Phonological Computation and Missing Vowels: Mapping Lexical Involvement in Reading*

Ram Frost†

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. How exactly 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; 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

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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, i.e. 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; and 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 hypothesis gains support also 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 be entirely 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 & Katz, 1989; Frost, 1994). 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, the strong phonological hypothesis argues 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, since 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 words units and whole spoken words 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) argue that this framework can account for naming in all alphabetic orthographies (see also Carello, Turvey, & Lukatela, in press).

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 be easily implemented in Hebrew.

In Hebrew, letters represent mostly consonants while 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. Since 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/, /i/) may be represented in print not only by points but also by letters (See Baluch & 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 be uniquely specified by the print. For example, the word “תפנ.Monad” (mitun/-meaning recession) contains two vowels, each of them represented by a letter (1,7). Note that the phonologic structure of such a word can be assembled almost as easily as it 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 be meaningfully pronounced in only one way (i.e., 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 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 which 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 the above rule allows 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...
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 Hebrew ambiguous 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.

**EXPERIMENT 1**

Experiment 1 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**

*Subjects.* The subjects 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 high- or low-frequency words; and as having a large or a small number of DFs. This created four groups of words, 64 words in each group. DFs were calculated 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 disambiguates a CVC cluster. Both the high-DF and low-DF words could be either frequent or nonfrequent, etc. 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, 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.

Procedure and apparatus: The stimuli were presented on a Macintosh II computer screen in a bold Hebrew font, size 24 (5mm). Subjects were tested individually in a dimly lighted room. They sat 70 cm from the screen so that the stimuli subtended a horizontal visual angle of 4 degrees 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 sec.

Results

Naming latencies were averaged across subjects for high- and low-frequency words with high- and low-DFs. Within each subject/condition combination, RTs that were outside a range of 2 SDs 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 the present 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 factors of DFs and frequency. The main effect of DFs was significant ($F_1(1,41) = 27.6, MS_e = 230, p < 0.001, F_2(1,252) = 7.2, MS_e = 1363, p < 0.007$), as was the main effect of frequency ($F_1(1,41) = 139, MS_e = 191, p < 0.001, F_2(1,252) = 28.8, MS_e = 1363, p < 0.001$). The two-way interaction was significant in the subjects analysis ($F(1,41) = 9.1, MS_e = 164, p < 0.004$), but not in the stimuli analysis ($F = 1.9$).

One possible source of the obtained DF effect is 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. In order to verify that the DF effect did not result just from fast RTs to zero DFs words and similar RTs to all the other words having one DF or more, only words with four letters were examined. 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 clear that the overall DF effect did not emerge just from the inclusion of zero DFs words.

<table>
<thead>
<tr>
<th>High-DF Words</th>
<th>Low-DF Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Form</td>
<td>הדיל - KBLN (3DFs)</td>
</tr>
<tr>
<td>Pronunciation and meaning:</td>
<td>/kablan/ - (&quot;contractor&quot;)</td>
</tr>
<tr>
<td>Printed form:</td>
<td>דסנתר - PSNTR (4 DFs)</td>
</tr>
<tr>
<td>Pronunciation and meaning:</td>
<td>/psanter/ - (&quot;piano&quot;)</td>
</tr>
</tbody>
</table>

Figure 1. Examples of high- and low-DF Hebrew words.
Table 1. Naming latencies (and SDs) for low- and high-frequency words with low- and high-DFs. Words are unpointed.

<table>
<thead>
<tr>
<th></th>
<th>Low-DF Words</th>
<th>High-DF Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency words</td>
<td>533 (37)</td>
<td>552 (41)</td>
</tr>
<tr>
<td>High-frequency words</td>
<td>514 (32)</td>
<td>521 (37)</td>
</tr>
<tr>
<td>Mean RTs</td>
<td>524</td>
<td>537</td>
</tr>
</tbody>
</table>

Table 2. Naming latencies for low- and high-frequency four-letter words having one or three DFs. Words are unpointed.

<table>
<thead>
<tr>
<th></th>
<th>1-DF Words</th>
<th>3-DF Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency words</td>
<td>532 (37)</td>
<td>556 (37)</td>
</tr>
<tr>
<td>High-frequency words</td>
<td>510 (29)</td>
<td>523 (41)</td>
</tr>
<tr>
<td>Mean RTs</td>
<td>521</td>
<td>540</td>
</tr>
</tbody>
</table>

The effect of number of phonemes on RTs 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. Thus, it was important to make sure that the number of phonemes perse did not affect naming latencies. The mean RTs for words having four or five phonemes was 530 ms, whereas the mean RTs 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 via letter-to-phoneme correspondences. When vowels are missing in the orthographic representation, only a partial phonological representation can be computed by the assembly process. This partial representation can be completed only 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 our 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 DFs words contain all the phonemic information in print, and their phonological structure can be assembled prelexically 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 milliseconds only) for words having zero DFs.

Table 3. Frequency effects in naming with words having zero to four DFs.

<table>
<thead>
<tr>
<th></th>
<th>0-DF</th>
<th>1-DF</th>
<th>2-DF</th>
<th>3-DF</th>
<th>4-DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-frequency</td>
<td>529</td>
<td>510</td>
<td>525</td>
<td>523</td>
<td>513</td>
</tr>
<tr>
<td>Low-frequency</td>
<td>535</td>
<td>532</td>
<td>549</td>
<td>556</td>
<td>546</td>
</tr>
</tbody>
</table>

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. 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 an RT 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 ($r = 0.3$ and $r = 0.41$ 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.

**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 are printed, they do not allow any degrees of freedom in reading each of the consonants, and all word are treated as having zero DFs. In Experiment 2, subjects 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.

**Methods**

*Subjects.* The subjects 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 subjects participated in Experiment 1.

The stimuli, design and procedure were identical to those employed in Experiment 1 with the only difference that all stimuli were pointed.

**Results**

Naming latencies were averaged across subjects 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 analysis of variance (ANOVA) across subjects ($F_1$) and across stimuli ($F_2$), with the factors of DFs and frequency. Only the effect of frequency was significant, $F_1(1,41) = 49, MS_e = 163, p < 0.001; F_2(1,252) = 9.8, MS_e = 1245, p < 0.001). The interaction was significant in the subject analysis ($F_1(1,41) = 12.5, MS_e = 75, p < 0.001$, but not in the item analysis ($F_2 = 1.1$).

**Discussion**

The results of Experiment 2 confirm that it is indeed the number of missing vowels that affected naming latencies in Experiment 1. When words are pointed they become phonologically transparent and each word contains 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 subjects assembled the pointed words’ phonology prelexically, using simple letter-to-phoneme conversion rules. These results conform with previous studies in Hebrew showing prelexical strategies of naming in pointed Hebrew (Frost, 1994). Overall, naming latencies in Experiment 2 were faster than in Experiment 1. This outcome is accordance with various studies showing faster naming performance in pointed than in unpointed Hebrew (e.g., Frost, 1994; see also Shimron, 1993). While 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 prior to a complete phonological analysis of the printed word (Bentin & Frost, 1987; Frost & Bentin, 1992b; Frost & Kampf, 1993; Frost, 1994). 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.

**Table 4.** Naming latencies (and SDs) for low- and high-frequency words with low- and high-DFs. Words are pointed.

<table>
<thead>
<tr>
<th></th>
<th>Low-DF Words</th>
<th>High-DF Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency</td>
<td>508</td>
<td>512</td>
</tr>
<tr>
<td>words</td>
<td>(36)</td>
<td>(34)</td>
</tr>
<tr>
<td>High-frequency</td>
<td>498</td>
<td>494</td>
</tr>
<tr>
<td>words</td>
<td>(36)</td>
<td>(34)</td>
</tr>
<tr>
<td>Mean RTs</td>
<td>503</td>
<td>503</td>
</tr>
</tbody>
</table>
Method

Subjects. 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 subjects participated in the previous experiments.

Stimuli and design: The stimuli consisted of the same word corpus employed in the naming experiments with the addition of 256 nonwords. Nonwords were created by altering randomly one or two letters of high- or low-frequency real words that were not employed 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 subjects in each condition (pointed or unpointed) received one list and half the other list, randomly. The procedure and apparatus were identical to those employed in Experiment 1 and 2 with the only difference that subjects conveyed their decision by pressing a "yes" or a "no" response key. The dominant hand was always used for the "yes" response.

Results

RTs 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 as well as unpointed print. Overall, lexical decision latencies in pointed and unpointed print were very similar.

Table 5. Lexical decision latencies (and SDs) for low- and high-frequency words with low- and high-DFs.

<table>
<thead>
<tr>
<th>POINTED</th>
<th>UNPOINTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-DF</td>
<td>High-DF</td>
</tr>
<tr>
<td>Words</td>
<td>Words</td>
</tr>
<tr>
<td>Low frequency words</td>
<td>598 (70)</td>
</tr>
<tr>
<td>High-frequency words</td>
<td>537 (58)</td>
</tr>
<tr>
<td>Mean RTs</td>
<td>568</td>
</tr>
</tbody>
</table>

Similar to the procedure of Experiments 1 and 2, separate analyses were performed on the pointed and unpointed data. The effect of DFs was not significant in both the pointed and the unpointed conditions (F₁, F₂ < 1.0). The effect of frequency was significant in both the pointed condition (F₁(1,29) = 217, MSₑ = 582, p < 0.001; F₂(1,252) = 144, MSₑ = 973, p < 0.001), and the unpointed condition (F₁(1,29) = 294, MSₑ = 405, p < 0.001, F₂(1,252) = 146, MSₑ = 816, p < 0.001). The two-way interaction was not significant in both the pointed condition (F₁ = 1.3, F₂ = 1.4), and the unpointed condition (F₁(1,29) = 294, MSₑ = 405, p < 0.001, F₂(1,252) = 146, MSₑ = 816, p < 0.001).

Discussion

The results of the lexical decision task confirm that DFs affect performance only when a phonological representation has to be constructed from the print. Several studies have repeatedly shown that lexical decisions are given prior to a deep phonological analysis of the printed word (e.g., Bentin & Frost, 1987; Frost & Bentin, 1992a; Frost, 1994; and 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 fit better his initial results (Koriat, 1984). The Results of Experiment 3 suggest that DFs are not confounded with factors affecting lexical access or lexical search. Rather, they are relevant only to the recovery of phonology from print.

GENERAL DISCUSSION

The aim of the present study was to examine the role of assembled versus addressed phonology in naming 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 which 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. The present study 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 or not. 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 employed in the present 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 which 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 which differed in the number of DFs they contained. The monotonical effect of missing vowels cannot be easily 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.

Experiments 2 and 3 reinforce this conclusion by providing two independent baselines. Because different words were employed 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 DFs words. The results of Experiment 2 show that when the words were pointed, the main effect of DFs disappeared and RTs 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 employed 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; and see 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 DFs play a role only when a full phonological representation is needed, as is the case in the naming task. The similar, almost identical RTs for low- and high-DF words again suggest that these words have a similar lexical status. Thus, Experiment 3 further supports 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 only using 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, 1992, 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 present study suggests that the process of generating a phonological representation may involve simultaneously 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 words like הַלֵּיתָן (LFTN, pronounced /lift/ăn/, 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 manner. However, recent results in English show a striking similarity to the results obtained in the present 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 which is less automatic and involves attention-demanding processing. Additional empirical support for a computational process in English has been recently provided by Treiman, Mullenix, and Bijeljac-Babic (1993). Similar to the DF manipulation of the present 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 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. The present 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 the present 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, the present 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 employed in the present 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 (But see Treiman, 1993). However the results of the present study suggest that even coarse grained measurements of levels of ambiguity can predict effects on naming latencies.

REFERENCES


**FOOTNOTES**

2. Also Department of Psychology, The Hebrew University.
3. The phonologic structure of an unpointed word containing vowel letters can be assembled almost 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 "a" can represent the vowel /a/ but also the consonant /l/. In a few cases the vowel letters can be read as consonants as well; the letter "a" 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.
4. The phonologic structure of an unpointed printed word containing vowel letters can be assembled almost 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 "a" can represent the vowel /a/ but also the consonant /l/. In a few cases the vowel letters can be read as consonants as well; the letter "a" 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.