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Phonological Constraints on Reading: Evidence from the Obligatory Contour Principle

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Hebrew frequently manifests gemination in its roots, but strictly constrains its position: Root-final gemination is extremely frequent (e.g., bbd), whereas root-initial gemination is rare (e.g., bdd). This asymmetry is explained by a universal constraint on phonological representations, the Obligatory Contour Principle (McCarthy, 1986). Three experiments examined whether this phonological constraint affects performance in a lexical decision task. The rejection of nonwords generated from novel roots with root-initial gemination (e.g., Ki-KuS) was significantly faster than roots with final gemination controls (e.g., Si-KuK). The emergence of this asymmetry regardless of the position of geminates in the word implicates a constraint on root, rather than simply word structure. Our results further indicate that speakers are sensitive to the structure of geminate bigrams, i.e., their identity. Nonwords formed from roots with final gemination (e.g., Si-KuK) were significantly more difficult to reject than foils generated from frequency-matched no gemination controls (e.g., Ni-KuS). Speakers are thus sensitive to the identity of geminates and constrain their location in the root. These findings suggest that the representations assembled in reading a deep orthography are structured linguistic entities, constrained by phonological competence. © 2001 Academic Press

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The role of phonology in the recognition of printed words has been the subject of a continuous research effort. Most research has focused on whether phonological representations constrain reading: Are words' meanings activated directly from print or is reading also constrained by phonological representations, assembled by mapping graphemes to phonemes? Less is known, however, about the structure of phonological representations assembled in reading. Do these representations consist of a linear chain of phonemes or are they multilinear linguistic entities?

There is some evidence suggesting the existence of linguistic organization in assembled phonological representations. For instance, readers are sensitive to the division of the syllable into onset and rime (e.g., Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; Treiman & Zukowski, 1988) and to the word's stress pattern (Colombo, 1992; Colombo & Tabossi, 1992; Miceli & Caramazza, 1993). Readers' sensitivity to the structure of printed words may indicate the presence of linguistic constraints on reading. If reading a word entails the recovery of its linguistic structure, then reading may not be fully explicable by simple associations between letters and sounds. The ability to assemble adequate phonological representations may require intact linguistic competence. Thus, both skilled and impaired reading must be ultimately explained by the interaction of decoding skills and linguistic knowledge (e.g., Berent & Perfetti, 1995; Farah, Stowe, & Levinson, 1996; Gough & Tummer, 1986; Harm & Seidenberg, 1999; I. Liberman & A. Liberman, 1990; I. Liberman & Shankweiler, 1991; Patterson, Suzuki, &

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Nakayama-Wydell, 1996; Pennington, 1990; Perfetti, 1985, 1992; Shaywitz, 1996; Studdert-Kennedy & Mody, 1995).

The present investigation addresses the role of phonological constraints on reading using the Obligatory Contour Principle (OCP) as a case study. The OCP is a universal ban on adjacent identical elements in phonological representations (McCarthy, 1979, 1986). OCP effects concerning segments, features, and tones have been documented in a variety of languages (e.g., Goldsmith, 1991, Kenstowicz, 1994; Leben, 1973; McCarthy, 1979, 1986; Yip, 1988, 1995). If reading is subject to linguistic constraints, then readers may exhibit sensitivity to the OCP in the performance of a silent reading task, lexical decision.

The Nature of OCP Effects: Lexical and Derivational Manifestations

Linguistic theory has documented two manifestations of identity avoidance in phonological representations (McCarthy, 1986; Yip, 1988). One manifestation of the OCP is found in the derivation of phonological representations. Morphological and phonological processes occasionally result in adjacent identical elements. The OCP intervenes to prevent such outputs by either blocking the operation of rules whose output is illicit or triggering phonological rules designed to repair such outputs. A familiar manifestation of the derivational OCP in English concerns the adjacency of coronals (Russel, 1997; Yip, 1988). Many English suffixes begin with a coronal consonant. The concatenation of such suffixes and a root ending with a coronal results in adjacent segments with an identical place of articulation, violating the OCP. The OCP repairs such illicit outputs in several ways, including vowel epenthesis (e.g., *buss* + s→*busses*; *want* + *d*→*wanted*, *add* + *ion*→*addition*) and segment deletion (e.g., *complete* + *tion*→*completion*; *ad* + *sist*→*assist*). The hypothesis that repair rules are triggered by identity avoidance offers a simple explanation for these otherwise arbitrary phonological changes applying during derivation (Yip, 1988). A second manifestation of the OCP is as a morphemic structure constraint: The OCP bans adjacent identical elements in the phonological representation of a morpheme in the lexicon. It is the lexical OCP that is the center of our investigation. One of the best known cases of the lexical OCP concerns the structure of Semitic roots. We thus assess its presence in Hebrew.

OCP Effects in Hebrew Root Structure

To understand the nature of OCP effects in Hebrew, we must first briefly consider word formation in this language. Hebrew words are formed by inserting a root into a word pattern. The root is a sequence of typically three consonants. For instance, the root *bdd* indicates the core meaning of isolation. To form a word, the root must be inserted into a word pattern. The word pattern includes place holders for the root consonants. It also supplies the vowels and affixes. For instance, the root *bdd* may be inserted in the word pattern CiCeC, resulting in the verb Bi-DeD[1], *he isolated*. The insertion of the same root in the word patterns CiCuC, CCiCut, and hitCoCeC yields the nouns *Bi-DuD* (isolation), *BDi-Dut* (loneliness), and the reflexive verb *hit-Bo-DeD* (I isolated myself), respectively. Thus, a single root may yield a family of morphologically related words.

Our main interest is in the structure of the root. Consider again the root *bdd*. This root contains the geminates *dd*. Hebrew frequently manifests gemination in its roots, but strictly constrains its position (a property found also in other Semitic languages, Greenberg, 1950). Gemination is highly frequent at the root's final position (e.g., bdd, gll, kff, sbb, smm). In contrast, gemination is extremely rare root initially (e.g., *ssm). This asymmetry requires an explanation. McCarthy (1979, 1986) provided an elegant account for this fact. His account assumes by assuming that phonological representations are multidimensional entities: Different phonological constituents, such as segments, tones, and syllables, are each arranged on separate tiers. These different tiers are anchored to a skeleton, an abstract set of timing units holding distinct

[1] To clarify the morphological structure of the word, we indicate the root consonants using uppercase letters. Syllable boundary is indicated by a hyphen. However, the orthography makes no distinction between the representation of root and nonroot graphemes nor does it mark syllable structure.

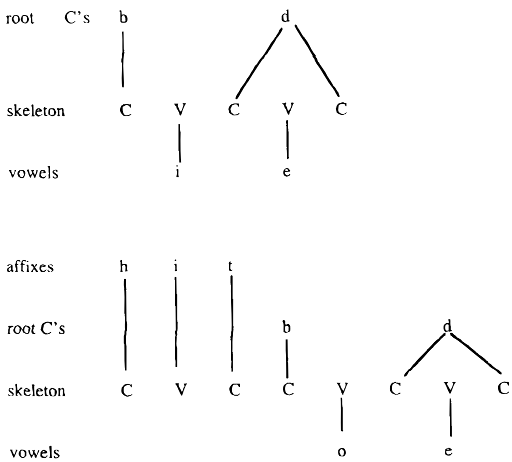

FIG. 1. The autosegmental representation of the verbs bided and hitboded. The root consonants are represented on a separate tier, segregated from vowels and affixes.

slots for consonants and vowels. Because the Semitic root morpheme is a phonological constituent, it is represented on its own tier, segregated from intermediate vowels and affixes. This representation nicely captures the integrity of root consonants, regardless of their surface adjacency. For instance, consider again the words *BiDeD* and *hit-Bo-DeD* (see Fig. 1). The representations of these verbs encode the root *bdd* on a separate tier. Thus, despite the presence of intermediate vowels and affixes, root radicals are psychologically adjacent elements in a coherent phonological constituent.

As a phonological constituent, however, the root consonants are subject to phonological constraints. According to the OCP, lexical phonological representations ban adjacent identical phonological elements. Because the geminates *dd* in *bdd* are adjacent identical elements, they may not be stored in the lexicon. On this view, the lexical representation of *bdd* is *bd*. Geminates may only emerge productively, during word formation. Specifically, during word formation, the root *bd* is aligned with the three root slots in the word pattern (see Fig. 2). The alignment proceeds from left to right, leaving the rightmost root slot empty. This slot is next filled by the spreading of the second root radical rightward. Consequently, a single radical, d, is now linked to two slots. The surface manifestation of this double linking is geminates, dd. In what follows, we refer to this process of geminate formation as reduplication (Everett & Berent, 1998; Gafos, 1998). Importantly, because geminates are the result of a productive process of reduplication, and because this process proceeds rightward, geminates can emerge only at the root's final position, not its initial position. Thus, geminates are well formed at the root's end but ill formed at its beginning.

Our previous research investigated this prediction. One set of experiments examined the acceptability of novel words formed from novel roots including geminates (Berent & Shimron, 1998; Berent, Everett, & Shimron, 2001). Our results demonstrated that speakers constrain the location of geminates in the root. Words whose roots manifest root final geminates (e.g., SiKeK) were rated as more acceptable than words whose roots exhibit geminates at their beginning (e.g., Ki-KeS) Similar findings were obtained in a production task (Berent, et al., 2001). When Hebrew speakers produce words from novel biconsonantal roots (e.g., SK), they frequently reduplicate the final radical (e.g., Si-Kek), but

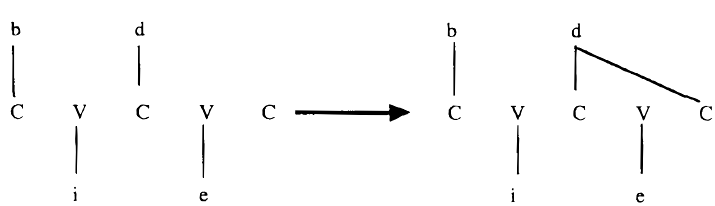

FIG. 2. The formation of root-final gemination from its underlying biconsonantal form. The left figure illustrates the alignment of the biconsonantal root **bd** with the word pattern CiCeC. Because the alignment proceeds from left to right, the rightmost consonant slot remains unfilled. The right figure describes the spreading of the phoneme into the free slot. The doubly linked phoneme surfaces as root final geminate, **bdd**.

they practically never reduplicate the initial radical (e.g., Si-SeK). These findings agree with the view that the OCP forms part of Hebrew speakers' linguistic competence. The question addressed here is whether this linguistic principle constrains reading. If the representation assembled in reading is constrained by phonological competence, then readers should exhibit sensitivity to the OCP in a silent on-line reading task.

TABLE 1

Structure of the Roots Employed for Targets and Foils in Experiments 1–3

	Word roots	Nonword roots
Initial gemination	—	KKS
Final gemination	KDD	SKK
No gemination	KDM	NKS

Does the OCP Constrain Reading?

To test the hypothesis that the OCP constrains reading, we examined readers' sensitivity to identical consonants within the root using a lexical decision task. Participants were simply asked to determine whether a printed stimulus corresponds to an existing Hebrew word. This task does not explicitly require that participants attend to the phonology of the word. The depth of the Hebrew orthography renders the computation of phonology particularly challenging. Hebrew is a consonantal writing system that omits most vowel information from the orthography. Consequently, the pronunciation of a Hebrew word cannot be predicted from its orthographic representation. For instance, the word KeLeB, dog, is written as a string of three consonants, KLB. In the absence of knowledge regarding its specific pronunciation, this string of letters may be pronounced as KiLiB, KuLuB, KaLaB, KaLiB, KoLoB, etc. If a word's phonology is assembled from left to right, then the absence of vowel information may block its computation altogether. Conversely, if the representations assembled in reading are multilinear entities, constrained by phonological competence, then consonant assembly may proceed despite the absence of vowels in the orthography (Berent & Perfetti, 1995). Assembled phonological representations may further exhibit the effects of phonological constraints, such as the OCP.

Our present experiments gauge for phonological constraints on reading by examining whether performance in the lexical decision task is sensitive to phonological well formedness, as defined by the OCP. To this end, we presented participants with words and nonwords that included gemination. Table 1 summarizes the root structure of the target words and foils used in our experiments. The target words exhibited either root-final gemination or no gemination. Because Hebrew has only two productive roots with initial gemination, it was impossible to fully explore the effect of root structure for existing roots. Our principal interest was thus in the structure of the nonword foils. The nonword foils were generated using the same word patterns as the target words, but their roots consisted of three-consonant combinations that did not correspond to existing Hebrew roots. These roots exhibited root-initial gemination, root-final gemination, or no gemination. Our experiments address three questions: (a) Are readers sensitive to the location of geminates? (b) Do readers represent the structure of geminates? (c) What is the domain of the constraint on gemination?

a. Readers' sensitivity to the location of geminates. The OCP constrains the location of geminates in the root: Root initial geminates are ill formed, whereas root final geminates are well formed. To examine readers' sensitivity to the location of geminates, we compared two root types. These roots both contain geminates, but differ in their location. One root type included geminates in its beginning (e.g., KKS) whereas a second root type included geminates at its end (e.g., SKK). If participants constrain the location of geminates in the root, then they should discriminate between these two root types. Root-initial gemination is ill formed hence it should be easier to reject than root-final gemination.

b. The representation of geminates' structure. A logical prerequisite for constraining the location of identical root consonants is the ability to represent identity. Identity is a formal relationship. Using the variable *X* to refer to any consonant, the structure of identical consonants is defined as *XX*. Although a distinction between root-initial and root-final geminates is consistent with the proposal that readers represent identity, these findings may also be explained by the statistical properties of these items. Because root-initial gemination is ill formed, such geminates correspond to rare bigrams. The easier rejection of roots with initial geminates may thus be due to the rarity of the geminate bigram, not its structure. However, not all forms of gemination are rare in Hebrew. Recall that root-final gemination is extremely frequent. Roots with final geminates thus permit investigating the representation of identity. To this end, we matched the foil roots with final gemination (e.g., SKK) and no gemination (e.g., NKS) for their root bigram frequency. If readers do not represent the identity of geminates, then root-final gemination should be indistinguishable from frequency-matched roots with no gemination. Conversely, if identity is represented, then readers should be able to discriminate root-final gemination from no gemination controls by virtue of their structure. Specifically, if the OCP is active, then root-final gemination must be formed by a grammatical process of reduplication. The formation of root-final gemination by the grammar may provide evidence for "wordhood." Thus, novel words formed from roots with final gemination may be more difficult to reject than words whose roots include no gemination.

c. The domain of the constraint on gemination. The lexical OCP constrains the location of geminates within the root morpheme. To represent the OCP, readers must be able to represent its domain, a morphological constituent. There is a growing body of evidence demonstrating that Hebrew readers decompose the root in reading. For instance, the priming of a Hebrew word by its root facilitates its identification relative to phonological, semantic, and orthographic controls (Bentin & Feldman, 1990; Deutsch, Frost, & Forster, 1998; Feldman & Bentin, 1994; Frost, Forster, & Deutsch, 1997). Likewise, the productivity of Hebrew roots facilitates their decomposition from their word patterns relative to morphologically unproductive controls (Feldman, Frost, & Pnini, 1995). These findings suggest that Hebrew speakers may routinely decompose the root from the word pattern. If so, then they may also exhibit sensitivity to the phonological characteristics of the root morpheme.

The predicted sensitivity to the presence of geminates and their location is consistent with a constraint on root structure. In the absence of proper experimental controls, however, such findings may also be explained by appealing to word structure. For instance, if our stimuli consisted entirely of the CiCuC word pattern, then a rejection of forms such as SiSuM and PiPuM might reflect the rejection of the word initial unit $C_x iC_x$ rather than the rejection of $C_xC_xC_y$ roots. To establish that the domain of this constraint concerns root, rather than merely word structure, our experiments vary the morphological structure of nonwords. In Experiment 1, targets and foils are all unaffixed (e.g., Ka-KoS). Consequently, root-initial gemination is invariably word initial whereas root-final gemination is always word final. In contrast, in Experiments 2 and 3 the root is affixed. Roots in Experiment 2 are followed by a suffix (e.g., Ka-KaS-tem), whereas in Experiment 3 they are sandwiched between a prefix and a suffix (e.g., hit-Ka-KaS-ti). A sensitivity to **word** structure should not result in a consistent rejection of root-initial gemination across our three experiments. Conversely, if readers constrain the structure of the **root**, then each experiment should result in a faster rejection of root-initial gemination than of final-gemination controls.

EXPERIMENT 1

Experiment 1 examines the rejection of nonword foils whose morphological structure is transparent. These nonwords were formed by inserting the root in nominal word patterns that include no affixes (see Table 2). The words and nonwords were matched for the structure of the word pattern, but differed in their roots. The target words all consisted of existing Hebrew roots. In contrast, nonwords were formed from novel roots exhibiting root-initial gemination, root-final gemination, or no gemination. If speakers are sensitive to the constraint on root structure, then root-initial gemination should be easier to reject than final gemination controls. If the constraint in question specifically appeals to

TABLE 2

Structure of the Targets and Foils in Experiment 1

	Words	Nonwords
Root-initial gemination	—	Gi-GuS
Root-final gemination	Di-MuM	Si-GuG
No gemination	Di-ʃuN	Ri-GuS

the structure of geminates, then the rejection of root-final gemination may also differ from that of frequency-matched no gemination controls.

Method

Participants. Twenty University of Haifa students who were native Hebrew speakers served as participants. They were paid to take part in the experiment.

Materials. The materials consisted of 90 words and 90 nonwords (see Appendix A). The words and nonwords were formed by inserting a root in one of several nominal word patterns: CiCuC, CaCiC, CoCeC, and CaCuC. Thus, the word patterns of the targets and foils corresponded to existing Hebrew nouns. The targets and foils shared the same word patterns. They differed, however, in their roots. Targets were formed from existing triliteral roots such that the combination of the root and word pattern corresponded to an existing Hebrew noun. In contrast, the roots of the nonword foils consisted of three consonants that do not correspond to an existing Hebrew root.

Nonword foil roots. The 90 nonword foils were generated from 30 trios of novel roots. Each trio included three root types: root-initial gemination (e.g., ggs) root-final gemination (e.g., sgg), and no gemination (e.g., rgs). The three members of the root were inserted in precisely the same word pattern such that the resulting words differed only in root structure. A comparison of performance with words generated form root initial vs. root-final gemination thus permits the assessment of participants' sensitivity to the location of geminates in the root.

To examine whether participants are also sensitive to the structure of the geminate bigram in these roots, we matched the roots with final gemination and no gemination for their summed bigram frequency. Hebrew does not have any counts of root frequency. To estimate the type bigram frequency of Hebrew roots, Berent et al. (2001) generated a database including all the productive triconsonantal roots from the Even-Shoshan (1993) Hebrew dictionary. We used this database to assess the frequency of our materials. We calculated the type summed bigram frequency of the root foils by adding the bigram frequency of the first two radicals, the second and the third radical, and the first and third radical. The consideration of both adjacent and disjoint bigrams was motivated by the presence of co-occurrence restrictions on adjacent as well as non-adjacent root consonants in Arabic (Frisch, Broe, & Pierrehumbert, 1995). The mean positional summed bigram frequency of our roots with final gemination and no gemination was 12.27 (SD = 3.72) and 11.83 (SD = 3.93), respectively.

Word target roots. The 90 words were generated from 45 pairs of existing Hebrew roots. The members of the pair shared the same word pattern, but differed in root structure. One member had root-final geminates (e.g., *dimum*, bleeding, from the root *dmm*) whereas the other member had a root with no geminates (e.g., *diʃun*, fertilization, from the root *dʃn*). There are only two productive Hebrew roots with root-initial gemination; hence, existing Hebrew words do not allow readers' sensitivity to the location of geminates in the root to be tested. The target words also do not allow for an accurate inspection of readers' sensitivity to the presence of geminates, since, in the absence of a word frequency count for Hebrew, it was impossible to match the frequency of words with final vs. no geminates. Our main interest thus concerns the effect of root structure on the identification of our nonword foils.

Practice trials. To familiarize the participants with the experimental task, they were first presented with practice trials, consisting of 20 words and 20 nonwords, presented twice in random order. These words and nonwords shared the same word patterns as the experimental stimuli. None of the practice stimuli appeared in the experimental trials. All stimuli in the practice and experimental trials were presented in 'uppercase' (*dfus*) Hebrew script without any diacritic marks.

Procedure. At the beginning of each trial, a fixation point consisting of four dots appeared at the center of the screen. Participants initiated the trial by pressing the space bar. They were then presented with a string of letters at the center of the computer screen, displayed until participants responded or a maximum of 2 s elapsed. Participants were asked to determine whether the string of letters corresponded to an existing Hebrew word. Word responses were given by pressing the 1 key. Nonword responses were given by pressing the 2 key. These two keys were marked by "yes" and "no" labels and positioned such that participants used their preferred hand to provide both responses. Slow responses (responses slower than 1500 ms) and inaccurate responses received negative feedback from the computer in the form of a tone and a computer message. The experiment initiated with the practice stimuli followed by the experimental trials. Participants were tested individually. The order of the trials in the experiment was random.

Results and Discussion

To eliminate the effect of outliers, we excluded correct responses falling 2.5 standard deviations beyond the mean response latencies for words and nonwords. This procedure resulted in the elimination of 2.97 and 2.57% of the correct word and nonword responses, respectively. In this and all subsequent experiments we adopt .05 as the level of statistical significance.

Root structure did not significantly affect performance for our target words. Response latency for words with root-final gemination (M = 666 ms) did not differ from responses to words with no gemination roots (M = 665 ms, $F_1(1,19) < 1$, MSE = 331.98; $F_2(1,44) < 1$, MSE = 2369.74). There were also no differences in response ac-curacy to root final (M = 94.3%) vs. no gemination targets (M = 93.9%, $F_1(1,19) < 1$, MSE = .002; $F_2(1,44) < 1$, MSE = .005). However, response latency (M = 665 ms) to words was significantly faster ($F_1(1,19) = 9.05$, MSE = 1125.88; $F_2(1,73) = 4.70$, MSE = 3597.83) than responses to nonwords (M = 697 ms). Response accuracy to words (M = 94%) and nonwords (M = 94%) did not differ ($F_1(1,19) < 1$, MSE = .002; $F_2(1,73) < 1$, MSE = .006).

TABLE 3

Response Latency and Accuracy in the Rejection of Nonword Foils in Experiment 1 as a Function of Root Structure

	Response latency (ms)	Response accuracy (% correct)
Root-initial gemination	696	95.4
Root-final gemination	738	88.9
No gemination	697	94.2

Our principal interest is in performance with nonwords. Specifically, we wish to examine the effect of the foils' root structure on their rejection. Table 3 shows the response latency and accuracy for nonword foils as a function of their root structure. One-way ANOVAs on the responses to nonword foils yielded significant main effects of root type in latency ($F_1(2,38) = 12.73$, MSE = 914.87; $F_2(2,58) = 5.74$, MSE = 3584.43) and accuracy ($F_1(2,38) = 13.18$, MSE = .002; $F_2(2,58) = 4.96$, MSE = .007). We next investigated the constraint on root geminates by means of planned comparison. If speakers constrain root structure in accord with the OCP, then they should be sensitive to the location of geminates in the root. Roots with initial gemination should be perceived as ill formed and hence less word-like than final-gemination controls. In accord with this prediction, root-initial gemination was rejected significantly faster than root-final gemination ($t_1(38) = 4.43$ $t_2(58) = 3.08$). Likewise, participants were significantly more accurate in the rejection of root-initial gemination than of root-final gemination controls ($t_1(38) = 4.81$; $t_2(58) = 2.96$).

We next examined whether participants represent the structure of geminates, namely, their identity. Our design equated root-final gemination and no gemination for their statistical structure. If readers represent the identity of geminates, then they may discriminate between these two roots despite their matched frequency. Our results support this prediction. Participants were significantly slower at rejecting root-final gemination than no gemination controls ($t_1(38)$ =

4.31; $t_2(58) = 2.77$). Likewise, root-final gemination resulted in lower accuracy than no gemination controls ($t_1(38) = 3.95$; $t_2(58) = 2.41$).

EXPERIMENT 2

The findings of Experiment 1 demonstrate that Hebrew readers are sensitive to the presence of geminates and strongly constrain their position. However, our present results cannot determine unequivocally the domain of the constraint on the position of geminates. According to McCarthy (1986), this constraint concerns **root** structure. Although our results are compatible with this view, they cannot rule out an explanation that merely appeals to the surface position of geminates in the **word**. The roots included in our first experiment were not affixed. Thus, the location of geminates in the root generally agrees with their word position. For instance, the root-initial gemination in Ka-KoS is also word initial. Our next two experiments dissociate root and word structure by presenting participants with roots that were affixed. In addition, these experiments demonstrate the generality of our findings for a new set of roots.

Experiment 2 examines lexical decision for target words and foils that were formed by inserting the root in a verbal word pattern that contains a suffix. For instance, the foil Ki-KaS-tem was formed by inserting a root with initial gemination, KKS, in the word pattern CiCaCtem indicating a verbal form in the past tense in the second person masculine plural. This nonword was compared to two controls generated from roots with either final gemination or no gemination, SKK and NKS. These roots were inserted in the same word pattern, yielding the words Si-KaK-tem and Ni-KaS-tem (see Table 4).

TABLE 4

Structure of the Targets and Foils in Experiment 2

	Words	Nonwords
Root initial gemination	—	Ki-KaS-tem
Root final gemination	Si-NaN-tem	Si-KaK-tem
No gemination	Si-MaN-tem	Ni-KaS-tem

If the constraint we observed in Experiment 1 merely concerns the location of geminates in the **word**, then the distinction between geminates at root initial and root-final position should be eliminated when the word-location of geminates is altered. Thus, words manifesting root, but not word, final gemination (e.g., Si-KaK-tem) should be no more difficult to reject relative to root-initial gemination (Ki-KaS-tem). In contrast, if the constraint on gemination concerns **root** structure, then the rejection of root-initial gemination should remain easier than final-gemination controls. As in Experiment 1, our design also probes for participants' sensitivity to the structure of geminates by equating roots with final gemination and no gemination controls for bigram frequency. If speakers are sensitive to the presence of geminates in the root, then root-final gemination (e.g., Si-KaK-tem) should be more difficult to reject than no gemination controls (e.g., Ni-KaS-tem) despite their opaque morphological structure.

Method

Participants. Participants were 20 University of Haifa students who were native speakers of Hebrew and did not participate in Experiment 1. They were paid to take part in the experiment.

Materials. The materials consisted of a new set of 90 words and 90 nonwords (see Appendix B). Target words and foils were formed by inserting a root in an affixed verbal word pattern. The word patterns were past tense forms in binyanim PaʔaL and PiʔeL (ʔrefers to a glottal stop). All nonwords were generated from the verbal pattern of PiʔeL in the past tense. Words consisted of real roots whose conjugation in their respective word patterns yielded an existing Hebrew verb, whereas nonword foils were generated from a sequence of three consonants that did not correspond to an existing Hebrew root. The roots of target words consisted of 45 pairs. Members of a pair were matched on their word pattern, but differed on their root structure. One member of the pair had root-final gemination whereas the other member exhibited no gemination. The foil roots consisted of 30 novel root trios, manifesting root-initial gemination, root-final gemination, or no gemination. The root foils with final and no gemination were equated for bigram frequency. The mean summed positional bigram frequency of root final and no gemination roots were 10.93 (*SD* = 5.58) and 10.63 (*SD* = 5.24), respectively.

Participants were first presented with practice trials, including 20 words and 20 nonwords. The words and nonwords shared the same word patterns as the experimental materials. None of the practice stimuli matched the experimental stimuli. The stimuli in the practice and experimental trials were presented in an upper case Hebrew script (dfus) without any diacritic marks.

Procedure. The procedure was as described in Experiment 1.

Results and Discussion

An error in the construction of the materials resulted in the inclusion of one foil whose root corresponded to an existing (albeit nonproductive) root, shpd. This item indeed resulted in a very high error rate (shipadti, M = 85% error). This root and its two matched trio members were thus excluded from all analyses. To eliminate the effect of outliers, we excluded responses falling 2.5 *SD* beyond the grand mean for words and nonwords. This procedure resulted in the elimination of 2.76 and 2.85% of the total correct responses for words and nonwords, respectively.

Root structure did not significantly affect performance with target words. Response latency to words with root-final gemination (M = 682 ms) did not significantly differ from responses to roots with no gemination (M = 677 ms, $F_1(1,19) < 1$, MSE = 622.402; $F_2(1,44) < 1$, MSE = 2723.93). Likewise, there were no differences in responses accuracy to existing roots with final gemination (M = 93.1%) and no gemination (M = 93.4%, $F_1(1,19) < 1$, MSE = .001; $F_2(1,44) < 1$, MSE = .006). As in Experiment 1, however, responses to words (M = 679 ms) were significantly faster ($F_1(1,19) = 27.70$, MSE = 846.78; $F_2(1,72) = 29.22$, MSE = 1403.80) than responses to nonwords (M = 727 ms). Response accuracy to words (M = 93.3%) and nonwords (M = 94.5%) did not differ significantly ($F_1(1,19)$ = 2.196, MSE = .001, p = .1584; $F_2(1,72) < 1$, MSE = .003).

TABLE 5

Response Latency and Accuracy in the Rejection of Nonword Foils in Experiment 2 as a Function of Root Structure

	Response latency (ms)	Response accuracy (% correct)
Root-initial gemination	709	94.8
Root-final gemination	751	93.7
No gemination	724	95.6

Our primary interest is in responses to nonword foils. Table 5 shows the response latency and accuracy for nonword foils as a function of their root structure. Root structure did not modulate response accuracy to nonword foils $F_1(2,38) < 1$, MSE = 0.002; $F_2(2,56) < 1$, MSE = 0.007). However, the ANOVAs on response latency revealed a significant effect of root structure ($F_1(2,38) = 10.77$, MSE = 827.30; $F_2(2,56)$ = 8.49, MSE = 1552.18). Replicating the findings of Experiment 1, root-initial gemination was rejected significantly faster than root-final gemination ($t_1(38) = 4.58$; $t_2(56) = 4.09$). The rejection of root-final gemination was also significantly slower than the rejection of no gemination controls ($t_1(38) = 2.92$; $t_2(56) = 2.48$).

EXPERIMENT 3

The findings of Experiment 2 demonstrate that readers are sensitive to the presence of geminates and constrain their location. The convergence between the findings of Experiments 1 and 2 suggests that this constraint is general with respect to the location of geminates in the word: Root-final gemination is more difficult to reject than root-initial gemination whether the geminates are word final, in Experiment 1 (e.g., Sa-KoK), or word internal, in Experiment 2 (e.g., Si-KaK-tem). The consistent performance across different word structures is incompatible with a constraint on word structure. In contrast, these findings are easily explained by assuming that speakers attend to the structure of the root: They decompose the root from the word pattern, treat it as a phonological constituent, and attend to the location of geminates within this abstract domain.

TABLE 6

Structure of the Targets and Foils in Experiment 3

	Words	Nonwords
Root-initial gemination	—	hit-Ka-KaS-ti
Root-final gemination	hit-Ba-SaS-ti	hiS-ta-KaK-ti
No gemination	hit-Ba-LaT-ti	hit-Na-KaS-ti

Experiment 3 provides an additional test for this hypothesis by creating a stronger dissociation between root and word structure. In this experiment, participants were presented with roots that were sandwiched between a prefix and a suffix (see Table 6). Thus, root-initial gemination is never word initial. Likewise, root-final gemination is never word final. For instance, the root trios KKS, SKK, and NKS were presented as hit-Ka-KaS-ti, hiS-ta-KaK-ti, and hit-Na-KaS-ti[2]. If the constraint on the location of geminates appeals to the root as its domain, and if readers attend to root structure despite the high opacity of these forms, then they should reject hit-Ka-KaS-ti more easily compared to hiS-ta-KaK-ti. If the constraint further appeals to the structure of geminates, then the presence of root-final gemination in hiS-ta-KaK-ti should also impair its rejection compared to the no gemination control, hit-Na-KaS-ti.

Method

Participants. A new group of 20 University of Haifa native Hebrew speakers served as participants. Participants were paid for taking part in the experiment.

Materials. The materials consisted of 90 words and 90 nonwords (see Appendix C). The words and nonwords shared the same word pattern: They were both generated by inserting a root in the word pattern of binyan hitpa?el and the addition of an inflectional suffix. For instance, the word *hitbasasti* (I established myself) was formed by inserting the root *bss* in the word pattern hitCaCaCti. Thus, the roots were always preceded by a prefix and a suffix. Word targets and foils differed, however, in their roots. The words were all formed from existing roots such that the resulting word is a familiar Hebrew verb whereas nonwords were formed from combinations of three consonants that do not correspond to an existing Hebrew root. As in previous experiments, target roots consisted of 45 pairs of triconsonantal roots. Members of the pair were matched on their word pattern and differed only on their root structure. One member of the pair manifested root-final gemination (e.g., bss) and one had no gemination (e.g., blt). The foil roots consisted of the 30 trios of novel triconsonantal roots used in Experiment 2. These trios included a root with initial gemination (e.g., KKS), final gemination (e.g., SKK), or no gemination (e.g., NKS). The three members of each trio were conjugated in precisely the same word pattern, so that they matched in all prefixes and suffixes, differing only in their root structure.

The participants were presented with practice trials consisting of 20 words and 20 nonwords, presented twice in a random order. The words and nonwords exhibited the same word patterns as the materials used in the experimental session. None of the practice stimuli matched the experimental stimuli. The stimuli in the practice and experimental trials were presented in an uppercase Hebrew script (dfus) without any diacritic marks.

The procedure was identical to that in Experiments 1 and 2.

Results and Discussion

One foil trio was excluded from all analysis because one of its members corresponded to an existing root (shpd). To eliminate the effect of outliers, we excluded responses falling 2.5 *SD* beyond the grand mean for words and nonwords, resulting in the exclusion of 3.29% of the correct word responses and 2.32% of the correct nonword responses.

As in previous experiments, root structure did not affect performance with target words. Response latency for words with root-final gemination (M = 690 ms) did not significantly differ

[2] The location of prefix t and the root-initial consonant S is switched due to a metathesis rule applying to root initial sibilants. This presents an extreme case of morphological opacity, as the root consonants are not only highly affixed but are linearly discontinuous. We assess the implications of this process in the General Discussion.

from words with no gemination roots (*M* = 683 ms, F_1(1,19) < 1, *MSE* = 429.52; F_2(1,44) < 1, *MSE* = 4010.90). There were also no significant differences in accuracy to words with root final (*M* = 91.0%) vs. no gemination roots (*M* = 91.1%, F_1(1,19) < 1, *MSE* = .002; F_2(1,44) < 1, *MSE* = .019). However, word responses (*M* = 686.72 ms, *M* = 94.8%) were significantly faster (F_1(1,19) = 28.09, *MSE* = 985.88; F_2(1,72) = 34.77, *MSE* = 1412.01) and more accurate (F_1(1,19) = 5.64, *MSE* = 0.002; F_2(1,72) = 2.96, *MSE* = 0.006. *p* = .0895) than nonword responses (*M* = 739.34 ms, *M* = 90.9%). Table 7 lists response latency and accuracy for nonword foils as a function of their root structure.

An ANOVA conducted on response latency to nonword foils yielded an effect of root type, significant in the latency data by participants (F_1(2,38) = 3.45, *MSE* = 956.07, and marginally significant by items (F_2(2,56) = 2.62, *MSE* = 2269.80, *p* = .08). Root type did not significantly affect response accuracy (F_1(2,38) = 1.26, *MSE* = .002, *p* = .2947; F_2(2,56) < 1, *MSE* = 0.009). Planned comparisons indicated significantly faster responses to roots with initial compared to final gemination (t_1(38) = 2.21; t_2(56) = 2.15. In addition, response latencies to roots with final gemination were slower than to no gemination controls, a trend significant by participants only (t_1(38) = 2.33; t_2(56) = 1.75, *p* = .08).

The results of Experiment 3 present a conceptual replication of our previous two experiments. Participants strongly constrain the location of geminates in the root and they also manifest some sensitivity to their presence. Evidently, despite the rich affixation of our materials, readers extract the root and constrain its phonological structure.

TABLE 7

Response Latency and Accuracy in the Rejection of Nonword Foils in Experiment 3 as a Function of Root Structure

	Response latency (ms)	Response accuracy (% correct)
Root-initial gemination	729	94.1
Root-final gemination	756	95.3
No gemination	734	93.3

GENERAL DISCUSSION

This research examined whether performance in a silent reading task is subject to a phonological constraint, the OCP. The OCP bans adjacent identical elements in lexical phonological representations. Consequently, root gemination can only be formed productively, by reduplication. Because reduplication proceeds rightward, geminates are well formed only at the root's final position, not at root initial position. Our experiments tested this prediction for nonwords generated from novel roots. If speakers possess a mental constraint such as the OCP, then they should consider nonwords with root-initial gemination as ill formed. The rejection of nonwords with root-initial gemination in a lexical decision task should thus be easier than that of roots with final gemination. The results of our three experiments support this prediction.

To secure the conclusion that the constraint in question concerns the structure of the root, rather than merely the word, we varied the location of the root within the word. For instance, a root with initial gemination, such as KKS, was presented as Ka-KoS in Experiment 1, Ka-KaS-tem in Experiment 2, and hit-Ka-KaS-ti in Experiment 3. Despite these marked differences in word structure, participants rejected each of these stimuli more easily than its final gemination control. The consistent performance with different words indicates that the constraint on geminates concerns the root.

Our experiments further investigated the representation of geminates' structure. Because roots with initial geminates are ill formed, the frequency of their constituent bigrams, and, specifically, their initial geminate bigram, tends to be low. Their easier rejection may thus reflect knowledge regarding the statistical frequency of consonant combinations, rather than, specifically, their identity. To probe for the representation of identity, we examined performance with root-final gemination. In each experiment, participants had difficulty in the rejection of root-final gemination compared to their frequency-matched no gemination controls. The distinction between geminates and frequency-matched nongeminates clearly indicates sensitivity to the structure of geminates, their identity.

Why are participants inhibited by the presence of identity at the root's end? The OCP provides a possible explanation for this finding: If identity is erased from the lexicon, then root-final gemination must be formed by a grammatical process of reduplication. The attribution of novel words with root final geminates to a grammatical operation may render them more wordlike, impairing their discrimination from existing words. On an alternative account, however, the deleterious effect of gemination reflects a task-specific strategy, rather than grammatical knowledge. Because the proportion of root final gemination among our experimental targets (M = 50%) is higher than among the nonword foils (M = 33%), participants could have acquired the association of root-final gemination with "wordhood" from exposure to the experimental list. Our findings do not support this view. An impairment in the rejection of root-final gemination relative to no gemination roots is evident early on in the experimental session, at the first third of the trials in each of our experiments (Experiment 1: M = 79 ms, $F_1(1,19) = 11.81$, $MSE = 5355$, $F_2(1, 29) = 11.11$, $MSE = 11594$; M = 7.1%, $F_1(1,19) = 5.49$, $MSE = .009$, $F_2(1,29) = 5.40$, $MSE = .011$; Experiment 2: M = 11 ms, $F_1(1,19) < 1$, $F_2(1,28) = 1.16$; Experiment 3: M = 22.85 ms, $F_1(1,19) = 4.26$, $MSE = 1225$, $F_2(1,28) = 4.0$, $MSE = 1743$). There is also no significant increase in the effect of gemination throughout the experimental session. An ANOVA (2 root × 2 block) comparing performance with root final gemination and no gemination controls presented at the first and last third of trials in each of our three experiments revealed no significant interaction of root type and block (all $p > .10$). In fact, the deleterious effect of gemination in the first third of the trials in Experiment 1 (M = 79 ms) was numerically larger relative to the last (M = 29 ms). The association of root-final gemination with wordhood thus seems to indicate, at least in part, some knowledge that is independent of the experimental manipulation. The view of root-final geminates as products of the grammar, as required by the OCP, may capture this knowledge.

The proposal that gemination is perceived as indicating wordhood can also explain additional aspects of our results. Our investigation probed for readers' knowledge of root structure by examining their sensitivity to the location of geminates in the root. We assessed the sensitivity to the location of geminates by comparing roots with initial and final geminates. Because these roots are matched for the presence of geminates, their discrimination must indicate sensitivity to the location of geminates in the root. Our results show significant differences between these root types. However, performance with root-initial gemination did not differ from roots with no geminates. This finding appears inconsistent with the view of root-initial gemination as ill formed, a conclusion firmly supported by our previous finding that root-initial gemination is rated as significantly less acceptable than no-gemination controls (Berent & Shimron, 1997; Berent et al., 2001). If root-initial gemination is ill formed, why aren't roots with initial gemination easier to reject than roots with no gemination in the lexical decision task?

This puzzle is solved upon a closer examination of the lexical decision task. Unlike our previous rating experiments, participants in lexical decision experiments were not asked to determine the acceptability of novel letter strings. Instead, they were required to discriminate them from familiar Hebrew words. Discriminability is clearly affected by well formedness, as evident in readers' sensitivity to the location of geminates in the root. Well formedness, however, may not be the only factor affecting discrimination. There is ample evidence for the sensitivity of speeded, forced-choice discrimination to the global familiarity with the stimulus (e.g., Balota & Chumbly, 1984), its wordlike appearance. The difficulty in rejecting root-final gemination indicates that gemination is perceived as evidence for wordhood. Consequently, gemination impairs foil rejection. A comparison of initial-gemination with no-gemination roots thus confounds the presence of geminates with their location. This comparison pits the deleterious effect of gemination against the facilitation resulting from their illicit location. The similarity in performance with root-initial gemination and no-gemination roots may reflect the cancellation of these conflicting forces. In contrast, the comparison of root-initial gemination with root-final gemination adequately controls for the deleterious effect of gemination. Such comparison yields strong evidence for an effect of geminates' location. These results reflect a phonological constraint in a silent reading task. We now examine in greater detail the nature of the representation implicated by readers' performance.

The Multilinear Representation of Printed Words: Evidence for Phonological Constraints in Silent Reading

The observation of OCP effects in the lexical decision task suggests that the representation assembled in silent reading encodes several aspects of the morphophonological structure of spoken Hebrew words. First, readers' sensitivity to root structure indicates that their representation segregates the root morpheme and affixes, as shown by previous research on morphological processing in Hebrew (Bentin & Feldman, 1990; Deutsch et al., 1998; Feldman & Bentin, 1994; Feldman et al., 1995; Frost et al., 1997). Second, our results indicate that readers encode the phonological structure of the root, specifically, the identity of adjacent root radicals and their location.

Readers' sensitivity to the location and structure of geminates agrees with the view of geminates as represented by means of multiple linking of a single phonological element onto two skeletal slots (e.g., Goldsmith, 1990; McCarthy, 1986), as described in Fig. 3a. Interestingly, root geminates are not necessarily adjacent phonemes. For instance, the root final geminates in the spoken word Sa-LaL (*he paved*) are separated by a vowel phoneme. Capturing the structure of such disjoint geminates within a linear representation would result in line-crossing, a fatal violation of the association convention in autosegmental phonology (Goldsmith, 1990). An account for such geminates thus requires that root consonants are encoded on their own tier, segregated

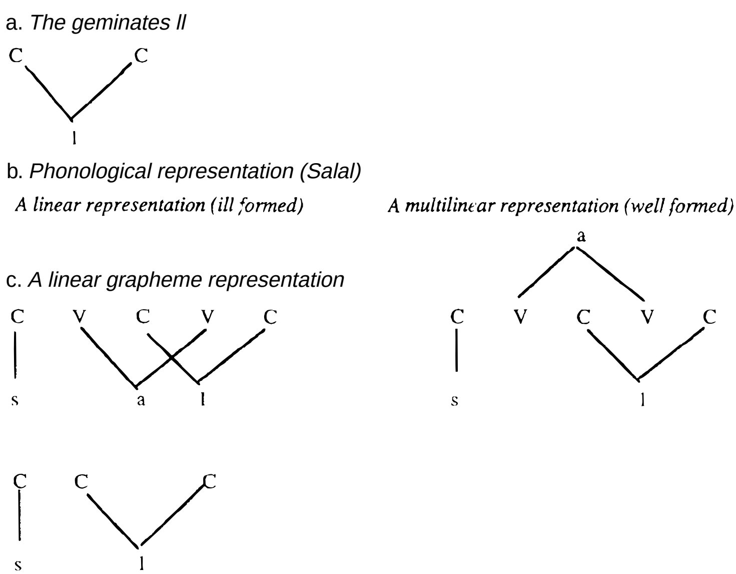

FIG. 3. The representation of geminates and its effect on tier segregation. Figure 3a illustrates the representation of the geminates ll by means of double linking of a single element to two skeletal slots. Figures 3b and 3c demonstrate the phonological and graphemic representation of a word containing these geminates, *salal* (he paved). The separation of geminates by a vowel in phonological representation (3b) requires the segregation of root consonants from vowels (see right panel), as the failure to do so results in line crossing (see left panel). In contrast, the consonantal Hebrew orthography renders these geminates adjacent graphemes, whose structure may be captured within a linear representation (3c).

from intermediate vowels and consonant affixes (see Fig. 3b). Indeed, the existence of disjoint geminates is a *prima facie* evidence for the view of phonological representations as multilinear. Although root radicals in spoken Hebrew are linearly disjoint, this is not necessarily the case for written words. Because the Hebrew orthography omits most vowels from the script, root geminates often correspond to linearly adjacent letters. The structure of such geminates may be captured by a linear graphemic account, as illustrated in Fig. 3c.

To assess the multilinearity of the representation assembled by readers, we attempted to dissociate the perceived adjacency of geminates from their linear position. To this end, we inspected performance with words that interrupt the integrity of geminates by an intermediate letter. Consider first root-final gemination. Twenty-two of the 30 novel words with root-final gemination in Experiment 1 had their geminates interrupted by a vowel letter. A separate analysis of these items revealed a robust impairment in their rejection relative to no-gemination controls (M = 51 ms, $F_1(1,19) = 18.59$, MSE = 1387; $F_2(1,21) = 7.71$, MSE = 3776; M = 5.4%, $F_1(1,19) = 14.89$, MSE = .002), $F_2(1,21) = 4.40$, MSe = .012). Thus, the disruption in the linear adjacency of geminates does not eliminate readers' sensitivity to the presence of root-final gemination. The lack of linear adjacency also does not appear to abolish the ill-formedness of root initial geminates. Seventeen of the 30 words with root-initial gemination in Experiment 1 had their root-initial geminates separated by a vowel letter. Despite the disruption in the linear adjacency of geminates, these items exhibited a sizable facilitation relative to their final gemination controls (M = 39 ms, $F_1(1,19) = 7.28$, MSe = 2063.01; $F_2(1,16) = 4.17$, MSe = 3799, p = .06). Likewise, 7 of the 30 items in Experiment 3 manifested a disruption of root-initial geminates by an intermediate consonant prefix due to sibilant metathesis in this word pattern (e.g., hiS-ta-SaK-ti, from the root SSK; see Bolozky, 1987). The rejection of such roots was nevertheless numerically faster compared to root-final gemination (M = 27 ms, $F_1(1,19) = 2.63$, MSe = 2879.81, p = .121, n.s; $F_2(1,6) = 1.32$, MSe = 3723, p = .3, n.s.). Finally, practically all the words used in Experiment 2 had their root-initial geminates separated by a vowel letter. Evidently, the sensitivity to the location of geminates emerged despite the lack of linear proximity.

The robustness of gemination effects with respect to the linear adjacency of geminates demonstrates that the perceived adjacency of root radicals is independent of their linear position. These findings suggest that the representation assembled in reading Hebrew is multilinear: It segregates root consonants on their own tier, separate from vowels and affixes, and it further distinguishes between geminates and nonidentical root radicals. Thus, the structure of the representation assembled in reading is shaped by linguistic competence.

Our results leave several unanswered questions. One question concerns the precise nature of the constraint on identity. According to the OCP, the lexical representation of triliterial roots with final gemination is biconsonantal. Although our findings agree with this account, they are also compatible with the view that root gemination is stored in the mental lexicon, but its location is constrained by the grammar, preferring root-final over root-initial gemination. A related issue concerns OCP violations. McCarthy's (1986) autosegmental analysis portrays the OCP as an inviolable constraint. Our experimental findings (Berent et al., 2001), however, converge with linguistic accounts (e.g., Odden, 1986) of the OCP as violable. Such facts favor the view of linguistic competence as governed by violable constraints (e.g., Optimality theory; Prince & Smolensky, 1997). The resolution of these issues falls beyond the scope of our present analysis.

Our results also cannot fully determine the contents of the representation assembled by readers. The similarity of the representation assembled in silent reading to the structure of spoken language agrees with the view that the representations assembled in silent reading encode phonological elements, such as phonemes and features. On an alternative account, however, the terminal nodes in the representation of printed words correspond to graphemes, not phonemes. Indeed, graphemic representations manifest multilinear structure that is quite similar to that implicated by our results. In particular, breakdowns to the graphemic system in Italian (Caramazza & Miceli, 1990) and English (McCloskey, Badecker, Goodman-Shulman, & Aliminosa, 1994) have been shown to result in specific impairment to the representation of geminate letters, including erroneous shift in the location of geminates (e.g., *pebble*→*peeble*) and geminate deletion (e.g., *cigarette*→*cigarete*). The fact that gemination in the English orthography exclusively concerns adjacent letters corresponding to a single phoneme, and the sensitivity of gemination errors in Italian to the co-occurrence of letters, violating the integrity of phonemes and phonological constraints, all implicate a graphemic, rather than a phonological, representation. In contrast to the Italian and English findings, root gemination in Hebrew always concerns two phonemes, geminates are not necessarily captured by adjacent letters, and their location is subject to a phonological constraint. Our results thus bear none of the hallmarks of a graphemic representation. On the grounds of parsimony, we prefer an account that attributes the effects of the OCP in written and spoken language to a single phonological representation over an account that assumes two isomorphic sets of constraints and representations, one in phonology and one in orthography. Regardless of the contents of the representation's terminal nodes as graphemes or phonemes, its structure clearly reflects phonological constraints.

The documentation of phonological constraints in reading Hebrew is of particular significance. Hebrew is a deep orthography whose vowel phonology is unpredictable from print (Berent & Frost, 1997). The fact that silent reading in this orthography nevertheless encodes the phonological structure of the language agrees with the fundamental role of phonological constraints in reading (e.g., Van Orden, Pennington, & Stone, 1990). Previous research on reading Hebrew demonstrated the role of phonology in the pronunciation of Hebrew words by observing the contribution of vowels to word pronunciation (e.g., Frost, 1994, 1995; Koriat, 1984, Navon & Shimron, 1981). Our results suggest that phonological constraints play a role even in the silent reading of a consonantal script. Thus, the representation assembled in silent reading is shaped by readers' phonological competence.

The Nature of Subword Constituents Assembled in Reading: The Representation of Mental Variables

Our conclusions regarding the effect of readers' linguistic knowledge on the representation of printed words converge with previous research demonstrating that readers encode phonological and morphological units at various grain sizes, such as the syllable and its constituents, and the onset and rime (e.g., Rapp, 1992; Treiman et al., 1995; Treiman & Zukowski, 1988), as well as morphological units (for reviews, see Marslen-Wilson, Komisarjevsky, Waksler, & Older, 1994; Pinker, 1999). An important question raised by these findings concerns the nature of the linguistic units assembled in reading. Symbolic accounts of cognition view morphemic and phonological constituents as variables, abstract place holders that can enumerate a large number of tokens, regardless of their idiosyncratic properties (Berent, Pinker, & Shimron, 1999; Kim, Marcus, Pinker, Hollander, & Coppola, 1994; Kim, Pinker, Prince, & Prasada, 1991; Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995; Pinker, 1991, 1994, 1999; Rapp, 1992). Conversely, associative accounts consider phonological and morphemic constituents as descriptive labels, standing for the coalition of orthographic, semantic, and phonological features of specific tokens. Readers' apparent sensitivity to morphemic and phonological units does not indicate the representation of variables. Instead, it reflects the statistical structure of phonological and morphemic correlates (e.g., Hare & Elman, 1995; Rueckl, Mikolinski, Raveh, Miner, & Mars, 1997; Rumelhart & McClelland, 1986; Seidenberg, 1987, 1997). The fierce debate surrounding the nature of morphemic and phonological constituents stems from its direct implications for understanding how the mind works (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; Fodor & Pylyshyn, 1988; Marcus, 1998, 2001; Pinker, 1997; Pinker & Prince, 1988; Rumelhart & McClelland, 1986). This debate also has some implications for accounts of reading. If readers encode the constituent structure of variables, then the representation of variables is central for the adequacy of reading models. OCP effects allow us to examine this issue.

The OCP constrains the location of identical elements in the root morpheme. The root and identity are both mental variables. Associative accounts eliminate variables; thus they render the OCP unpresentable. The elimination of variables, however, does not necessarily erase the distinction among root types. If the constraint in question could be inferred from the statistical structure of specific word instances, then participants' behavior could mimic the OCP despite their inability to represent it. Specifically, to exhibit OCP effects, an associative system must achieve two goals: It must identify the root as the domain of the constraint and encode the location of identical elements within this domain. The success of associative accounts with respect to the first goal, the abstraction of root-like units, is presently uncertain. Hebrew roots share no phonological orthographic or semantic features. The ability of associative models to identify these dissimilar objects as members of a single class remains to be demonstrated. In contrast, the representation of identity in contemporary connectionist models has been recently subject to close scrutiny. These conclusions have implications for associative accounts of OCP effects.

Identity is a formal relationship between variables, namely, *XX*. Marcus (1998) systematically investigated the representation of an identity function by multilayer perceptrons, including feedforward networks and a simple recurrent network. Such networks are capable of representing specific instances of an identity function (e.g., *a rose is a rose*). However, these models are unable to generalize this function to novel instances that fall outside the model's representational space of training items, its training space. This failure does not stem from the inability to represent the novel items, as the problem persisted despite the acquisition of the novel items in the context of an unrelated function. Marcus (1998) further demonstrated that this generalization failure is not specific to the training algorithm or the representation format (localist vs. distributed representations). The problem is principled: the independence in learning the weights of connections on any given unit (input or output) from connections on other units. To be sure, these conclusions do not challenge the adequacy of connectionism as a computational framework. Indeed, there are several proposals concerning the representation of identity in connectionist networks that include variables (e.g., Marcus, 2001; Shastri, 1999). Marcus' conclusions specifically challenge a well-defined subset of connectionist networks, those that eliminate variables. Such networks are unable to freely generalize the identity function. This failure stands in marked contrast to human behavior. Marcus, Vijayan, Bandi Rao, and Vishton (1999) demonstrated that 7-month-old infants can acquire an artificial grammar that constrains the location of identity in short sequences. For instance, infants trained on ABB sequences (e.g., *galala*) discriminated novel ABB sequences (e.g., *wofefe*) from novel AAB sequences (e.g., *wowofe*). Marcus et al. (1999) further showed that the acquired constraint on identity cannot be due to the statistical properties of their materials. Thus, the elimination of variables prevents associative systems from capturing human behavior.

The constraint on root identity has some close similarities to the artificial languages studied by Marcus et al. (1999). Our investigation of statistical properties of Hebrew roots lends no support to a statistical account for the representation of identity. Readers in our present experiments discriminate roots with final geminates from no-gemination roots despite their equation for statistical properties. Likewise, in a previous investigation examining the formation of triliteral roots from their biconsonatal representations (Berent et al., 2001), we observed a marked contrast between the observed frequency of root final gemination responses and its expected probability based on the statistical structure of Hebrew roots. The distinction between root final gemination and no gemination controls is thus inexplicable by the statistical structure of Hebrew roots. In fact, Berent, Marcus, and Shimron (2001) recently observed the constraint on root structure even when speakers have no knowledge regarding the distribution of root-radicals, for roots containing novel phonemes composed of novel phonological features. Such results challenge associative accounts of OCP effects.

The OCP effects in the lexical decision task suggest that the representation assembled by readers encodes mental variables. Thus, despite readers' undeniable sensitivity to the statistical structure of printed words, associative accounts (e.g., Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989) may not fully capture their performance. The representation of variables appears central to the adequacy of reading models. Taken as a whole, our results indicate that readers assemble multilinear representations that encode the constituent structure of mental variables in accord with their phonological competence. These results indicate the presence of linguistic constraints on reading.

APPENDIX A

Materials Employed in Experiment 1

Note: Hebrew nonback stop consonants p, b, and k undergo spirantization to p, v, and x, respectively, in post vocalic positions (Bolozky, 1978). To capture phonemic structure, a structure reflected also in the orthography, the transcription does not specify spirantization. In addition, note that most vowels provided here are not encoded in the orthography.

Target words		Nonword foils		
ʔitut	ʔitur	babiz	zabib	razib
dimum	diʃun	momel	lomem	rodeb
hisus	himur	pipuz	zipup	zerub
zikuk	zeruz	baboʔ	ʔabob	padol
xidud	xiduʃ	bibuʔ	ʔibub	ʔiduk
xitut	xitul	babic	cabib	raʃib
ximum	xikuy	poped	dopep	dopeʃ
kinun	kivun	gigun	nigug	pigud
likuk	likuy	kakos	sakok	nakos
ʔerur	ʔerub	kokeʔ	ʔokek	ʃomel
citut	cilum	gagib	bagig	bagiʃ
kidud	kiʃut	gigus	sigug	rigus
kerur	kerub	goger	rogeg	bogen
ʔidud	ʔimut	kakod	dakok	radok
basis	bariʔ	gagil	lagig	tagib
galil	kaʃir	xixub	bixux	niʔub
dakik	dabik	xaxiz	zaxix	baʔin
hagig	habil	ʔoʔeʃ	ʃoʔeʔ	noʔek
dalil	dalik	xaxod	daxox	daxog
xalil	xaric	xixut	tixux	tixuk
xaʃiʃ	xasin	reruz	zerur	ceruk
sabib	sabil	roret	torer	mores
tamim	tapil	nanob	banon	banoʃ
tanin	palit	nanid	danin	gapiʃ
borer	boxer	zizur	rizuz	ʃibun
gozez	gozem	tatul	latut	razum
goses	goneb	sosel	loses	coneb
gorer	gomer	ʃaʃiʔ	ʔaʃiʃ	lagiʃ
zolel	zorem	zizun	nizuz	nizux
zomem	ʃoken	toten	notet	notem
kolel	koʔes			
mocec	moxec			
noded	noʃeb			
nocec	nodep			

Target words		Nonword foils
solel	soxer	
colel	corem	
ʃokek	rokel	
maror	marom	
paʃoʃ	paʔot	
ʃanun	ʃabur	
talul	tabur	
taʃuʃ	kaxuʃ	
cnon	cxok	
cror	bkor	
dror	thom	

APPENDIX B

Materials Employed in Experiment 2

Target words		Nonword foils		
ʔotatnu	ʔitarnu	bibaʔti	ʔibabti	pidalti
bodadtem	bidartem	bibagnu	zibabnu	rizabnu
bisasti	biʃalti	bibamtem	mibabtem	cibagtem
gazazti	gazarti	sisakti	xisasti	xilarti
gasasnu	gabarnu	didaxno	lidadnu	dilabnu
garartem	gazamtem	didaztem	pidadtem	pidaktem
dimamti	dibarti	gigatnuti	gagnuti	gaznu
hisasnu	hidarnu	gigacti	cigagti	cigaʃti
zalaltem	zakartem	lilartem	rilaltem	bilartem
zamamti	zaxalti	lilatnu	nilalnu	rilamnu
zikaknu	zimarnu	mimabti	bimamti	gimabti
xibabtem	xibartem	mimaptem	pimamtem	ximaptem
xagagti	xagarti	ninabti	dinanti	dinakti
xidadnu	xidaʃnu	ninattem	tinantem	ʃinattem
ximamtem	ximaʃtem	pipabnu	bipapnu	nipabnu
xapapti	xaparti	pipadti	zipapti	ʃipadti
xaʃaʃnu	xaraʃnu	kikabnu	mikaknu	pikabnu
xacactem	xacabtem	kikastem	sikaktem	nikastem
yilalnu	yiʃabnu	kikaʔti	ʔikakti	dipakti
likaktem	limadtem	kikaznu	tikaknu	bikatnu
madadti	makarti	riralnu	lirarnu	miralnu
macacnu	malaknu	ʃiʃazti	ziʃaʃti	ziʃatti
nadadtem	nadartem	titagnu	gitatnu	ʃitagnu
nopapti	nitarti	titantem	nitattem	nitamtem
sobabti	sibakti	cicagti	gicacti	bicagti
salalnu	saparnu	cicaʃnu	ʃicacnu	bicaʃnu
sinantem	simantem	xixaztem	zixaxtem	bixaztem
ʔodadti	ʔibadti	zizanti	nizazti	nizaxti
ʔorarnu	ʔerabnu	zizarnu	rizaznu	dizarnu
pocactem	picaltem	zizaʃtem	ʃizaztem	bizaʃtem
porarti	perakti			
cidadnu	cilamnu			
calaltem	cabartem			
cinanti	cimakti			
carartem	caramtem			
kidadnu	kidamnu			

Target words		Nonword foils
komamti	kibalti	
kacactem	kaʃartem	
kerarnu	kerabnu	
romamti	rokanti	
risasnu	ripaʔnu	
roʃaʃtem	ritaktem	
ʃadadti	ʃabarti	
ʃotatnu	ʃidarnu	
ʃalaltem	ʃamartem	

APPENDIX C

Materials Employed in Experiment 3

Target words		Nonword foils		
hitʔonantem	hitʔabaltem	hitbabaʔti	hitʔababti	hitpadalti
hitʔoʃaʃti	hitʔabanti	hitbabagnu	hizdababnu	hitrazabnu
hitbodadnu	hitʔadamnu	hitbabamtem	hitmababtem	hictagabtem
hitbasasti	hitbalatti	histasakti	hitxasasti	hitxalarti
hitbonantem	hitgalaxtem	hitdadaxnu	hitladadnu	hitdalabnu
hitbolalnu	hitbacarnu	hitdadaztem	hitpadadtem	hitpadaktem
hitgonantem	hitganabtem	hitgagatti	hittagagti	hittagazti
hitboʃaʃti	hitgalaʃti	hitgagacnu	hictagagnu	hictagaʃnu
hitgodadnu	hitgamadnu	hitlalartem	hitralaltem	hibalartem
hitgorarnu	hitgaʔaʃnu	hitlalatti	hitnalalti	hitralamti
hitgoʃaʃti	hitgaradti	hitmamabtem	hitbamamtem	hitgamabtem
hizdakaktem	hizdahabtem	hitmamapnu	hitpamamnu	hitxamapnu
hitxababnu	hizdahamnu	hitnanabtem	hitdanantem	hitdanaktem
hitxolaltem	hitxabattem	hitnanatti	hittananti	hiʃtanatti
hitxamamti	hitxabakti	hitpapabti	hitbapapti	hitnapabti
hitxanantem	hitxadaʃtem	hitpapadtem	hizdapaptem	hiʃtapadtem
hityadadnu	hitxazaknu	hitkakabnu	hitmakaknu	hitpakabnu
hitronanti	hitkabadti	hitkakasti	histakakti	hitnakasti
hitkopapnu	hitkabasnu	hitkakaʔtem	hitʔakaktem	hitdakaptem
hitlonanti	hitkaxaʃti	hitkakaznu	hittakaknu	hitbakatnu
hitlocactem	hitlabaʃtem	hitraralti	hitlararti	hitmaralti
hitlakaknu	hitlahatnu	hiʃtaʃazti	hizdaʃaʃti	hizdaʃatti
hitnosastem	hitlaxaʃtem	hittatagnu	hitgatatnu	hiʃtatagnu
hitnocacti	hitlamadti	hittatantem	hitnatattem	hitnatamtem
histobabtem	histabantem	hictacagti	hitgacacti	hitbagacti
histodadnu	histadarnu	hictacaʃnu	hiʃtacacnu	hitbacaʃnu
histananti	histaʔarti	hitxaxaztem	hizdaxaxtem	hitbaxaztem
hitʔodadti	hitʔatapti	hizdazanti	hitnazazti	hitnazaxti
hitʔalaltem	hitʔatartem	hizdazarnu	hitrazaznu	hitdazarnu
hictanantem	hictaxaktem	hizdazaʃtem	hiʃtazaztem	hitbazaʃtem
hitʔorarnu	hitʔataʃnu			
hictopapti	hictalamti			
hitromamnu	hitragalnu			
hitronanti	hitragaʃti			
hitrocactem	hitraxabtem			
hitroʃaʃnu	hitraxaknu			
hiʃtobabtem	hitratabtem			
hiʃtomamti	hitrasakti			

Target words		Nonword foils
hitgolalnu	hitrapaknu	
hitgapaptem	hitraʃamtem	
hitxababti	hiʃtadalti	
hitxadadnu	hiʃtatapnu	
hiʃtomamtem	hitgalamtem	
hiʃtolalnu	hiʃtalatnu	
hiʃtokakti	hiʃtaparti	

REFERENCES

Balota, D., & Chumbly, J. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance*, **10,** 340–357.

Bentin, S., & Feldman, L. B. (1990). The contribution of morphological and semantic relatedness. Repetition priming at short and long lags: Evidence from Hebrew. *Quarterly Journal of Experimental Psychology*, **42,** 693.

Berent, I., Everett, D., & Shimron, J. (2001). Do phonological representations specify variables? Evidence from the Obligatory Contour Principle. *Cognitive Psychology*, **42,** 1–60.

Berent, I., & Frost, R. (1997). The inhibition of polygraphic consonants in spelling Hebrew: Evidence for a recurrent assembly of spelling and phonology in visual word recognition. In C. Perfetti, M. Fayol, and L. Rieben (Eds.), *Learning to spell: Research, theory and practice across languages* (pp. 195–219), Hillsdale, NJ: Erlbaum.

Berent, I., Marcus, G. F., Shimron, J. & Gafos, D. (2001). *The scope of linguistic generalizations: Evidence from Hebrew word-formation*. Manuscript submitted for preparation.

Berent, I., & Perfetti, C. A. (1995). A rose is a REEZ: The two cycles model of phonology assembly in reading English. *Psychological Review*, **102,** 146–184.

Berent, I., Pinker, S., & Shimron, J. (1999). Default nominal inflection in Hebrew: Evidence for mental variables. *Cognition*, **72,** 1–44.

Berent, I., & Shimron, J. (1997). The representation of Hebrew words: Evidence from the Obligatory Contour Principle. *Cognition*, **64,** 39–72.

Bolozky, S. (1987). Some aspects of Modern Hebrew phonology. In R. Aronson Berman (Ed.), *Modern Hebrew structure* (pp. 11–67), Tel Aviv: Universities Publishing Projects.

Caramazza, A., & Miceli, G. (1990). The structure of graphemic representations. *Cognition*, **37,** 243–297.

Colombo, L. (1992). Lexical stress effect and its interaction with frequency in word pronunciation. *Journal of Experimental Psychology: Human Perception and Performance*, **18,** 987–1003.

Colombo, L., & Tabossi, P. (1992). Strategies and stress assignment: Evidence from a shallow orthography. *Advances in Psychology*, **94,** 319–342.

Deutsch, A., Frost, R., & Forster, K. I. (1998). Verbs and nouns are organized and accessed differently in the mental lexicon: Evidence from Hebrew. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **24,** 1238.

Elman, J., Bates, E., Johnson, M., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.

Even-Shoshan, A. (1993). *Ha'milon ha'xadash* [The new dictionary] Jerusalem: Kiryat-Sefer.

Everett, D. L., & Berent, I. (1998). *An experimental approach to the OCP: Evidence for violable identity constraints in Hebrew roots. Rutgers Optimality Archive, Available*: (ROA–235).

Farah, M., Stowe R., & Levinson, K. (1996). Phonological dyslexia: loss of a reading-specific component of the cognitive architecture? *Cognitive Neuropsychology*, **13,** 849–868.

Feldman, L. B., & Bentin, S. (1994). Morphological analysis of disrupted morphemes: Evidence from Hebrew. *Quarterly Journal of Experimental Psychology*, **47,** 407–435.

Feldman, L. B., Frost, R., & Pnini, T. (1995). Decomposing words into their constituent morphemes: Evidence from English and Hebrew. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **21,** 947.

Fodor, J., & Pylyshyn, Z. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, **28,** 3–71.

Frisch, S., Broe, M., & Pierrehumbert. J. (1995). *The role of similarity in phonotactic constraints*. Unpublished manuscript, Northwestern University at Evanston, IL.

Frost, R. (1994). Prelexical and postlexical strategies in reading: Evidence from a deep and a shallow orthography. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **20,** 116–129.

Frost, R. (1995). Phonological computation and missing vowels: Mapping lexical involvement in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **21,** 398–408.

Frost, R., Forster, K., & Deutsch, A. (1997). What can we learn from the morphology of Hebrew? A masked-priming investigation of morphological representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **23,** 829–856.

Gafos, D. (1998). Eliminating long-distance consonantal spreading. *Natural Language and Linguistic Theory*, **16,** 223.

Goldsmith, J. A. (1990). *Autosegmental and metrical phonology*. Cambridge, MA: Basil Blackwell.

Gough, P., & Tummer, W. (1986). Decoding, reading and reading ability. *Remedial and Special Education*, **7,** 6–10.

Greenberg, J. (1950). The patterning of morphemes in Semitic. *Word*, **4,** 196–208.

Hare, M., & Elman, J. (1995). Learning and morphological change. *Cognition*, **56,** 61–98.

Harm, M. W., & Seidenberg, M. S. (1999). Phonology, reading acquisitions, and dyslexia: Insights from connectionist models. *Psychological Review*, **106,** 491–528.

Kenstowicz, M. (1994). *Phonology in Generative Grammar*. Cambridge, MA: Blackwell.

Kim, J., Marcus, G., Pinker, S., Hollander, M., & Coppola, M. (1994). Sensitivity of children's inflection to grammatical structure. *Journal of Child Language*, **21,** 179–209.

Kim, J., Pinker, S., Prince, A., & Prasada, S. (1991). Why no mere mortal has ever flown out to center field. *Cognitive Science*, **15,** 173–218.

Koriat, A. (1984). Reading without vowels: Lexical access in Hebrew. In H. Bouma, D. & G. Bouwhuis (Eds.), *Attention and performance: Control of language processes* (pp. 227–242). Hillsdale, NJ: Erlbaum.

Leben, L. (1973). *Suprasegmental phonology*, dissertation, Cambridge, MA: MIT Press.

Liberman, I., & Liberman, A. (1990). Whole language vs. code emphasis: Underlying assumptions and their implications for reading instruction. *Annals of Dyslexia*, **40,** 51–76.

Liberman, I., & Shankweiler, D. (1991). Speech, the alphabet and teaching to read. In L. B. Resnick, & P. A. Weaver (Eds.), *Theory and practice of early reading* (Vol. 2, pp. 103–132), Hillsdale, NJ: Erlbaum.

Marcus, G. (1998). Rethinking eliminative connectionism. *Cognitive Psychology*, **37,** 243–282, doi:10.1006/cogp.1998.0694.

Marcus, G. (in press). *The algebraic mind: Integrating connectionism and cognitive science*. Cambridge, MA: MIT Press.

Marcus, G., Brinkmann, U., Clahsen, H., Wiese, R., & Pinker, S. (1995). German inflection: The exception that proves the rule. *Cognitive Psychology*, **29,** 189–256, doi:10.1006/cogp.1995.1015.

Marcus, G. F., Vijayan, S., Bandi Rao, S., & Vishton, P. M. (1999). Rule learning by seven-month-old infants. *Science*, **283,** 77–80.

Marslen-Wilson, W., Komisarjevsky, L., Waksler, R., & Older, L. (1994). Morphology and meaning in the English mental lexicon. *Psychological Review*, **101,** 3–33.

McCarthy, J. (1979). *Formal problems in Semitic phonology and morphology*. Doctoral dissertation, MIT, Cambridge, MA. Distributed by Indiana University Linguistic Club. Published by Garland Press, New York, 1985.

McCarthy, J. (1986). OCP effects: Gemination and antigemination. *Linguistic Inquiry*, **17,** 207–263.

McCloskey, M., Badecker, W., Goodman-Shulman, R. A., & Aliminosa, D. (1994). The structure of graphemic representations in spelling: Evidence from a case acquired dysgraphia. *Cognitive Neuropsychology*, **11,** 341–392.

Miceli, G., & Caramazza, A. (1993). The assignment of word stress: Evidence from a case acquired dyslexia. *Cognitive Neuropsychology*, **10,** 273–296.

Navon, D., & Shimron, J. (1981). Does word naming involve grapheme- to-phoneme translation? Evidence from Hebrew. *Journal of Verbal Learning and Verbal Behavior*, **20,** 97–109.

Odden, D. (1986). On the Obligatory Contour Principle. *Language*, **62,** 352–383.

Patterson, K., Suzuki, T., & Nakayama-Wydell, T. (1996). Interpreting a case of Japanese phonological alexia: The key is in phonology. *Cognitive Neuropsychology*, **13,** 803–822.

Pennington, B. (1990). Annotation: The genetics of Dyslexia. *Journal of Child Psychology*, **31,** 193–201.

Perfetti, C. A. (1985). *Reading ability*. New York: Oxford University Press.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. Gough, L. Ehri, & R. Treiman, (Eds), *Reading acquisition* (pp. 145–174), Hillsdale, NJ: Erlbaum.

Pinker, S. (1991). Rules of language. *Science*, **253,** 530–535.

Pinker, S. (1994). *The language instinct*. New York: Morrow.

Pinker, S. (1997). Words and rules in the human brain. *Nature*, **387,** 547–548.

Pinker, S. (1999). *Words and rules: The ingredients of language*. New York: Basic Books.

Pinker, S., & Prince, A. (1988). On language and connectionism: Analysis of parallel distributed processing model of language acquisition. *Cognition*, **28,** 73–193.

Plaut, D., McClelland, J., Seidenberg, M., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, **103,** 56–115.

Prince, A., & Smolensky, P. (1997). Optimality: From neural networks to Universal Grammar. *Science*, **275,** 1604–1610.

Rapp, B. (1992). The nature of sublexical orthographic organization: The bigram trough hypothesis examined. *Journal of Memory and Language*, **31,** 33–53.

Rueckl, J., Mikolinski, M., Raveh, M., Miner, C., & Mars, F. (1997). Morphological priming, fragment completion, and connectionist networks. *Journal of Memory and Language*, **36,** 382–405, doi:10.1006/jmla.1996.2489.

Rumelhart, D. E., & McClelland, J. L. (1986). On learning the past tense of English verbs: Implicit rules or parallel distributed processing? In J. L. McClelland, D. E. Rumelhart, & The PDP Research Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition: Vol. 2: Psychological and biological models* (pp. 216–271), Cambridge, MA: Bransford Books/ MIT Press.

Russel, K. (1997). Optimality theory and morphology. In D. Archangeli, & L. Langendoen (Eds.), *Optimality Theory* (pp. 102–133), Oxford: Blackwell.

Seidenberg, M. (1987). Sublexical structures in visual word recognition: Access units of orthographic redundancy? In M. Coltheart, (Ed.), *Attention and performance XII: Reading* (pp. 245–263), Hillsdale, NJ: Erlbaum.

Seidenberg, M. (1997). Language acquisition and use: Leaning and applying probabilistic contraints. *Science*, **275,** 1599–1603.

Seidenberg, M., & McClelland, J. (1989). A distributed developmental model of word recognition and naming. *Psychological Review*, **96,** 523–568.

Shastri, L. (1999). Infants learning algebraic rules. *Science*, **285,** 1673–1674.

Shaywitz, S. (1996). Dyslexia. *Scientific America*, **275,** 98–104.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading impaired: A critical review of the evidence. *Psychonomic Bulletin and Review*, **2,** 508–514.

Treiman, R., Mullennix, J. W., Bijeljac-Babic, R., & Richmond-Welty, E. D. (1995). The special role of rimes in the description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General*, **124,** 107–136.

Treiman, R., & Zukowski, A. (1988). Units in reading and spelling. *Journal of Memory and Language*, **27,** 466–477.

Van Orden, G. C., Pennington, B. F., & Stone, G. O. (1990). Word identification in reading proceeds from spelling to sound to meaning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **14,** 371–386.

Yip, M. (1988). The Obligatory Contour Principle and phonological rules: A loss of identity. *Linguistic Inquiry*, **19,** 65–100.

Yip, M. (1995). Identity avoidance in phonology and morphology. In *Rutgers Optimality Archive*. Available: (http://ruccs.rutgers.edu/roz.html).

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