in the English language (Simpson & Burgess, 1985). This divergence suggests that the process of disambiguating polysemous words might involve language-specific components. Possible interpretations of these results are elaborated in the general discussion.

Across-Experiments Comparisons

Several formal comparisons were conducted to assess priming effects involving heterophonic primes at all SOAs (Experiments 1a and 1b) and priming effects involving homophonic primes (Experiments 3a and 3b). For these analyses, the relevant data from the four experiments were combined in mixed ANOVA designs in which the type of homographs was introduced as an additional between-subjects factor. First, we compared the pattern of semantic facilitation of the subordinate meanings only across all SOAs for the two types of homographs. The three-way interaction of relatedness, SOA, and homograph type was significant, $F1(1, 98) = 6.9$, $p < .009$, $MS_e = 1914$, $F2(1, 74) = 3.6$, $p < .06$, $MS_e = 2926$, suggesting a reliable difference in the time course of activating the subordinate meanings of heterophonic and homophonic homographs.

Another finding regarding the two types of homographs was that the average effects of semantic priming of the dominant alternatives across all SOAs were twice as strong for heterophonic homographs (35-ms facilitation) than for homophonic homographs (16-ms facilitation). The statistical significance of this difference was assessed by a mixed ANOVA design in which RTs to the dominant meanings of heterophonic homographs at all three SOAs were compared with the respective RTs to the dominant meanings of homophonic homographs. The type of homography served again as a between-subjects factor. This analysis revealed a significant interaction of relatedness and homography type, $F1(1, 98) = 7.6$, $p < .007$, $MS_e = 1675$, $F2(1, 74) = 6$, $p < .02$, $MS_e = 1994$. Whether the shrinking of the priming effect for homophonic homographs relative to heterophonic homographs reflects primarily differences in processing the two types of homographs or merely a floor effect as a result of much faster responses to homophonic than heterophonic homographs was not clear. Therefore, we replicated Experiment 1a using an identical number of subjects and identical methods.

The purpose of replicating Experiment 1a was, in fact, twofold. First, because the comparison of heterophonic and homophonic homographs was based on a different pool of subjects, and because the most important difference relied on one data point, we aimed at reexamining the absence of priming effect (or the possible inhibition) for heterophonic homographs at 100-ms SOA. Second, we wanted to examine whether the larger priming effects found for heterophonic relative to homophonic homographs were due to an incidental overall slower performance of the subjects sampled in Experiment 1a.

The results of this replication are presented in Table 4. As in the original experiment, lexical decisions for targets related to the subordinate meanings of the primes were not facilitated at 100-ms SOA. In addition, the nonsignificant trend of inhibition observed in this condition in Experiment 1a proved to be unreliable. Overall, the RTs in the replication were faster than the original experiment. This suggests that the subjects used in Experiment 1a were generally slower than all other subjects in this study. Nevertheless, the pattern of the semantic facilitation with unvoweled ambiguous heterophonic homographs was replicated. The statistical significance of the priming effects was assessed by ANOVA across subjects ($F1$) and across stimuli ($F2$). The main effects of relatedness and dominance were significant, $F1(1, 39) = 4.6$, $p < .04$, $MS_e = 1436$, $F2(1, 39) = 5$, $p < .03$, $MS_e = 1834$, $F1(1, 39) = 12.6$, $p < .001$, $MS_e = 1552$, and $F2\ (1, 39) = 9.9$, $p < .003$, $MS_e = 2648$, respectively. The two-way interaction did not reach significance in the stimuli analysis, $F1(1, 39) = 3.6$, $p < .06$, $MS_e = 1741$, $F2(1, 39) = 2.4$, $p < .1$, $MS_e = 1756$. Planned comparisons revealed that RTs to targets related to the subordinate alternatives of the prime meanings at 250-ms SOA were significantly faster than RTs to targets in the unrelated condition, $t(1, 39) = 3.1$, $p < .004$. We refer to the additional implications of this replication in the General Discussion section.

General Discussion

In the present study, we examined the process of disambiguating Hebrew heterophonic and homophonic homographs presented in the absence of biasing context. To summarize the results of our investigation, it appears that regardless of relative dominance at least two different meanings of each homograph were retrieved. However, the time course of activating the different meanings and possibly the amount of

Table 4
Reaction Times and Percentage of Errors to Related and Unrelated Targets in the Replication of Experiment 1a

Variable	Dominant primes		Subordinate primes		Nonwords
SOA	100	250	100	250	
Unrelated	626	588	635	609	677
% of errors	9%	10%	13%	11%	8%
Related	601	557	635	588	
% of errors	8%	5%	10%	10%	
Priming effect	25	31	0	21	

Note. SOA = stimulus onset asynchrony.

activation were influenced by phonological factors. With homophonic homographs, subordinate as well as dominant meanings were active as early as 100 ms from stimulus onset. Alternatively, with heterophonic homographs, only the dominant meaning was available at 100-ms SOA, whereas the availability of the subordinate meaning was delayed. In contrast to the differences found at the onset of meaning activation, the decay of activation of subordinate meanings of homophonic and heterophonic homographs was similar; they all remained active as late as 750 ms from stimulus onset. Thus, the onset-activation pattern of Hebrew heterophonic homographs observed in the present study is in agreement with the ordered-access model suggested by Simpson and Burgess (1985). At present, this conclusion must be limited to heterophonic homographs because, unlike Simpson and Burgess (1985), we did not use SOAs shorter than 100 ms. Our findings suggest, then, that heterophonic homographs and homophonic homographs are disambiguated differently. This difference and the long-lasting activation of subordinate meanings of Hebrew but not English homographs may provide some insights regarding the lexical structure and the process of word identification.

The lexical representation of homophonic homographs is controversial. Some authors asserted that homophonic homographs entertain different lexical entries: one for each meaning (Forster & Bednall, 1976; Jastrembski, 1981; Kellas et al., 1988). Others claimed that a homograph has only one lexical entry related to multiple nodes in a semantic network (Cottrell & Small, 1983; Seidenberg et al., 1982). Alternatively, heterophonic homographs are by definition represented by several phonological units in the lexicon. Thus, phonologically ambiguous letter strings refer to different lexical entries: one for each phonological realization. The relatively delayed access to the subordinate meanings of heterophonic homographs compared with subordinate meanings of homophonic homographs could be more easily accounted for by assuming only one lexical entry for homophonic homographs and several entries for heterophonic homographs.[3] According to such a model, the alternative lexical entries are automatically activated by the unique orthographical pattern although at different onset times. The present data and the results of our previous studies (e.g., Bentin & Frost, 1897) indicate that, in the absence of biasing context, the order of activation is determined by the relative word frequency; higher frequency words are accessed before lower frequency words. As a consequence of the multiple-entries structure and the ordered-access process, heterophonic homographs are phonologically disambiguated before the semantic network is accessed. Each activated word (in the lexicon) is unequivocally related to a meaning. Because entries of dominant words are accessed before those of subordinate words, the origin of the dominance effect on the time course of activating the meanings of a heterophonic homograph could have been the well-documented frequency effect on lexical access.

This interpretation may also account for the overall greater priming effects found for heterophonic than for homophonic homographs. It suggests that when one lexical unit activates two or more semantic nodes each of these nodes is activated less than nodes that are unequivocally related to phonological units in the lexicon. If, in contrast to heterophonic homographs, homophonic homographs were represented by only one lexical entry that is related to several semantic nodes, the process of disambiguating the different meanings should have been less affected by the relative frequency (dominance) of using each meaning. Our hypothesis is that activating a lexical entry in an unbiased semantic context should automatically initiate the retrieval of all its related meanings. Because only one lexical entry is active, the relative dominance of the alternative meanings is irrelevant at the stage of lexical access. Relative frequency factors might affect the order of their retrieval at later processing stages, but our results suggest that, at least for the SOAs that have been examined in the present study, such an effect was not observed.

One caveat that must be considered while interpreting the difference in the amount of priming with homophonic versus heterophonic homographs is that the former homographs were overall faster than the latter. The reduction in overall RT latencies in the replication of Experiment 1a relative to the original experiment and the comparison of the nonword data across all experiments help to clarify this issue. Because the RTs to nonwords in the replication were identical to those in Experiment 3a, we can assume that these two groups of

[3] Seidenberg et al. (1982) presented a similar kind of single versus multiple argument for noun–noun versus noun–verb homophonic homographs, but they drew slightly different inferences. They argued that noun–verb homographs (e.g., train) have different entries in the lexicon and, hence, both meanings are always accessed for such words even when a strong priming word is presented in the context. In contrast, for noun–noun ambiguities (e.g., boxer), there is only one entry in the lexicon, and meanings are accessed in order of relative activation levels.

subjects were comparable in overall speed of performance. Nevertheless, RTs to targets related to heterophonic homographs were slower by about 40 ms than RTs to targets related to homophonic homographs. This difference was not entirely unexpected; it conforms with a previous finding in Hebrew showing faster RTs for phonological unequivocal words than for phonologically ambiguous words (Bentin et al., 1984). However, this pattern might have caused a floor effect in the RTs to homophonic homographs that attenuated the absolute magnitude of the priming effect. A floor effect as a sole explanation for this attenuation is not entirely supported by the data. Note that although the overall difference in RTs in the two homographic conditions was reduced by a factor of 3 (from 120 to 40 ms) when the replication rather than the original experiment was considered, the respective reduction of the priming effect for the dominant alternatives was relatively small (from 35 ms to 28 ms). Second, the smallest effect of semantic facilitation for homophonic homographs (11 ms) was obtained for dominant primes at 100-ms SOA that were slower by 50 ms than the primes at 250-ms SOA (which revealed a much larger facilitation). Thus, the observed difference in the magnitude of the priming effects between homophonic and heterophonic homographs is consistent with the hypothesis that they have different lexical structures.

In addition to the implications on the lexical structure, our data are also relevant to arguments regarding the use of phonology in word identification. One class of models suggests 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). Such a mechanism had been invoked to explain, for example, how homophones such as *sale* and *sail* are correctly understood or how patients with acquired dyslexia can understand written words without being able to read them aloud (Kay & Patterson, 1985).

An alternative class of models asserts that, most of the time, access to meaning is mediated by phonology (e.g., Van Orden, Johnston, & Hale, 1988; Perfetti, Bell, & Delaney, 1988). The latter class of models is supported by theoretical considerations such as the parsimony of having only one mechanism that mediates access to meaning for both speech and reading (e.g., Liberman & Mattingly, 1989) and by evidence that when the ability to derive phonology from print is poor (as in deep dyslexia) semantic errors in reading are abundant (see, for a review, Marshall & Newcombe, 1980). Moreover, when the direct connection from orthography to meaning is impaired (as in some patients with surface dyslexia), the meaning of printed words can be retrieved by prelexical application of grapheme-to-phoneme transformation rules (Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Marshall & Newcombe, 1973).

As we pointed out in previous articles, lexical decisions for unvoweled Hebrew words are based primarily on orthographic codes (Bentin et al., 1984; Bentin & Frost, 1987), and even for naming prelexical word phonology is not usually used by skilled readers (Frost et al., 1987). Nevertheless, the present results suggest that, in contrast to lexical decisions, the retrieval of meaning requires the activation of the phonological structure to which the printed word refers. If meaning was retrieved directly from the orthographic input, no difference should have been found between processing homophonic and heterophonic homographs. The delayed onset of activating the meanings of the subordinate phonological alternatives relative to the subordinate meanings of homophonic homographs, and possibly the overall more robust priming effects observed when the primes were phonologically ambiguous than when they were homophonic homographs, suggests that the former involved phonological disambiguation before the disambiguation of meaning.

One of the most intriguing results of the present study was that subordinate meanings of both heterophonic and homophonic homographs were still available and used 750 ms from stimulus onset. This result contrasts with the relatively fast decay of subordinate meanings of English homographs (Kellas et al., 1988; Simpson & Burgess, 1985). Because the decay pattern was similar for both types of Hebrew homographs, the divergence from the English language should be probably accounted for by language-related factors. One possible source of the different results obtained in Hebrew and in English may be related to the homographic characteristics of the Hebrew orthography. Hebrew, like other Semitic languages, is based on word families derived from triconsonant roots. The root is contained in all of its derivations; therefore, Hebrew contains many homophonic and heterophonic homographs. The wide spread of homography might have shaped the readers' reading strategies. Because ambiguity is so prevalent in reading, the process of semantic and phonological disambiguation is governed mainly by context. Because the disambiguating context often follows rather than precedes the ambiguous homographs, the most efficient strategy of processing them should consist of maintaining their phonological or semantic alternatives in working memory until the context selects the appropriate one. Note that by this interpretation the subordinate alternatives do not decay automatically but remain in memory until disambiguation by context has occurred. However, a complete account of the specific characteristics of the Hebrew orthography that might have influenced our results with homophonic and heterophonic homographs deserves further investigation.

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Received October 15, 1990
Revision received June 13, 1991
Accepted June 14, 1991 ■