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Phonological Computation and Missing Vowels: Mapping Lexical Involvement in Reading

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The role of assembled versus addressed phonology in reading was investigated by examining the size of the minimal phonological unit that is recovered in the reading process. Readers named words in unpointed Hebrew that had many or few missing vowels in their printed forms. Naming latencies were monotonically related to the number of missing vowels. Missing vowels had no effects on lexical decision latencies. These results support a strong phonological model of naming and suggest that even in deep orthographies, phonology is not retrieved from the mental lexicon as a holistic lexical unit but is initially computed by applying letter-to-phoneme computation rules. The partial phonological representation is shaped and completed through top–down activation.

Although the process of reading acquisition ultimately involves the extraction of meaning from print, there is a fairly general agreement that at some stage this process requires the recovery of phonologic information from the orthographic structure. Exactly how the printed form is converted into phonology is a topic for current debate. Two possible mechanisms have been suggested to account for the reading process. The first mechanism assembles phonology from print by applying a set of conversion rules (or through weighted connections in a neural network) that transform letters, letter clusters, or graphemes into phonemes or phonemic clusters. The assembly of phonology in this case is a computational process that involves a set of transformations that connect minimal orthographic and minimal phonologic units (letters and phonemes in the case of alphabetic orthographies like English; letters and syllables in the case of syllabic orthographies like Japanese; and graphemes and morphemes in the case of logographic orthographies like Chinese). The second mechanism involves a direct mapping of whole-word orthographic units into whole-word phonologic units. The complete phonologic structure of the printed word is then addressed by its orthographic form and retrieved as a whole from the mental lexicon. Thus, in contrast to assembled phonology, addressed phonology does not involve any computation at the subword unit level but is derived from straightforward connections between the printed and the spoken representations of a word.

The relative use of addressed versus assembled phonology in naming has been the focus of heated debates because it bears on an old but fundamental issue in the reading literature: the speed and efficiency of visual orthographic encoding in visual word recognition (see Katz & Frost, 1992, for a review). What is usually labeled the *visual encoding hypothesis* assumes that regardless of the type of orthography, it is usually more efficient to visually access the lexicon and retrieve from it the complete phonologic structure of the printed word rather than to assemble it using prelexical conversion rules. This is because the visual encoding hypothesis posits that at least for high-frequency words visual encoding is fastest and involves minimal cognitive resources. Moreover, the visual encoding hypothesis assumes that, once the lexicon is accessed, the process of retrieving the phonologic information from it does not involve significant cognitive effort (e.g., Baluch & Besner, 1991; Besner & Smith, 1992; Seidenberg, 1985; Tabossi & Laghi, 1992). In contrast to the visual encoding hypothesis, the *phonological hypothesis* suggests that the default operation of the cognitive system in word recognition is the use of prelexical rather than addressed phonology. The basic argument of the phonological hypothesis is that all writing systems are phonological in nature and their primary aim is to convey phonologic structures, that is, words, regardless of the graphemic structure adopted by each system (see De Francis, 1989; Mattingly, 1992, for a discussion). The computation of phonological structures from print is, therefore, a primary function of the system. The phonological hypothesis suggests that if readers can successfully assemble a prelexical phonological representation from print, then at least in the naming task, it will be used first. The easier it is to generate a prelexical representation, the more often it will be used. For example, if an orthography is shallow in that it has direct and consistent correspondences between letters and phonology, then readers of this orthography will be able to utilize these correspondences for naming and will use minimal resources in the process (see Katz & Frost, 1992, for a discussion).

The phonological hypothesis is supported by studies showing extensive phonologic recoding in shallow orthographies (e.g., Feldman & Turvey, 1983; Frost, Katz, & Bentin, 1987; Katz & Feldman, 1981, 1983; Turvey, Feldman, & Lukatela, 1984; see Carello, Turvey, & Lukatela, 1992, for a review) and by findings showing that readers in shallow orthographies strategically prefer prelexical phonological assembly over the retrieval of phonological information from the lexicon following visual access (Frost, 1994). Moreover, the phonological

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hypothesis also gains support from increasing evidence that prelexical phonology is used by readers of deeper orthographies, like English (e.g., Perfetti, Bell, & Delaney, 1988; Perfetti, Zhang, & Berent, 1992; Van Orden, 1987; Van Orden, Johnston, & Hale, 1988).

Two versions of the phonological hypothesis can be distinguished. The weak version views the generation of phonological information from print as a process that may involve, in principle, both addressed and assembled phonology. According to this hypothesis, the relative clarity of mapping between orthography and phonology determines how exactly phonology is derived from print. To cast it in activation terms, the weak hypothesis proposes that there are computations at the level of subword units (e.g., letter to phoneme), but there are also direct connections of whole-word orthographic units and whole-word phonologic units, allowing whole-word orthographic units to directly activate whole-word phonologic units regardless of the computation at the prelexical level. What determines the final outcome of such a "race" is the ease with which prelexical processing may be achieved. Thus, although the default of the system is to assemble phonology from print, the prelexical computation process could be bypassed, and phonology may entirely be addressed rather than assembled when the orthography represents phonology in a complex way and the relations between graphemes and phonemes are inconsistent and opaque (Frost, 1994; Frost & Katz, 1989). Note that such complexity may be found both within writing systems (i.e., irregularly spelled words) and as a factor distinguishing between writing systems, so-called deep and shallow orthographies (e.g., Frost et al., 1987).

On the other hand, with the strong phonological hypothesis, it is argued that a model for generating phonology from print does not need to assume connections between whole-word orthographic units and whole-word phonologic units and that phonology is always assembled. Thus, in any alphabetic orthography, the initial process of recovering phonologic information from print necessarily involves a computation of graphemes into phonemes. The computed phonological representation may well be affected by lexical knowledge if it is poor or incomplete. However, the strong phonological hypothesis denies that lexical effects in pronunciation result from visual access of the lexicon and retrieval of phonologic information of the whole word from it (i.e., from direct activation of whole-word phonologic units by whole-word orthographic units). Rather, the mandatory process of transforming letter clusters into phonemic clusters is said to be interactively affected by lexical knowledge through top–down activation. In a nutshell, the strong phonological hypothesis does not make use of the notion of addressed phonology at all because phonology is never entirely addressed, but always computed (e.g., Carello et al., 1992; Lukatela & Turvey, 1990; Lukatela, Turvey, Feldman, Carello, & Katz, 1989; Seidenberg & McClelland, 1989; Van Orden, Pennington, & Stone, 1990).

An example of a strong phonological model is the one offered by Turvey and his colleagues to represent reading in bi-alphabetical writing systems like Serbo-Croatian (e.g., Lukatela et al., 1989). The architecture of this model allows the reader a fast computation of phonology in both Roman and Cyrillic writing systems even though they share letters representing different phonemes (e.g., *B* representing the phoneme /b/ in Roman script but /v/ in Cyrillic script). The model specifies how the Roman and the Cyrillic graphemic units in the Serbo-Croatian reader's lexicon are connected to phonemic units, without allowing any direct links between whole printed-word units and whole spoken-word units. Orthographic ambiguity is resolved entirely by interactive processes between the word unit level and the phoneme unit level within the phonologic lexicon. Carello et al. (1992) argued that this framework can account for naming in all alphabetic orthographies (see also Carello, Turvey, & Lukatela, 1994).

Providing empirical evidence to distinguish between the weak and the strong versions of the phonological hypothesis is not a simple task because both models predict prelexical as well as lexical effects in naming. Note that the difference between addressed and lexically shaped phonology is a unit-size difference. That is, the distinction between the two versions lies only in the way in which word pronunciation is obtained—as a whole-word unit following visual lookup, or as a top–down shaping of prelexical phonological computation of subword units. The aim of the present study was to address this theoretical distinction with a methodology that can easily be implemented in Hebrew.

In Hebrew, letters represent mostly consonants, whereas most of the vowels can optionally be superimposed on the consonants as diacritical marks (points). The diacritical marks, however, are omitted from most reading material and can be found only in poetry, children's literature, and religious scriptures. Because different vowels may be inserted into the same string of consonants to form different words or nonwords, Hebrew unpointed print cannot specify a unique phonological unit. Therefore, a printed consonant string is always phonologically ambiguous and often represents more than one word, each with a different meaning. Some vowels, however, (mainly /o/, /u/, and /i/) may be represented in print not only by points but also by letters (see Baluch and Besner, 1991, for a similar characteristic of Persian).

These letters are not always used and are often considered optional by the writer.[1] When they are used, however, the complete phonologic structure of unpointed Hebrew words may uniquely be specified by the print. For example, the word מיתון (/mitun/meaning *recession*) contains two vowels, each of them represented by a letter (ו,י). Note that the phonologic structure of such a word can be assembled almost as easily as it

[1] The origin of vowel letters reflects an ancient distinction between different forms of vowels that differ mainly in their duration, long vowels being represented by letters. This distinction, however, has no true phonetic reality in modern Hebrew. There are specific grammatical rules that determine when a long or a short vowel should be used, and consequently, these rules specify whether the vowel should be printed with a letter or not. However, because the different printed forms of those vowels do not reflect a phonetic distinction in the spoken language, these rules are often not known to the adult writer and the inclusion of vowel letters is sometimes optional. Consequently, many words may appear with or without the vowel letters in different texts or within the same text (see Shimron, 1993, for a discussion).

can be assembled in pointed print.[2] Because some words in unpointed Hebrew include vowel letters and some do not, printed words differ in their level of phonological ambiguity. The following theoretical construct aims to characterize the nature of this ambiguity.

Degrees of Freedom

When readers of Hebrew are presented with an unpointed printed word that can meaningfully be pronounced in only one way (i.e., a lexically unambiguous word), they face the problem of assigning to the letter string the correct vowel configuration so as to interpret or pronounce the printed word correctly. This process of filling in the missing vowels characterizes the reading of almost any word in unpointed Hebrew, even if it is lexically unequivocal. The concept of *degrees of freedom* (DF) represents the amount of ambiguity involved in this process. Consider the following computational rule: Every letter that represents a consonant that may potentially take a vowel adds one degree of freedom to the reading process, whereas any consonant letter that is disambiguated by a following vowel letter does not.

If, for example, a consonant letter is followed by another consonant letter, the initial letter can be pronounced, in principle, with any vowel (or with a silent vowel) and contributes, according to the above definition, one DF to the reading task. If, on the other hand, a consonant letter is followed by a vowel letter, the cluster represented by the two letters is a phonologically unequivocal syllable, which does not add any DFs to the reading process. Final letters are in most cases not followed by any vowel and do not add DFs to the reading process. In a nutshell, the number of DFs a word contains refers to the number of vowels not represented by letters, and consequently, reflects the amount of missing phonological information that is necessary for correct pronunciation of this word.

It is important to note that although this rule allows for an easy computation of the number of DFs a printed word contains, this number only approximates the level of phonological ambiguity faced by the reader. First, our computation procedure does not take into account the number of possible vowels that each consonant can take or their relative probabilities. Second, it does not consider constraints on permissible vowel patterns in Hebrew or on possible combinations of vowels and consonants allowed by the Hebrew morphology (for a discussion of Hebrew morphology, see Bentin & Frost, 1994; Frost & Bentin, 1992b; Shimron, 1993). The number of DFs presents, therefore, only a coarse-grained calculation of the amount of ambiguity each word poses to the reader. Nevertheless, for the purpose of this study, this measure seemed sufficient.

Degrees of Freedom and Naming Time

In the present context, DFs are of theoretical importance only when phonology is computed and assembled at the level of sub-word units. If the phonological representation of a printed word is addressed following visual access and retrieved as a unit from the mental lexicon, at least for lexically unambiguous words, the overall number of DFs computed from the individual letters should not play a significant role in naming. What characterizes the process of addressing phonology from the lexicon is the direct connection between a holistic orthographic cluster and a holistic phonological structure. If the visual word pattern directly and unequivocally addresses one spoken word, the phonemic information conveyed by single letters should not affect naming. Thus, for unambiguous words, the number of missing vowels in unpointed Hebrew print should matter only if reading involves some computation at the letter-to-phoneme level.

The strong phonological hypothesis makes specific predictions concerning the effect of DFs on naming latencies. Not only does it predict that DFs should affect naming performance, but it also predicts that this effect should be monotonic. Thus, for a given number of letters in a printed word, the more DFs these letters represent, the slower naming should be. This is because the bottom-up process of computing phonology from print recovers only partial phonological information; the consonantal phonemic cluster. The vowel information necessary for correct pronunciation must be filled in through top–down activation from the word unit level to the phoneme unit level. However, the more phonemes have to be filled through this interactive process, the more impoverished is the computed prelexical representation, the slower is the buildup of activation within the system, and consequently the slower the naming latencies will be.

Monitoring the effect of DFs on naming performance would, therefore, constitute a critical test concerning the validity of the weak and the strong phonological hypothesis. Showing that DFs are good predictors of naming latencies would suggest that prelexical phonological computation occurs in the pronunciation task. On the other hand, showing that DFs do not affect naming performance would support the claim that phonology is mainly addressed in Hebrew, rather than assembled, as the weak phonological hypothesis would predict. Previous studies have shown that the reader of unpointed Hebrew relies extensively on orthographic recoding in word recognition (Bentin & Frost, 1987; Frost, 1992; Frost & Bentin, 1992a, 1992b; Frost et al., 1987). For example, Bentin and Frost (1987) have shown that lexical decisions for unpointed ambiguous Hebrew words were faster than lexical decisions to either of the disambiguated pointed alternatives. This outcome suggested that lexical decisions in unpointed Hebrew were based on the early recognition of the orthographic structure that was shared by the phonological and semantic alternatives. Thus, a demonstration of prelexical computation in an orthography as deep as unpointed Hebrew would provide significant evidence in support of the strong phonological hypothesis.

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[2] The phonologic structure of an unpointed printed word containing vowel letters can *almost* be assembled as easily as in pointed print because the vowel letters still contain some ambiguity. First, the same letter represents both /o/ and /u/. Second, in a few cases, the vowel letters can be read as consonants as well; the letter י can represent the vowel /i/ but also the consonant /j/, whereas the letter ו can represent the vowels /o/ and /u/ but also the consonant /v/. This additional source of ambiguity, however, is limited because these letters are usually doubled to convey the consonant reading.

	High-DF Words	Low-DF Words
Printed form:	קבלן - KBLN (3 DFs)	נזיר - NZIR (1 DF)
Pronunciation and meaning:	/kablan/ - ("contractor")	/nazir/ - ("monk")
Printed form:	פסנתר - PSNTR (4 DFs)	תינוק-TINOK (0 DF)
Pronunciation and meaning:	/psanter/ - ("piano")	/tinok/ - ("baby")

Figure 1. Examples of high- and low-DF Hebrew words. DF stands for degree of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels.

Experiment 1

In Experiment 1, I measured naming latencies for a corpus of 256 unpointed words differing in their DF values and their frequency. Both DF and frequency were collapsed into high and low levels. The aim of the experiment was to examine whether words with a large number of DFs will be named slower than words with a small number of DFs and whether this effect interacts with frequency.

Method

Participants. The participants were 42 undergraduate students at the Hebrew University, all native speakers of Hebrew, who participated in the experiment for course credit or for payment.

Stimuli and design. The stimuli consisted of 256 Hebrew words that were three to five letters long and contained two or three syllables with five to eight phonemes. All words were unambiguous and could be pronounced as only one meaningful word. Words were classified as being of high or low frequency and as having a large or a small number of DFs. This created four groups of words, 64 words in each group. I calculated DFs following the rules described above. For different word lengths, the corpus included a high-DF word and a low-DF word that could be either high frequency or low frequency. For example, a four-letter word could have three DFs if the four letters consisted of four consonants (the final letter almost never takes a vowel) or one DF if the four letters included a vowel that disambiguated a consonant-vowel-consonant (CVC) cluster. Both the high-DF and low-DF words could be either frequent or nonfrequent, and so forth. Examples of various Hebrew words with a large or small number of DFs are presented in Figure 1.

In the absence of a reliable frequency count in Hebrew, the subjective frequency of each word was estimated by 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. The average frequencies for high-DF words were 4.82 for frequent words and 2.46 for nonfrequent words. The average frequencies for low-DF words were 4.97 for frequent words and 2.58 for nonfrequent words.[3]

Procedure and apparatus. The stimuli were presented on a Macintosh II computer screen in a bold Hebrew font, size 24 (5 mm). Participants were individually tested in a dimly lighted room. They sat 70 cm from the screen so that the stimuli subtended a horizontal visual angle of 4° on the average. Naming latencies were monitored by a Mura-DX 118 microphone connected to a voice key. Each experiment started with 16 practice trials, which were followed by the 256 experimental trials presented in two blocks. The intertrial interval was 2.5 s.

Results

Naming latencies were averaged across participants for high- and low-frequency words with high and low DFs. Within each participant–condition combination, response times that were outside a range of two standard deviations from the respective mean were excluded, and the mean was recalculated. Outliers accounted for less than 5% of all responses. This procedure was repeated in all the experiments of this study. Because nonwords were not included in the experiment, the overall percentage of errors (mainly wrong pronunciations) was quite small (1%) and did not allow a reliable analysis. The results are presented in Table 1.

DFs affected naming latencies; high-DF words were slower to name than low-DF words. The statistical significance of the results was assessed by an analysis of variance (ANOVA) across subjects (F_1) and across stimuli (F_2), with the main variables of DFs and frequency. The main effect of DFs was significant, $F_1(1, 41) = 27.6, p < .001, MSE = 230$; $F_2(1, 252) = 7.2$, $p < .007$, $MSE = 1{,}363$, as was the main effect of frequency, $F_1(1, 41) = 139, p < .001, MSE = 191$; $F_2(1, 252) = 28.8$, $p < .001$, $MSE = 1{,}363$. The two-way interaction was significant in the subject analysis, $F_1(1, 41) = 9.1, p < .004$, $MSE = 164$, but not in the stimuli analysis ($F_2 = 1.9$).

One possible source of the obtained DF effect was the number of words having zero DFs. Because the phonological structure of these words could have been computed entirely prelexically, it is possible that all of the DF effect has emerged because these words were contrasted with words having one or more DFs. Note that the strong phonological hypothesis predicts a *monotonic* effect of DFs and not merely a difference between phonologically opaque and phonologically transparent words. To verify that the DF effect did not result just from fast response times to zero-DF words and similar response times to all of the other words having one DF or more, I examined words with only four letters. As can be seen in Figure 1, all four-letter words in the corpus had either one or three DFs, but never zero DFs. Thus, even in the low-DF condition, these words were not entirely phonologically transparent. The results of this post hoc procedure are presented in Table 2. As can be seen, the same, and even greater, advantage of low-DF words over high-DF words was obtained. Thus, it is

[3] Given the variance of the frequency ratings ($SD = 1.3$), these small differences in word frequency were not reliable, $F(1, 254) < 1.0$.

Table 1
Mean Naming Latencies (in Milliseconds) and Standard Deviations for Low- and High-Frequency Words With Low- and High-DFs

	Low-DF words		High-DF words	
Condition	*M*	*SD*	*M*	*SD*
Low-frequency words	533	37	552	41
High-frequency words	514	32	521	37
Mean RT	524		537	

Note. Words are unpointed. DF stands for degrees of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels. RT = response time.

clear that the overall DF effect did not emerge just from the inclusion of zero-DF words.

The effect of number of phonemes on response times was examined as well, because on the average, low-DF words have fewer phonemes than high-DF words when the number of letters is kept constant.[4] Thus, it was important to make sure that the number of phonemes per se did not affect naming latencies. The mean response times for words having four or five phonemes was 530 ms, whereas the mean response times for words having six to eight phonemes was 532 ms, suggesting that the number of phonemes in itself did not affect naming time.

Discussion

The results of Experiment 1 suggest that DFs affect naming time. When the number of letters was kept constant, the more DFs were contained in a printed word, the longer were the naming latencies. This outcome suggests that the phonological structure of the printed words was not retrieved as a unit from the mental lexicon following visual access but was assembled by means of letter-to-phoneme correspondences. When vowels were missing in the orthographic representation, only a partial phonological representation could be computed by the assembly process. This partial representation can only be completed through a top–down shaping process that involves lexical knowledge. As the number of missing vowels increased, this interactive process slowed down, resulting in slower naming latencies.

It is possible to gain some insight into the involvement of the mental lexicon in pronunciation by examining the frequency effect. The results suggest a reliable frequency effect across DFs, supporting the notion of lexical involvement in naming. However, if this hypothesized computation procedure is correct, a significant frequency effect should appear only when there is some ambiguity in the printed word, that is, only with DFs greater than zero. In contrast, words having zero DFs should not show any frequency effect, or should show it to a much lesser extent. This is because zero-DF words contain all of the phonemic information in print, and their phonological structure can prelexically be assembled without lexical contribution. An analysis of the frequency effect across DFs supports these predictions. Table 3 depicts the frequency effects for each DF level. There was a fairly strong frequency effect for all DFs greater than zero, but it became small and nonsignificant (6 ms only) for words having zero DFs.

Another point of interest concerning word frequency is the size of the DF effect for high- and for low-frequency words. The results are not unequivocal. The results in Tables 1 and 2 suggest that DFs had a greater effect for low-frequency words than for high-frequency words. This interaction, however, was significant only in the subject analysis. One possible problem with the item analysis is that frequency was made into a dichotomous variable. Therefore, a more robust test of the interaction was carried out by treating the frequency ratings as a continuous variable, which served as a response time predictor separately for high- and for low-DF words. A regression analysis revealed that the slopes of the two regression lines were not significantly different ($r = .3$ and $r = .41$ for high- and low-DF words, respectively, $Z = 0.76$). Thus, the results seem to suggest that DFs affect naming latencies for frequent and nonfrequent words in a similar manner. Whether the size of the effect changes with word frequency is unclear.

Table 2
Mean Naming Latencies (in Milliseconds) and Standard Deviations for Low- and High-Frequency Four-Letter Words Having One or Three DFs

	One-DF words		Three-DF words	
Condition	*M*	*SD*	*M*	*SD*
Low-frequency words	532	37	556	37
High-frequency words	510	29	523	41
Mean RT	521		540	

Note. Words are unpointed. DF stands for degrees of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels. RT = response time.

Experiment 2

The aim of Experiment 2 was to provide a baseline for the process of phonological assembly. If naming latencies are affected by the number of missing vowels in the printed word, then the effect of DFs should disappear in pointed print. Pointed Hebrew print disambiguates the consonantal structure by providing the missing vowels in the form of diacritical marks. When the vowel marks were printed, they did not allow any DFs in reading each of the consonants, and all words were treated as having zero DFs. In Experiment 2, participants named the same words as in Experiment 1, but all words were fully pointed. The purpose of the experiment was to demonstrate that in this condition DFs will not affect naming time.

Method

Participants. The participants were 42 undergraduate students at the Hebrew University, all native speakers of Hebrew, who participated in the experiment for course credit or for payment. None of the participants had been involved in Experiment 1.

[4] Low-DF words have fewer phonemes than high-DF words when the number of letters is kept constant because some of the letters of low-DF words are vowels, whereas most letters of high-DF words are consonants. Because each of the consonants can take a vowel, the overall number of phonemes contained in high-DF words is larger.

Table 3
Frequency Effects (in Milliseconds) in Naming With Words Having Zero to Four DFs

Condition	0 DF	1 DF	2 DF	3 DF	4 DF
High-frequency words	529	510	525	523	513
Low-frequency words	535	532	549	556	546
Frequency effect	6	22	24	33	33

Note. DF stands for degrees of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels.

Stimuli, design, and procedure. These were identical to those used in Experiment 1, with the only difference being that all stimuli were pointed.

Results

I averaged naming latencies across participants for high- and low-frequency words with high and low DFs. As in Experiment 1, outliers accounted for less than 5% of all responses. The results are presented in Table 4. DFs had no effect on naming latencies (503 ms for both high and low DFs). There was a frequency effect, but it was much smaller (14 ms) than the effect obtained in Experiment 1 with unpointed print (27 ms). The overall percentage of errors was less than 1%.

The statistical significance of the results was assessed by an ANOVA across subjects and across stimuli, with the variables of DFs and frequency. Only the effect of frequency was significant, $F_1(1, 41) = 49, p < .001, MSE = 163$; $F_2(1, 252) = 9.8, p < .001, MSE = 1{,}245$. The interaction was significant in the subject analysis, $F_1(1, 41) = 12.5, p < .001, MSE = 75$, but not in the item analysis ($F_2 = 1.1$).

Discussion

The results of Experiment 2 confirm that it was indeed the number of missing vowels that affected naming latencies in Experiment 1. When words were pointed they became phonologically transparent, and each word contained practically zero DFs. The addition of vowel marks eliminated the main effect of DF and reduced the frequency effect considerably. This suggests that in most cases participants assembled the pointed words' phonology prelexically by using simple letter-to-phoneme conversion rules. These results conform with those of previous studies in Hebrew that show prelexical strategies of naming in pointed Hebrew (Frost, 1994). Overall, naming latencies in Experiment 2 were faster than in Experiment 1. This outcome is in accordance with various studies that show faster naming performance in pointed than in unpointed Hebrew (e.g., Frost, 1994; see also Shimron, 1993). Although there was no main effect of DF in Experiment 2, the interaction of DF and frequency was significant in the subject analysis. This could suggest that DF had a more deleterious effect for low-frequency words than for high-frequency words. However, given the instability of the effect, this possibility should be treated with caution.

Experiment 3

The aim of Experiment 3 was to map the effect of DFs on lexical decision for pointed and unpointed words. Previous studies have shown that lexical decisions in Hebrew are based on the recognition of the orthographic structure and are made before a complete phonological analysis of the printed word (Bentin & Frost, 1987; Frost, 1994; Frost & Bentin, 1992b; Frost & Kampf, 1993). If lexical decisions do not involve a deep phonological analysis of the printed word, then DFs should not affect decision latencies for both pointed and unpointed words. Whether a letter cluster contains several missing vowels or none should not affect response time.

Method

Participants. Sixty undergraduate students at the Hebrew University, all native speakers of Hebrew, participated in the experiment for course credit or for payment. Thirty of them were assigned to the unpointed condition, and the other 30 were assigned to the pointed condition. None of the participants had been involved in the previous experiments.

Stimuli and design. The stimuli consisted of the same word corpus used in the naming experiments with the addition of 256 nonwords. Nonwords were created by randomly altering one or two letters of high- or low-frequency real words that were not used in the experiment. The nonwords were all pronounceable and did not violate the phonotactic rules of Hebrew. The 512 stimuli were divided into two lists, containing 128 words and 128 nonwords each. Half of the participants in each condition (pointed or unpointed) received one list, and the other half received the other list, randomly.

Procedure and apparatus. These were identical to those used in Experiments 1 and 2, with the only difference being that participants conveyed their decision by pressing a *yes* or a *no* response key. The dominant hand was always used for the *yes* response key.

Results

Response times in the different experimental conditions for unpointed and pointed print are presented in Table 5. Again, outliers accounted for less than 5% of all responses. DFs had no effect on lexical decisions in pointed and unpointed print. Overall, lexical decision latencies in pointed and unpointed print were very similar. Similar to the procedure of Experiments 1 and 2, I performed separate analyses on the pointed and unpointed data. The effect of DFs was not significant in both the pointed and the unpointed conditions (both $Fs < 1.0$). The effect of frequency was significant in both the pointed condition, $F_1(1, 29) = 217, p < .001, MSE = 582$; $F_2(1, 252) = 144, p < .001, MSE = 973$, and the unpointed condition, $F_1(1, 29) = 294, p < .001, MSE = 405$; $F_2(1, 252) = 146, p < .001$,

Table 4
Mean Naming Latencies (in Milliseconds) and Standard Deviations for Low- and High-Frequency Words With Low and High DFs

	Low-DF words		High-DF words	
Condition	*M*	*SD*	*M*	*SD*
Low-frequency words	508	36	512	34
High-frequency words	498	36	494	34
Mean RT	503		503	

Note. Words are pointed. DF stands for degrees of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels. RT = response time.

Table 5
Mean Lexical Decision Latencies (in Milliseconds) and Standard Deviations for Low- and High-Frequency Words With Low and High DFs

	Pointed				Unpointed			
	Low-DF words		High-DF words		Low-DF words		High-DF words	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Low-frequency words	598	70	604	79	594	70	600	77
High-frequency words	537	58	535	60	536	65	533	67
Mean RT	568		570		565		567	

Note. DF stands for degrees of freedom, which is a concept that represents the amount of ambiguity involved in the process of filling in missing vowels. RT = response time.

$MSE = 816$. The two-way interaction was not significant in both the pointed condition ($F_1 = 1.3$ and $F_2 = 1.4$) and the unpointed condition, $F_1 = 3.2, p < .08, MSE = 162; F_2 < 1.0$.

Discussion

The results of the lexical decision task confirm that DFs affected performance only when a phonological representation had to be constructed from the print. Several studies have repeatedly shown that lexical decisions are given before a deep phonologic analysis of the printed word (e.g., Bentin & Frost, 1987; Frost, 1994; Frost & Bentin, 1992a; see Frost & Bentin, 1992a, for a review). These studies would predict, therefore, that DFs will not affect lexical decision time. The similar results for pointed and unpointed stimuli are in accordance with a previous study by Koriat (1984), who showed almost identical lexical decision latencies for pointed and unpointed print. In a subsequent study, however, Koriat (1985) found that the presentation of vowel marks had some beneficial effect on lexical decisions for low-frequency words. This evidence, however, was inconclusive. The present data seem to better fit his initial results (Koriat, 1984). The results of Experiment 3 suggest that DFs were not confounded with factors affecting lexical access or lexical search. Rather, they were relevant only to the recovery of phonology from print.

General Discussion

The aim of this study was to examine the role of assembled versus addressed phonology in naming by using a novel methodology. The two routes for generating a phonological representation from print are often differentiated in terms of lexical involvement (or lack of it) in naming. Therefore, previous studies have monitored the extent of lexical contribution to correct pronunciation by measuring semantic priming and frequency effects (e.g., Baluch & Besner, 1991; Frost, 1994; Frost et al., 1987). However, the theoretical distinction between assembled and addressed phonology may be based on a different criterion that relates to the size of the minimal phonological unit that is recovered in the reading process. When the phonological structure of the printed word is lexically addressed, it is retrieved as a whole unit from the lexicon following visual access. In contrast, when it is assembled, it is recovered segment by segment through a process of prelexical conversion of letter or letter clusters into phonemes or phonemic clusters. In this study, I aimed to examine the size of the recovered phonological units in naming by manipulating ambiguity at the letter level.

Unpointed Hebrew provides a unique opportunity to assess the effect of letter ambiguity on pronunciation. This is because each unpointed consonant in Hebrew represents a phonological puzzle to the reader concerning the exact vowel that should follow this consonant. The assessment of ambiguity in the study was somewhat simplified. Each letter slot was treated categorically by merely assessing whether it added to the overall ambiguity score. Obviously, the permissible word patterns in Hebrew constrain the possible vowels that each consonant can take, thereby affecting the level of complexity of each discrete puzzle. Thus, it is possible that the actual contribution of a missing vowel slot to the overall ambiguity score was higher or lower than the contribution of its neighboring vowel slots. Nevertheless, the DF score assigned to each word reflected, to a close approximation, the amount of missing phonological information that was necessary for successful assembly.

DFs allow, therefore, a critical test of two contrasting hypotheses concerning word naming. Does the printed word undergo a process of phonologic computation at the subword unit level, or is the word's phonology retrieved as a holistic unit following a lexical lookup? The words used in this study were phonologically and semantically unambiguous at the word level. That is, their orthographic structure pointed to only one lexical entry. This entry contained but one phonological representation and one semantic meaning. Thus, if only the word level is examined, these words did not present to the reader any form of lexical ambiguity. Their phonology could be, in principle, unequivocally retrieved following lexical lookup. The concept of DFs relates only to the ambiguity at the level of letters-to-phonemes conversion. It is exactly this feature that provides the ability to test the weak and the strong phonological hypotheses. If the initial phase of generating a phonological representation from print entails computation at the subword unit levels, then DFs should affect this process. The more ambiguity has to be resolved at the subword level, the longer should be the process of generating a complete phonological representation. If, on the other hand, the orthographic structure is used to access the lexicon visually and retrieve the printed word's phonology following a lexical lookup, ambiguity at the letter level should not affect this process.

The results of Experiment 1 provide significant support for the strong phonological hypothesis. DFs affected naming latencies when both frequency and word length were kept constant. Words with a larger number of DFs took longer to pronounce than words with a smaller number of DFs. This effect was not restricted to a comparison between completely transparent words (having zero DFs) and opaque words but persisted within opaque words that differed in the number of DFs they contained. The monotonical effect of missing vowels cannot easily be accommodated by a model that considers naming as the result of mapping entire orthographic structures into holistic phonologic structures. The data of Experiment 1 thus suggest that the phonologic representation of the printed words was computed piecemeal rather than retrieved holistically.

The results of Experiments 2 and 3 reinforce this conclusion by providing two independent baselines. Because different words were used in the high-DF and the low-DF conditions, it was necessary to ensure that the DF effect did not emerge from trivial differences between word samples. In Experiment 2, the words of Experiment 1 were presented in their pointed form. Thus, the only difference between Experiment 1 and 2 was that all words became zero-DF words. The results of Experiment 2 show that when the words were pointed, the main effect of DFs disappeared and response times to the two word samples were virtually identical. This outcome confirmed that it was indeed the differential ambiguity of the unpointed stimuli that has caused the DF effect in Experiment 1 and not other possible factors related to the stimuli used in the different experimental conditions.

Similar conclusions arise from the results with lexical decision in Experiment 3. DFs, in general, allow a powerful test of the hypothesis that phonological recoding occurs in lexical decision. Previous studies in Hebrew have established that lexical decisions in Hebrew do not involve a deep phonological analysis of the printed word but are based on the shallow recognition of letter strings that may represent several different words with different meanings (Bentin & Frost, 1987; Frost, 1992; Frost, 1994; Frost & Bentin, 1992a, 1992b; Koriat, 1984; see also Shimron, 1993, for a review). The results of Experiment 3 confirmed, therefore, that detailed phonologic recoding is not necessary for lexical decisions in Hebrew and that DFs play a role only when a full phonological representation is needed, as is the case in the naming task. The similar, almost identical response times for low- and high-DF words again suggest that these words have a similar lexical status. Thus, the results of Experiment 3 further support the contention that the different naming latencies obtained in Experiment 1 were only due to the amount of ambiguity at the letter level as measured by the DF analysis.

An important outcome of Experiment 1 concerns the contribution of lexical factors to the assembly of phonology as revealed by the frequency effect. There was a strong effect of frequency on naming latencies for DFs greater than zero. This result suggests that lexical involvement occurred whenever a complete phonological representation could not be assembled by using only letter-to-phoneme conversion rules. When the printed words were completely transparent, word frequency did not have a strong effect on naming latencies, suggesting that phonology was assembled with minimal lexical contribution. However, when some phonological ambiguity was present in the letter string, lexical involvement was immediately apparent.

However, a more important conclusion concerning the frequency effect is its co-occurrence with the effect of DFs. Previous studies that examined the relative use of addressed versus assembled phonology have distinguished between the two routes by monitoring the existence of lexical involvement in naming. Lexical factors like semantic priming or word frequency were taken as evidence for getting the word's phonology through a process of lexical lookup and not through prelexical computation (e.g., Baluch & Besner, 1991, Frost, 1994). Thus, according to the classical dual-route view, phonology can be either lexical or assembled, and the two routes for obtaining it are independent (e.g., Paap, Noel, & Johansen, 1992). The results of this study suggest that the process of generating a phonological representation may simultaneously involve both prelexical and lexical processing. Thus, if the orthography is not extremely shallow, both processes come into play. By this view, the two routes are not functionally independent but interact to allow a correct pronunciation.

A model that can accommodate these results is an interactive model that views the process of generating phonology from print as a process of converting letters or letter clusters into phonemes or syllables. This process, however, in most cases cannot compute a complete and accurate phonological representation. Thus, the output of the computation process is shaped by top–down lexical knowledge that inserts missing phonemic information like the missing vowels of unpointed Hebrew or fills in the correct pronunciation of irregular words in English. Such a process is exemplified in Figure 2. The figure depicts the phases of naming a high-DF Hebrew word like לפתן (LFTN, pronounced /liftan/, meaning *desert*). LFTN has three missing vowel slots. The initial phase of getting its phonology is a computation process that transforms the consonantal information into phonemes and creates an incomplete phonological representation. The vowels are inserted during or following this process, whether serially or in parallel, by top–down lexical shaping. This provides a complete phonological representation that allows the correct pronunciation. Hence, the complete phonological representation of LFTN is not retrieved from the lexicon as a holistic unit following visual access caused by the four letters. Rather, it involves both an assembly process and a lexical contribution. This model is very similar in nature to the model proposed by Lukatela et al. (1989) to account for reading in Serbo-Croatian and is in accordance with the strong phonological hypothesis. The importance of the results in unpointed Hebrew is that the demonstration of an assembly process in such a deep orthography provides significant support for the strong phonological view.

Although the model in Figure 2 describes the computation of phonology in Hebrew, its general framework can serve to account for pronunciation in English or any alphabetic orthography. Note that the ambiguity faced by the Hebrew reader is different from that faced by English speakers. In Hebrew, the mapping of letters into phonemes is fairly consistent, and phonological ambiguity results from missing phonemic information in print. In English, on the other hand, the letters represent all of the word's phonemes, but in an inconsistent

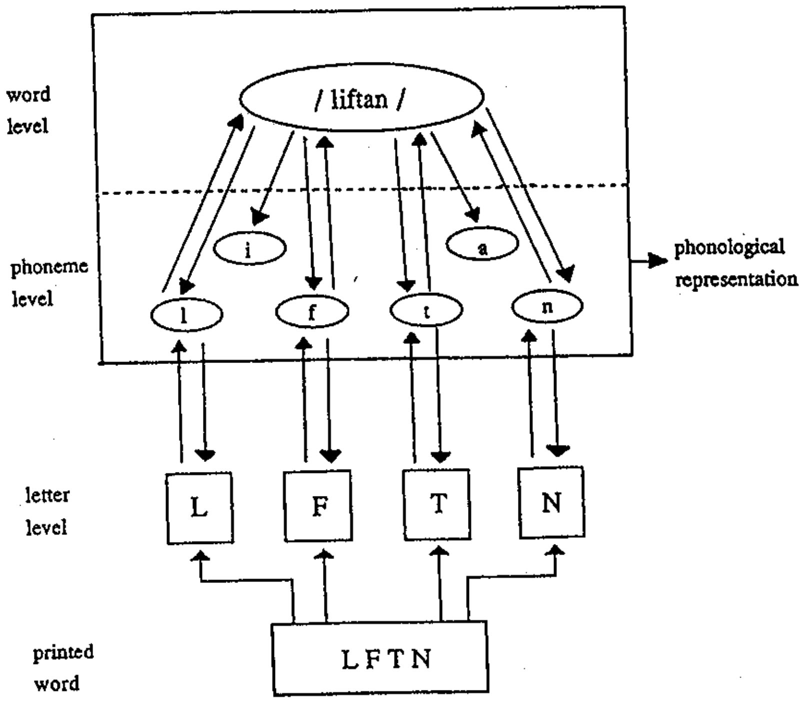

Figure 2. A model for computing phonology of unpointed Hebrew words.

manner. However, recent results in English show a striking similarity to the results obtained in this study. Using a backward masking paradigm, Berent and Perfetti (1993) have shown that the phonological representation of English CVC words is not lexically addressed but computed in two processing cycles with different time courses. The consonants are computed first in a process that is fast and automatic, whereas the vowels, which are the main source of phonological ambiguity, are computed in a subsequent cycle that is less automatic and involves attention-demanding processing. Additional empirical support for a computational process in English has recently been provided by Treiman, Mullenix, and Bijeljac-Babic (1993). Similar to the DF manipulation of this study, Treiman and her colleagues mapped the spelling-to-sound relations of all CVC words in the English dictionary and assigned a pronunciation consistency score to the CV or VC subword units. A regression analysis of naming latencies revealed that the consistency of VC subword units had a significant contribution to the prediction of performance in word pronunciation. These results suggest that even for three-letter frequent English words, phonology is assembled rather than addressed as a unit from the lexicon.

Thus, a strong phonological model that accounts for naming in English will regard the initial phase of phonological computation as a conversion of letters into phonemes (unambiguous letters first) by using prelexical conversion rules. This initial phase can only provide the reader with a poor phonological representation, given the depth of the English orthography. This representation is shaped through lexical knowledge to allow a correct pronunciation. Such a model could, in principle, have a similar structure to the model offered by Seidenberg and McClelland (1989), with the difference being that lexical information concerning the specific word pronunciation does play an indispensable role in pronunciation.

The mandatory interaction between assembled and lexical phonology has been argued in length by Turvey and his colleagues (e.g., Carello et al., 1992), to account for naming in shallower orthographies like Serbo-Croatian. Several studies in Serbo-Croatian have shown that lexical involvement is apparent even in an extremely shallow orthography. This study offers a point of reference in the opposite side of the orthographic depth continuum, suggesting that prelexical computation occurs even in the deepest orthographies. By this view, phonology is always assembled and always lexically shaped, but not holistically addressed.

Admittedly, the weak phonological hypothesis or even the visual hypothesis could, in principle, accommodate the effect of DF on naming, but not without a considerable cost. One could argue, for example, that phonology is retrieved holistically, but the mapping of whole-word orthographic units into whole-word phonological units becomes slower with increasing numbers of missing vowels. In other words, increased numbers of missing vowels in the orthographic representation (high-DF words) could lead to increased difficulty in making contact with the whole-word phonological units in the lexicon. However, this account would deprive addressed phonology and visual access of their major appeal in reading theory, which is to bypass the many inconsistencies in mapping graphemes into phonemes in deep orthographies. Moreover, by this view, phonology is perhaps addressed but in a manner that mimics a piecemeal assembly process. Addressed phonology would consequently retain nothing but its label, losing its theoretical significance.

Another possible interpretation of the DF effect could suggest that for some words phonology was entirely addressed, whereas for some words it was assembled. Consequently, the overall DF effect obtained in this study emerged merely from the subset of words for which prelexical computation was not bypassed by the fast lexical routine. This possibility is not well supported by our results. First, if the DF effect was restricted to a subset of words (presumably very low frequency, for which addressed phonology has no advantage over assembled phonology), it would not be reliable in the item analysis. Moreover, a clear interaction of DF and frequency would have emerged, in this case, especially in the item analysis. The results of Experiment 1 show an opposite pattern. The main effect of DF was reliable by items, whereas the interaction was not. Thus, this study provides strong support for a model of naming that assumes a mandatory prelexical computation of phonology and a parallel lexical shaping of these computed representations.

The methodology used in this study offers a new approach to examine the assembly process, mainly to examine the size of the computed units. In principle, such methodology could be implemented in English if an ambiguity score could be computed for each letter slot, and if consequently a DF score could be assigned to each word. This might entail complex computations (see Treiman et al., 1993). However, the results of this study suggest that even coarse-grained measurements of levels of ambiguity can predict effects on naming latencies.

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