Journal of Experimental Psychology:
Human Perception and Performance
2010, Vol. 36, No. 1, 212–223

© 2010 American Psychological Association
0096-1523/10/$12.00 DOI: 10.1037/a0017638

Universal Constraints on the Sound Structure of Language: Phonological or Acoustic?

Iris Berent and Tracy Lennertz
Northeastern University

Languages are known to exhibit universal restrictions on sound structure. The source of such restrictions, however, is contentious: Do they reflect abstract phonological knowledge, or properties of linguistic experience and auditory perception? We address this question by investigating the restrictions on onset structure. Across languages, onsets of small sonority distances are dispreferred (e.g., *lb* is dispreferred to *bn*). Previous research with aural materials demonstrates such preferences modulate the perception of unattested onsets by English speakers: Universally ill-formed onsets are systematically misperceived (e.g., *lba* → *leba*) relative to well-formed onsets (e.g., *bn*). Here, we show that the difficulty to process universally ill-formed onsets extends to printed materials. Auxiliary tests indicate that such difficulties reflect phonological, rather than orthographic knowledge, and regression analyses demonstrate such knowledge goes beyond the statistical properties of the lexicon. These findings suggest that speakers have abstract, possibly universal, phonological knowledge that is general with respect to input modality.

Keywords: language-universals, phonology, reading, sonority, optimality-theory

A large body of research demonstrates that speakers are equipped with productive phonological knowledge regarding the sound structure of their language. For example, English speakers consider *blif*, but not *lbif*, a possible English word, and they tend to agree on such judgments even though they have never heard either word before. Although the existence of productive phonological knowledge is widely recognized, its nature is contentious. One view attributes phonological knowledge to the properties of linguistic experience and domain-general restrictions on auditory perception and motor-control (Blevins, 2004; Browman & Goldstein, 1989; Elman et al., 1996; Lindblom, 1998; MacNeilage & Davis, 2000; Ohala, 1990; Oudeyer, 2005; Rumelhart & McClelland, 1986). In this view, speakers prefer structures that are frequent and are easy to perceive and articulate. For example, the preference for *blif* might reflect its resemblance to *black* and *cliff*, and the greater ease of perceiving and articulating the *bl* compared to the *lb* sequence. On an alternative account, speakers possess universal grammatical restrictions on language structure (Chomsky, 1965; Chomsky, 1980; Fodor, 1983; Pinker, 1994). One such theory, Optimality Theory (Prince & Smolensky, 1993/2004; Smolensky & Legendre, 2006), asserts that such universal grammatical restrictions are active in the brains of all adult speakers. Although processing demands could have shaped the grammar in ontogeny and phylogeny (Hayes & Steriade, 2004), grammatical knowledge of such universals is assumed to apply across the board, irrespective of the functional properties of specific linguistic inputs. Thus, the relative dispreference for *lbif*, for instance, might reflect, in part, on universal grammatical restrictions against onsets like *lb*, rather than the specific phonetic properties of these auditory inputs and their frequency in experience alone.

To adjudicate between these two views, one might investigate whether speakers are equipped with grammatical preferences regarding structures that are unattested in their language (for related work, see Davidson, 2006; Moreton, 2008; Wilson, 2006; Zuraw, 2007). In a recent line of research, we have addressed this question by examining the universal restrictions on the structure of onset clusters (Berent, Steriade, Lennertz, & Vaknin, 2007; Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Berent, Lennertz, Smolensky, & Vaknin-Nusbaum, 2009). Across languages, onsets like *bn* are preferred to onsets such as *bd*, which, in turn, are preferred to onsets such as *lb*. Neither onset type is attested in English. But remarkably, English speakers appear to be sensitive to their structure: Clusters that are universally ill-formed (e.g., *lb*) are systematically misperceived relative to those that are relatively well-formed. Our goal here is to gauge the source of such misperceptions—Are they due to the phonological ill-formedness of such clusters, or to difficulties in auditory processing? To this end, we examine whether the difficulties in processing ill-formed clusters extend to printed forms. If the misperception of ill-formed clusters only reflects specific auditory difficulties, then results with printed and auditory words should diverge. In contrast, a convergence across modalities would implicate broad phonological knowledge that is independent of the phonetic properties of the input. Before describing our experimental investigation with printed materials, we must first describe the grammatical restrictions on onset consonants and their effect on the processing of auditory stimuli.

Restrictions on the Sonority-Sequencing of Onset Consonants

Languages are known to systematically restrict the co-occurrence of consonants in their onsets (i.e., consonant sequence

Iris Berent and Tracy Lennertz, Department of Psychology, Northeastern University.

This research was supported by NIH grant DC003277 to the first author.

Correspondence concerning this article to should be addressed to Iris Berent, Department of Psychology, Northeastern University, 125 Nightingale Hall, 360 Huntington Ave., Boston MA 02115-5000. E-mail: i.berent@neu.edu

found at the beginning of a syllable, e.g., *bl* in *block*). For example, *lb*-type clusters are universally under-represented: They are less frequent across languages, and languages that allow *lb* type structures are likely to allow *bl*-type clusters, but not vice versa (e.g., see data from Greenberg, 1978; reanalyzed in Berent et al., 2007). Such preferences have been attributed to the sonority profile of these clusters (e.g., Clements, 1990; Steriade, 1982; Zec, 2007). Sonority (hereafter, *s*) is a phonological property that correlates with the loudness of segments–louder segments are considered more sonorous than more quiet segments (Parker, 2002; Wright, 2004). Most sonorous on this scale are glides (e.g., *w, y*), with a sonority level of 4 ($s = 4$), followed by liquids (*l, r;* $s = 3$), and nasals (e.g., *m, n;* $s = 2$); least sonorous on the scale are obstruents, namely, stops (e.g., *b, d, p, t, k, g*) and fricatives (e.g., *f, v*), with a sonority level of 1 (e.g., Clements, 1990). Accordingly, onsets as in *blif* exhibit a large rise in sonority (from the obstruent to the liquid, $\Delta s = 2$); *bnif* manifests a smaller rise (from the obstruent to the nasal, $\Delta s = 1$) in *bdif*, the onset includes two obstruents, so it manifests a sonority plateau ($\Delta s = 0$); finally, onsets like *lbif* exhibit a fall in sonority (from the liquid to the obstruent, $\Delta s = -2$). The cross-linguistic preference (denoted by > for *bl*>*bn*>*bd*>*lb* can thus be captured by a grammatical constraint that renders large sonority distances more well-formed relative to smaller distances (e.g., Clements, 1990; Smolensky, 2006). Of interest is whether such universal grammatical preferences are psychologically active among all speakers.

Although many studies have examined preferences regarding clusters that are attested in participants' language (e.g., Fowler, Treiman, & Gross, 1993; Treiman, 1984; Treiman & Danis, 1988; Treiman, Bowey, & Bourassa, 2002), speakers' preferences for unattested clusters is relatively unexplored (for a review, see Berent et al., 2009; Berent et al., 2007). In previous research, we have investigated whether English speakers are sensitive to the *bn*>*bd*>*lb* scale despite the absence of all three types of clusters in their language (Berent et al., 2007). Our investigation of such universal preferences exploits the well-documented effects of ill-formedness on perception. Previous research has demonstrated that ill-formed clusters are systematically misperceived (Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Dupoux, Pallier, Kakehi, & Mehler, 2001): Speakers tend to misperceive the consonant sequence as if it were separated by a vowel (e.g., *tla* → *tela*, Pitt, 1998, see also Buchwald, Rapp, & Stone, 2007). Of interest is whether such misperception—a hallmark of ill-formedness—depends on universal grammatical restrictions that are unattested in one's language. Results show that, as the universal ill-formedness of the cluster increased, English speakers were likely to misperceive it epenthetically (Berent et al., 2007). Specifically, people were more likely to misperceive the most ill-formed onsets with sonority falls (e.g., *lb*) compared to less ill-formed onsets with sonority plateaus (e.g., *bd*); sonority plateaus, in turn, were perceived less accurately than the least ill-formed onsets of rising sonority (e.g., *bn*). Auxiliary analyses suggested that the misperception of universally ill-formed onsets was not due to several statistical properties of the English lexicon. Further support for this conclusion is offered by subsequent work, documenting similar preferences among speakers of Korean—a language that arguably lacks onset clusters altogether (Berent et al., 2008). Thus the misperception of onsets with small sonority distances does not appear to solely reflect their statistical properties.

The Restrictions on Processing Ill-Formed Clusters: Phonological or Phonetic?

Why are clusters that are typologically under-represented misperceived by English speakers? One possibility is that such misperception is due to grammatical ill-formedness. But on an alternative explanation, they reflect only the acoustic properties of such clusters. For example, onsets such as *lbif* might be confusable with *lebif* because the acoustic cues for the sonorant *l* (in *lbif*) are confusable with those of the pretonic vowel *e* in *lebif*. Berent et al. (2007) have argued against a purely auditory explanation for this phenomenon. In their view, spoken words are encoded in two formats: a phonetic format and a phonological one. The misperception of ill-formed onsets reflects their phonological repair by the grammar, not a failure to encode their phonetic properties from the auditory signal.

Two arguments support this proposal. First, when task demands encourage participants to attend to phonetic detail (specifically, to the presence of the pretonic vowel in the auditory input), people are able to perceive highly ill-formed *lbif*-type clusters accurately–as accurately as they perceived their better formed *bdif*-type counterparts (Berent et al., 2007, Experiments 5-6). Accordingly, the typical misperception of ill-formed onsets cannot be due only to a failure to encode their phonetic form. Rather, such misperceptions might reflect the active phonological repair of such clusters by the phonological grammar (e.g., the repair of *lbif* as *lebif*). Because people typically base their responses on (repaired) phonological representations, they normally misperceive ill-formed onsets. However, conditions that encourage phonetic encoding can effect a shift from the default reliance on phonological representation to the inspection of the phonetic form. The finding that such conditions promote equal accuracy in the processing of ill-formed and well-formed clusters suggests that the phonetic representation of ill-formed onsets is not necessarily inaccurate.

A second argument against a purely phonetic failure is presented by findings suggesting that the aversion to ill-formed onsets affects the processing of their disyllabic counterparts. When required to determine whether the input includes one syllable or two, participants are significantly less accurate with *benif* relative to *lebif* (Berent et al., 2007; Berent et al., 2008). There is no reason to assume that the difficulty with *benif* reflects its phonetic properties, such as the duration of the pretonic vowel—the result remains significant after statistically controlling for this factor. Instead, this phenomenon appears to reflect a competition between the two alternative representations for the input—a (faithful) disyllabic representation (e.g., *lebif*) and its monosyllabic counterpart (e.g., *lbif*). An aversion to ill-formed clusters like *lbif* is thus expected to decrease their competitive power, thereby protecting their counterpart *lebif* from misperceptions. Crucially, such aversion is evidenced when no cluster is aurally present, so it cannot depend only on auditory properties.

Although these arguments challenge a purely phonetic source for the misperception of ill-formed onsets, other results appear to support it. A recent investigation (Berent, 2008) compared the sensitivity of hearers and readers to the sonority profile of unattested clusters presented either aurally or visually in a lexical decision task. In accord with previous research, the findings from aural materials showed that speakers were sensitive to the ill-formedness of unattested clusters even after controlling for numerous statistical properties of the auditory inputs. But when the same items were presented in print, readers were only sensitive to the narrow distinction between small sonority rises (which are similar to attested English onsets) and plateaus (which are not)—they were indifferent to the broader distinction between onsets of level and falling sonority. Moreover, readers' narrow preference for onsets of rising sonority was entirely due to their statistical properties: Once these properties were statistically controlled in a regression analysis, no unique grammatical effect was found.

The discrepancy between the results obtained with auditory and printed materials opens up the possibility that the misperception of ill-formed onsets reflects difficulties in processing the acoustic signal, not an abstract grammatical constraint. Alternatively, the source of the discrepancy might be strictly methodological. Although readers are known to rapidly assemble phonological representations from print (e.g., Lukatela & Turvey, 1990; Lukatela & Turvey, 1993; Lukatela, Eaton, Moreno, & Turvey, 2007; Perfetti & Bell, 1991; Van Orden, Pennington, & Stone, 1990), the typically faster time-course of visual lexical decision responses might not allow for the computation of grammatical phonological restrictions. This possibility is supported by recent results concerning the repair of illicit onsets in Spanish. Spanish speakers are known to repair s-initial onset clusters (e.g., *special* → *especial*) in the perception of either aural (Theodore & Schmidt, 2003) or printed forms (Hallé, Dominguez, Cuetos, & Segui, 2008). But crucially, with printed words, repair obtains only at long SOAs between the target and prime (e.g., *special* → *especial;* Halle et al., 2008). Because the ill-formedness of unattested auditory onsets is evidenced by their repair (e.g., *lbif* → *lbif*), the absence of such effects in the visual lexical decision task might be due to the faster time course of visual lexical decision, rather than stimulus modality per se. The present research is designed to adjudicate these possibilities.

Do the Restrictions on Unattested Onsets Extend to Printed Words?

The present research examines whether the dislike of onsets with small sonority distances extends to printed materials. Unlike the on-line lexical decision task used in Berent (2008), here we use a procedure that encourages the decoding of phonological structure from print. The task—an identity judgment task—is a visual variant of the identity judgment task used in our previous investigation with auditory materials (Berent et al., 2007; Berent et al., 2008; Berent et al., 2009). In each trial, English-speaking participants are presented with two printed words (e.g., *lbif-LEBIF*), and they are asked to determine whether the two items are identical. The long SOA between the two words—3 seconds—their different type-case and their separation by a pattern mask are designed to increase working memory demands, thereby encouraging the assembly of a phonological representation from print. Of interest is whether these conditions would allow readers to compute the grammatical structure of onsets that are unattested in their language.

To examine this question, we compare responses to three types of unattested onsets, arrayed according to their ill-formedness along the sonority-scale: Onsets with small sonority rises (e.g., *bnif*, $\Delta s = 1$), onsets with sonority plateaus (e.g., *bdif,* $\Delta s = 2$), and onsets with sonority falls (e.g., *lbif,* $\Delta s = –2$). As a methodological check, we also included a group of onsets with large sonority rises (e.g., *blif,* $\Delta s = 2$), onsets that are attested in English. Such onsets should be preferred to unattested onsets on grounds of either familiarity or grammatical structure, as such large sonority rises are better-formed than either of their counterparts (e.g., *bnif, bdif, lbif*). We also presented participants with the disyllabic counterparts of these onsets (e.g., *belif, benif, bedif,* and *lebif*). Monosyllabic and disyllabic forms were presented in pairs. In half of the trials, pair members were identical (either monosyllabic e.g., *lbif-LBIF*, or disyllabic, e.g., *lebif-LEBIF*), whereas in the other half, they were nonidentical, and differed only on the pretonic vowel (e.g., *lbif-LEBIF*, *lebif-LBIF*).

Our main interest is in nonidentity trials. Previous research has shown that, as the grammatical ill-formedness of the cluster increases, hearers are more likely to misperceive the cluster as identical to its disyllabic counterpart (e.g., *lbif* = *lebif*). The use of printed materials allows us to better gauge the source of such misperceptions. If the misperception of ill-formed onsets is due to a phonetic failure—a failure to extract the phonetic cues from the acoustic input—then no such misperceptions should be present when the materials are presented visually. In contrast, if the misperception of ill-formed onsets reflects a phonological process of grammatical repair, and if people assemble phonological structure from print, then as ill-formedness increases, misperception should emerge even with visual materials. Although participants could partly circumvent the misperception of printed ill-formed onsets by attending to graphemic cues (e.g., the presence of the pretonic vowel-letter *e* in the disyllabic form and its absence in the monosyllabic counterpart), such additional processing should elevate response time. Thus, as the ill-formedness of the onset increases, participants should take longer to discriminate it from its disyllabic counterpart.

To determine whether readers do, in fact, engage in phonological processing, each of our experiments introduced a subsidiary manipulation, designed to gauge the assembly of phonology from print. Both manipulations examine whether readers are sensitive to the phonological similarity among nonidentical items while controlling for their graphemic overlap. In Experiment 1, we exploit the effect of forward inconsistency in mapping graphemes to phonemes (Glushko, 1979). Because the mapping of the grapheme *c* to its phoneme is inconsistent (*c* → */k/ or /s/*), nonidentical items that begin with a *c* differ from each other by two phonemes (e.g., *crik-CERIK*, /krɪk/-/sərɪk/), hence, their phonological dissimilarity is greater relative to consistent spelling controls (e.g., *plik-PELIK,* /plɪk/-pəlɪk/). In Experiment 2, we compared pairs like *crek-KEREK*, which differ on one phoneme, to spelling controls (e.g., *prek-KEREK*), which differ on two phonemes (in both pairs, members mismatch on two letters). If readers assemble phonology from print, then each experiment should yield easier discrimination among nonidentical control pair members that are phonologically dissimilar (e.g., *crik-CERIK; prek-KEREK*) compared to their graphemically matched controls (e.g., *plik-PELIK, crek-KEREK*).

Experiment 1

Method

Participants. Twenty-six native English speakers, students at Florida Atlantic University took part in the experiment in partial fulfillment of a course requirement.

Materials. The materials consisted of 30 quadruples of monosyllabic nonce words (e.g., *blif, bnif, bdif, lbif*, see Appendix A) and their disyllabic counterparts (e.g., *belif, benif, bedif, lebif*). These items are a visual representation of the auditory materials used in Berent et al. (2007). Monosyllabic items had an onset cluster, followed by a vowel and a consonant letter. These items were arranged in quartets that varied the structure of the onset cluster, either a large sonority rise that is attested in English (e.g., *blif*), or an unattested cluster consisting of a small sonority rise, a sonority plateau or a sonority fall (e.g., *bnif, bdif, lbif*). Quartet members with rises and plateaus shared the same initial consonants, whereas the falls were generated by reordering the consonants in large rises. Most (25/30) quartet members shared the rhyme. Disyllabic items differed from their monosyllabic counterparts only on the presence of the letter *e* between the two consonants forming the onset cluster.

The materials were arranged in pairs—half were identical (either monosyllabic, e.g., *blif-BLIF* or disyllabic, e.g., *belif-BELIF*) and half were nonidentical items that were ‘repair’-related (e.g., *blif-BELIF*). Nonidentical trials varied the order of the monosyllabic or disyllabic members (e.g., *blif-BELIF, belif-BLIF*). These pairs were set in two lists, matched for the number of stimuli per condition (onset type × identity × order) and counterbalanced, such that, within a list, each item appeared in either the identity or the nonidentity condition but not both. Each participant was assigned to one list.

Procedure. Participants initiated the trial by pressing the space bar. Each trial began with a fixation point (*) presented for 100 ms followed by the first nonword, presented in lower case for 500 ms, a pattern mask (XXXXXX) presented for 2,500 ms and the second nonword, presented in upper case until participants made their response. Participants indicated whether the two stimuli were identical by pressing the 1 or 2 keys, for “identical” and “nonidentical” responses, respectively. Slow responses (RT > 1,200 ms) received a computerized warning signal. We also provided participants with computerized feedback regarding their accuracy (for both incorrect fast responses as well as correct responses). Prior to the experiment, participants were given a short practice using English words (e.g., *plight-PLIGHT* vs. *polite-PLIGHT*). Participants were tested in groups of up to four people.

Results and Discussion

Outliers (slow responses falling 2.5 *SD* above the mean or faster than 200 ms—less than 2% of the total correct observations)—were excluded from the analyses of response time. We also excluded the data from one of the quadruplets (*clim, cnim, cpim, lpim*) in the nonidentity condition because it was displayed incorrectly. All analyses of response accuracy in Experiments 1–2 were conducted on the proportion of correct responses. In this and the subsequent experiment, we adopted .05 as the level of significance. As a preliminary check, we first verified that responses to the identity condition (e.g., *blif-BLIF; belif-BELIF*) were fast (M = 710 ms) and accurate (M = 88.5%). Our main interest is in nonidentity trials (e.g., *blif-BELIF*).

An inspection of the means (see Figure 1) suggests that readers were sensitive to the sonority profile of the onset: As the ill-formedness of the onset increased, participants took longer to distinguish onset clusters from their disyllabic counterparts. A one-way ANOVA yielded a significant main effect of onset type, $F1(3, 75) = 5.35$, $MSE = 1115$, $p < .003$, $\eta^2 = .176$; $F2(3, 84) = 3.18$, $MSE = 1499$, $p < .03$, $\eta^2 = .102$; this effect was not

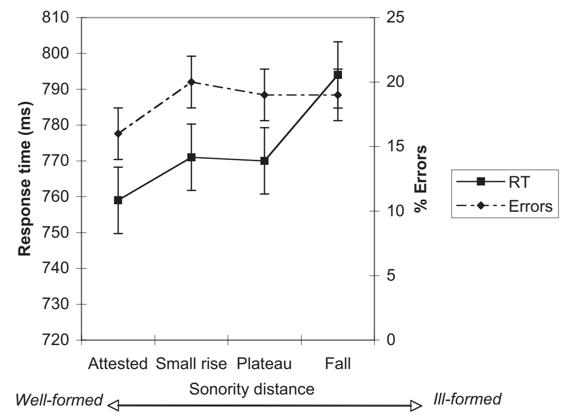

Figure 1. The effect of onset type on response time and accuracy to the nonidentity trials in Experiment 1. Bars indicate confidence intervals for the difference between the means.

significant in response accuracy, $p > .12$.[1] Fisher PLSD tests showed that the most ill-formed onsets of falling sonority produced slower responses relative to the best-formed onsets with large sonority rises, $t1(75) = 3.91$, $p < .0003$; $t2(84) = 2.99$, $p < .004$. Interestingly, participants were also sensitive to the structure of onsets that are all unattested in their language. Specifically, ill-formed onsets of falling sonority produced significantly slower responses compared to onsets of level sonority, $t1(75) = 2.61$, $p < .02$; $t2(84) = 2.17$, $p < .04$, and marginally so relative to onsets with small sonority rises, $t1(75) = 2.49$, $p < .02$; $t2(84) = 1.78$, $p < .08$. No other contrasts were significant.

Readers’ sensitivity to onset structure might suggest that they encode the phonological structure of printed onsets and constrain their sonority profile. Because onsets with small sonority distances are ill-formed, they might undergo repair by the phonological grammar (e.g., *lbif* → *lebif*), hence, they are difficult to discriminate from their disyllabic counterparts. On an alternative explanation, however, the difficulty responding to items like *lbif* is of non-phonological origin. Because pair-members invariably manifested different letter-case (e.g., *lbif-LEBIF*), their discrimination cannot be based on visual cues alone. Nonetheless, the difficulty to discriminate *lbif* from *LEBIF* might reflect their graphemic structure. For example, participants might be unfamiliar with onsets whose first letter is an *l*, and it is the unfamiliarity with such grapheme sequences, not phonological structure, that impairs performance.

A sub-group of the materials allows us to evaluate this possibility. Recall that some of the items had onsets beginning with a

[1] Recall that nonidentical pair members were presented with order counter-balanced, such that the target is either monosyllabic or disyllabic. We next evaluated the effect of order by means of auxiliary 2 order × 4 onset type ANOVAs. The main effect of order was significant in both response time, $F1(1, 25) = 27.03$, $MSE = 53987$, $p < .0001$, $\eta^2 = .520$; $F2(1, 28) = 28.41$, $MSE = 2253$, $p < .0001$, $\eta^2 = .433$, and accuracy $F1(1, 25) = 6.01$, $MSE = .021$, $p < .03$, $\eta^2 = .194$; $F2(1, 28) = 14.47$, $MSE = .009$, $p < .0008$, $\eta^2 = .341$, suggesting that trials requiring the maintenance of the onset cluster in working memory (i.e., trials with disyllabic targets) elicited slower and less accurate responses. However, the order of presentation did not further modulate the effect of onset type.

c—a grapheme whose mapping to phoneme is inconsistent. Unlike the majority of the items, in which nonidentical items differ on only a single phoneme (e.g., *plik-PELIK,* /plɪk/-pəlɪk/), *c*-initial pairs differ on two phonemes (e.g., *crik-CERIK*, /krɪk/-/sərɪk/). If participants assemble phonology from print, then they should be sensitive to the phonological similarity among nonidentical items: Responses to nonidentical items should be easier for the dissimilar *c*-initial items compared to the rest of the materials, which differ only by a single phoneme. Our materials included five quadruplets in which three of the onset types were *c*-initial (i.e., attested onsets, onsets with small rises and plateaus—because sonority falls begin with a sonorant, it was impossible to extend the manipulation to those items). A 2 similarity × 3 type ANOVA of response accuracy yielded a significant effect of similarity, $F1(1, 25) = 7.89$, $MSE = .010$, $p < .01$, $\eta^2 = .240$; $F2(1, 27) = 6.31$, $MSE = .005$, $p < .02$, $\eta^2 = .191$; that was not further modulated by onset type (all $F < 1$). No effects of similarity were observed in response times (all $F < 1$, $M = 770$ ms and $M = 763$ ms, for similar and dissimilar items, respectively). As expected, response accuracy to phonologically dissimilar *c*-initial pairs ($M = 85.6\%$) was significantly higher compared to phonologically similar controls ($M = 80.6\%$). These results demonstrate that participants in this task assemble the phonology of the items from print. Accordingly, the difficulty to process ill-formed onsets is likely to reflect their phonological structure, rather than their orthographic properties alone.

Experiment 2

The findings from Experiment 1 suggest that readers are sensitive to the phonological structure of onsets that are unattested in their language. Although the effects of onset type with printed materials are weaker than those previously documented with auditory materials (an issue we address in the General Discussion) the overall patterns are similar: As sonority distance decreases, people take longer to distinguish monosyllabic forms with onset clusters from their disyllabic counterparts. The convergence might suggest that like hearers, readers encode the phonological structure of printed onsets and constrain their sonority profile.

Experiment 2 seeks to replicate these findings and obtain additional evidence for the assembly of phonology from print. As in Experiment 1, we examine whether the discrimination among nonidentical items depends on their phonological similarity. But in Experiment 2, our manipulation of phonological similarity exploits homophony: We compare nonidentical items whose first consonant is phonologically identical (e.g., *crek-KEREK*, /krɛk/-kərɛk/) and graphemic controls (e.g., *prek-KEREK,* /prɛk/-kərɛk/). Both pair members mismatch on two letters, but differ on their phonological similarity. Members of the *crek-KEREK* pair differ by one phoneme, whereas members the *prek-KEREK* pair differ by two phonemes. If readers assemble the phonology of such clusters from print, then they should be sensitive to the phonological similarity among pair members.

Method

Participants. Forty native English speakers, students at Florida Atlantic University took part in the experiment in partial fulfillment of a course requirement.

Materials. The materials (see Appendix B) included two equal groups of identity and nonidentity items. The structure of these materials matched those used in Experiment 1, including an attested member with a large sonority rise, and unattested clusters with smaller rises, plateaus and falls.

A subset of 16 quartets was specifically designed to gauge the assembly of phonology from print in the nonidentity condition. Unlike the nonidentity condition in the main set of materials, in this subset, nonidentical pair members differed on two letters (e.g., *clim-KELIM*) and their phonological similarity was manipulated. In eight quadruplets, pair members differed on one phoneme, a vowel (e.g., *clim-KELIM*), whereas in the remaining eight quadruplets, pair members differed on two phonemes, a consonant and a vowel (e.g., *blim-KELIM*). Similar pair-members invariably differed on the spelling of the phoneme /k/ (e.g., *clim-KELIM*; *rcof-REKOF*); dissimilar and similar clusters were paired with the same disyllabic counterparts (e.g., *clim-KELIM* vs. *blim-KELIM*). In view of the restrictions on the phonological properties of the onsets (i.e., falls must begin with a sonorant whereas all other clusters begin with an obstruent), it was impossible to control the location of the mismatching consonants in all four types. The design nonetheless attempted to dissociate the effect of the location of the mismatching consonant from sonority distance by matching sonority falls and plateaus on the location of the change. Thus, in onsets with large and small rises, the mismatching consonant was the first member of the onset (e.g., *clim-KELIM*), whereas in plateaus and falls, it was the second consonant (e.g, *rcof-REKOF*).

The 16 quadruplets of similar and dissimilar items were arranged in two lists. Each list included eight quadruplets, counterbalanced for phonological similarity, onset type, and order. Each sub-list of eight quadruplets was combined with the remaining 22 quadruplets from Experiment 1 to form a total of 120 nonidentity trials, counterbalanced for onset type and order. The remaining 120 trials in each list consisted of identity trials, either monosyllabic (e.g., *blif-BLIF*) or disyllabic (e.g., *belif-BELIF*), including all four types of onsets or their disyllabic counterparts. Identity trials comprised 30 quadruplets, 22 of those were taken from Experiment 1; the remaining eight quadruplets were generated from the set of eight phonologically similar quadruplets by replacing the letter *c* with a *k* (e.g., *clim* was presented as *klim*).

Identity and nonidentity trials were combined into two lists, matched for the number of stimuli per condition (onset type × identity × order × phonological similarity) and counterbalanced, such that, within a list, each item appeared in either the identity or the nonidentity condition but not both. Each participant was assigned to one list. The procedure was as in Experiment 1.

Results and Discussion

Outliers (slow responses falling 2.5 *SD* above the mean or faster than 200 ms)—less than 3% of the total correct observations—were excluded from the analyses of response time. As in the previous experiment, we verified that responses to identity trials were fast ($M = 670$ ms) and accurate ($M = 89\%$). Of main interest are responses to nonidentity trials (see Figure 2).

An inspection of the means suggests that responses were modulated by the sonority profile of the onset. A one-way ANOVA yielded a significant effect of onset type in the analysis of response time, $F1(3, 117) = 3.33$, $MSE = 913$, $p < .03$, $\eta^2 = .079$; $F2(3,$

148) = 3.40, *MSE* = 1173, $p < .02$, $\eta^2 = .065$; for response accuracy: *F*1(3, 117) = 2.81, *MSE* = .004, $p < .05$, $\eta^2 = .067$; *F*2(3, 148) = 1.34, *MSE* = .006, $p < .27$, $\eta^2 = .027$. This effect was further investigated using Fisher PLSD tests. As in Experiment 1, the best-formed and familiar onsets with large sonority rises (e.g., *bl*) produced faster responses compared to worst-formed onsets of falling sonority, e.g., *lb*, t1(117) = 2.86, $p < .006$; *t*2(148) = 2.80, $p < .006$. This advantage of onsets with large sonority rises could be due to either the familiarity with such onsets or to their structure. As in Experiment 1, however, participants were also sensitive to the structure of onsets that are all unattested in their language: the worst-formed onsets of falling sonority (e.g., *lb*) produced slower responses relative to unattested onsets of rising sonority (e.g., *bn*, t1(117) = 2.27, $p < .03$; *t*2(148) = 2.40, $p < .02$).[2] No other contrasts were significant.

To determine whether the increase in processing demands of ill-formed onsets reflects their phonological structure, we next turned to evaluate whether the discrimination of nonidentical pair members is sensitive to their phonological similarity. Recall that a sub-group of the items consisted of pairs of nonidentical items that were matched for their orthographic resemblance, but differed on their phonological similarity (e.g., *crep-KEREP* vs. *brep-KEREP*). If participants assemble phonology from print, then their ability to discriminate among nonidentity items should depend on their phonological similarity. The results are presented in Table 1.

A 2 similarity × 4 onset type ANOVA did not yield a significant interaction (for responses time: all $F < 1$; for accuracy: *F*1(3, 117) = 2.05, *MSE* = .013, $p < .12$, $\eta^2 = .105$; *F*2(3, 28) = 3.86, *MSE* = .002, $p < .02$, $\eta^2 = .292$. An inspection of the means, however, suggested that this null result might be due to the failure to consider the effect of phonological attestation: When the monosyllabic pair member was attested, similar pairs (e.g., *clim-KELIM*) yielded more accurate responses compared to dissimilar ones (e.g., *blim-KELIM*), whereas unattested onsets produced the opposite pattern. To further investigate the effect of phonological similarity on unattested onsets, we next compared attested onsets to unattested ones (collapsed over onset type) using a two-way (2 similarity × 2 attestation) ANOVA. The interaction was highly significant: in response accuracy: *F*1(1, 39) = 7.61, *MSE* = .007, $p < .009$, $\eta^2 = .163$; *F*2(1, 30) = 11.20, *MSE* = .0016, $p < .003$, $\eta^2 = .273$; in reaction time, $F < 1$. Simple main effect analysis indicated that participants responded significantly more accurately to unattested onsets that are phonologically dissimilar relative to similar ones *F*1(1, 39) = 6.66, *MSE* = .015, $p < .02$, $\eta^2 = .161$; *F*2(1, 23) = 7.36, *MSE* = .002, $p < .02$, $\eta^2 = .236$. Attested onsets showed the opposite trend: Participants were better able to discriminate among nonidentity items that were phonologically similar *F*1(1, 39) = 4.06, *MSE* = .009, $p < .06$, $\eta^2 = .098$; *F*2(1, 7) = 8.79, *MSE* = .001, $p < .03$, $\eta^2 = .558$. This paradoxical drop in accuracy for attested items that are phonologically dissimilar—the condition that is arguably easiest to process—might suggest that the ease of phonological processing has led participants to reduce their vigilance.

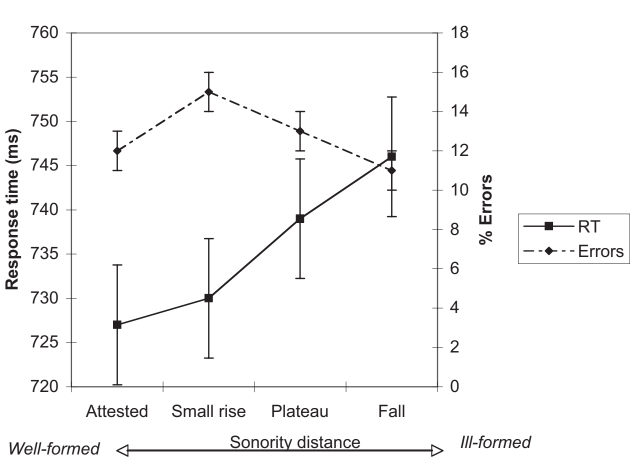

Figure 2. The effect of onset type on response time and accuracy to the nonidentity trials in Experiment 2. Bars indicate confidence intervals for the difference between the means.

Table 1
Response Accuracy (% Correct) as a Function of Phonological Similarity and Attestation in Experiment 1 (Nonidentity Trials)

	Phonological similarity	
Onset type	Similar	Dissimilar
Attested onsets	98.75	94.37
Unattested onsets		
Rise	93.12	95.00
Plateau	93.12	96.87
Fall	94.50	97.17

Crucially, however, Experiment 2 demonstrates that the ease of phonological processing depends on the ill-formedness of the onset: Ill-formed onsets require more extensive processing. The difficulties in the processing of such onsets are consistent with the proposal that they are prone to misperception (e.g., *lbif* = *lebif*) even in print.

General Discussion

In previous research, we showed that speakers are sensitive to the structure of onsets that are unattested in their language, and the perception of such onsets reflects their distribution across languages: Onsets that are under-represented across languages tend to be misperceived (Berent et al., 2007; Berent et al., 2008; Berent, 2008; Berent et al., 2009). The present research was designed to gauge the source of such misperceptions—are they due to difficulties in processing such auditory inputs or to their phonological ill-formedness, captured by their sonority distance. To this end, we examined whether the misperception of universally ill-formed onsets extends to printed words. The results of Experiments 1–2 suggest that ill-formed onsets with small sonority distances elicit

[2] Auxiliary analyses, examining the effect of presentation order (e.g., *blif-belif* vs. *belif-blif*) yielded a significant main effect of order. As in Experiment 1, trials requiring the maintenance of the monosyllabic target in working memory elicited slower, *F*1(1, 39) = 18.87, *MSE* = 3050, $p < .0001$, $\eta^2 = 326$; *F*2(1, 29) = 34.76, *MSE* = 1107, $p < .0001$, $\eta^2 = .545$) and less accurate responses, *F*1(1, 39) = 16.01, *MSE* = .018, $p < .0003$, $\eta^2 = 291$; *F*2(1, 29) = 33.59, *MSE* = .007, $p < .0001$, $\eta^2 = .555$) but this effect of order did not further interact with onset type (all $F < 1$).

additional processing: Participants took longer to distinguish ill-formed onsets from their disyllabic counterpart (e.g., *lbif-LEBIF*) compared to better-formed ones (e.g., *bnif-BENIF*). This result is consistent with the proposal that ill-formed onsets undergo grammatical repair that inserts a vowel between the onset consonants (e.g., *lbif* → *lebif*). These findings suggest that readers are sensitive to the phonological properties of unattested onsets.

Further support for this conclusion comes from auxiliary manipulations, designed to gauge the assembly of phonology from print. In each of the two experiments, monosyllables were harder to process when the order of presentation required their commitment to phonological working memory—when the monosyllable was presented first, followed by the disyllable (see Footnotes 1-2). Participants in the two experiments were also sensitive to the phonological similarity among nonidentical items with unattested onsets. Nonidentical pairs whose members were phonologically dissimilar (e.g., *cnip-CENIP; dnim-KENIM*; in Experiments 1-2, respectively) were discriminated more easily than similar pairs (e.g., *bnop-BENOP, cnim-KENIM* in Experiments 1-2, respectively). These results suggest that participants are sensitive to the phonological structure of printed words, not merely their orthographic properties.

As a whole, the results show that people have productive knowledge regarding the phonological structure of onsets that are unattested in their language. However, these findings cannot determine the precise nature of this knowledge. One possibility is that speakers possess relevant grammatical knowledge. Alternatively, the knowledge available to participants might concern only non-grammatical sources—the statistical similarity of unattested forms to the English lexicon, and the ease of their perception and production. We consider each of these explanations in turn.

According to the statistical explanation, readers experience difficulty in processing forms like *lbif* because of their infrequent statistical properties. To evaluate this possibility, we submitted the responses to nonidentity trials in the two experiments to a combined step-wise regression analysis including three steps. In the first step, we assessed the effect of three extraneous variables that are not directly related to sonority, including (a) the homorganicity of onset consonants (whether the two consonants share the same place of articulation—a property known to modulate the distribution of onsets across languages and affect their processing; Greenberg, 1978; Hallé, Segui, Frauenfelder, & Meunier, 1998); (b) the number of non-shared letters among nonidentical items (either one, in Experiment 1 or two, in some of the materials in Experiment 2) and (c) the position of the altered letter (either word internal or initial).

At the second step, we entered two sets of statistical properties corresponding to the statistical measures considered in Berent (2008). One set captures the statistical orthographic properties of the word as a whole (see Table 2), including the number of neighbors (the number of words obtained by adding, deleting or substituting one letter), their summed frequency, bigram count and bigram frequency. Neighborhood counts were based on the *Speech & Hearing Lab Neighborhood Database*, the bigram calculations were based on Solso and Juel (1980). A second set of four statistical measures concerns the combination of the onset consonants specifically. These measures include the number of four-letter words that share the item's first consonant, the summed frequency of those words, the number of four letter words that share the target's second consonants, and the summed frequency of those words. These four measures were calculated based on the *Speech & Hearing Lab Neighborhood Database*.

To assess the unique contribution of sonority distance, we forced it as the third and last step into the regression analyses. We conducted several such analyses– one analysis assessed the unique contribution of sonority across the four types of onsets; additional analyses compared responses to onsets of adjacent sonority levels (i.e., attested onsets vs. unattested rises, unattested rises vs. pla-

Table 2
The Statistical Properties of the Materials Used in Experiments 1–2

			Whole word properties				Cluster properties			
Exp.	Statistic	Cluster type	Bigram count	Bigram frequency	#of neighbors	Neighbors' frequency	#C1	C1 frequency	#C2	C2 frequency
1	Mean	Attested	33.37	1212.93	2.43	55.03	98.33	11171.87	69.20	3851.77
		Small rises	12.67	391.40	0.50	34.27	98.33	11171.87	32.33	5165.13
		Plateaus	10.60	357.77	0.73	47.73	98.33	11171.87	13.33	427.07
		Falls	11.97	378.80	0.57	20.13	89.80	5954.83	13.53	374.50
	SD	Attested	29.16	1564.40	2.97	91.81	21.82	11004.21	32.79	2709.78
		Small rises	12.67	456.02	1.04	107.66	21.82	11004.21	26.16	5632.96
		Plateaus	10.38	455.32	1.68	110.66	21.82	11004.21	6.18	364.29
		Falls	13.01	512.60	1.10	67.76	8.15	3461.33	5.56	299.30
2	Mean	Attested	37.74	1264.39	2.37	85.18	107.21	11033.63	71.53	3937.18
		Small rises	11.53	360.16	0.55	31.13	107.24	11609.84	30.47	5333.63
		Plateaus	10.13	292.82	0.66	35.32	106.63	15941.74	13.74	349.11
		Falls	13.37	447.95	0.66	12.08	90.37	6069.11	15.00	401.53
	SD	Attested	31.83	1505.95	2.76	181.32	2.97	10900.91	31.53	2620.44
		Small rises	11.58	432.24	0.92	96.76	2.96	11258.30	23.86	5699.01
		Plateaus	9.75	396.87	0.88	89.29	1.73	12549.79	4.00	313.12
		Falls	18.19	642.81	1.05	25.86	8.35	3405.16	3.34	284.41

Note. Exp. = Experiment; #of neighbors = number of neighbors; #C1 and #C2 = number of words sharing the target's initial or second letter, respectively; C1 frequency and C2 frequency = summed frequency of the words sharing the target's first and second letter, respectively.

teaus and plateaus vs. fall). The results (see Table 3) suggest that onset type accounted for unique variance after controlling for the effect of homorganicity, overlap, and statistical properties. Specifically, the unique effect of onset type was significant across the four types of onsets (in both response time and accuracy) and in the comparison of plateaus versus falls (in response time). There were also marginally significant effects of onset type in the comparisons of attested onsets versus rises (in response time) and rises versus plateaus (in response accuracy).

In a second set of analyses, we examined the unique contribution of statistical properties, entered in the last step (see Table 4). Across the four onset types, statistical properties uniquely predicted overall response accuracy after controlling for the contribution of onset type. This effect, however, was mainly due to the comparison of sonority rises to attested onsets. Statistical properties did not uniquely account for any of the comparisons involving only unattested onsets. Thus, responses to unattested onsets are uniquely explained only by their grammatical phonological structure (see Table 3), not their statistical properties (see Table 4).

The present results also do not lend themselves to phonetic explanations. An acoustic phonetic account is obviously ruled out by the use of printed materials. Likewise, our findings are not readily explained by the possibility that the cost associated with processing ill-formed onsets might be solely due to the inability to articulate these items (Redford, 2008). Indeed, there is no evidence that participants in our experiments attempted to articulate the stimuli (either overtly or covertly). Moreover, an articulatory explanation does not account for the emergence of similar findings with auditory materials, presented at faster asynchrony (an asynchrony of 1,500 ms, which presumably, reduced the potential for articulation), nor does it explain why the aversion to ill-formed onsets affects the processing of their disyllabic counterparts (e.g., *lebif* vs. *benif*)—forms that lack clusters altogether, and consequently, pose no special challenges for either auditory perception or articulation (Berent et al., 2007; Berent et al., 2008).

Unlike the statistical and phonetic accounts, a grammatical phonological account can easily accommodate the persistent misperception of ill-formed onsets across modalities. In this view, the ill-formedness of such onsets triggers their repair (as disyllabic) and protects their disyllabic counterparts from misperception (e.g., an aversion of *lbif* renders it a less likely competitor to the representation of the input *lebif*).

These conclusions also carry some important implications to reading research. The convergence between the sensitivity of hearers and readers to broad grammatical restrictions might suggest that the representations computed in the two modalities are isomorphic, and they are both constrained by broad grammatical restrictions. Nonetheless, the quality and specificity of the phonological representation assembled to print might depend on task dynamics. Previous experiments using the lexical decision task (Berent, 2008) indicate that people attend to broad grammatical properties of unattested onsets with given auditory materials, but not with printed stimuli—stimuli that also elicited faster responses. The reemergence of these grammatical effects under the longer SOA in our present experiments suggests that the discrepancy between the findings with auditory and printed materials in previous research is probably due to differences in the time-course of processing within the two modalities, rather than a principled inability to compute grammatical phonological structure from print.

Nonetheless, the effects observed in reading are weaker than those previously documented with spoken language. The present

Table 3
Step-Wise Linear Regression Analysis of Responses in Experiments 1–2 Forcing Onset Type in the Last Step

Comparison	Step	Predictor	R^2 change	F change	df	$p <$
Response time						
All onsets	1	Homorganicity, overlap	0.222	25.38	3,267	0.001
	2	Statistical properties	0.026	1.14	8,259	0.339
	3	Type	0.023	8.09	1,258	0.006
Attested vs. rise	1	Homorganicity, overlap	0.325	31.74	2,132	0.001
	2	Statistical properties	0.123	3.46	8,124	0.002
	3	Type	0.017	3.88	1,123	0.060
Rise vs. plateau	1	Homorganicity, overlap	0.249	14.51	3,131	0.001
	2	Statistical properties	0.040	<1	8,123	
	3	Type	0.000	<1	1,122	
Plateau vs. fall	1	Homorganicity, overlap	0.094	6.92	2,133	0.001
	2	Statistical properties	0.040	<1	8,125	
	3	Type	0.028	4.12	1,124	0.050
Accuracy						
All onsets	1	Homorganicity, overlap	0.407	61.11	3,267	0.000
	2	Statistical properties	0.042	2.45	8,259	0.014
	3	Type	0.019	9.27	1,258	0.003
Attested vs. rise	1	Homorganicity, overlap	0.406	45.18	2,132	0.001
	2	Statistical properties	0.127	4.21	8,124	0.001
	3	Type	0.000	<1	1,123	
Rise vs. plateau	1	Homorganicity, overlap	0.468	38.72	3,132	0.001
	2	Statistical properties	0.042	1.31	8,124	0.242
	3	Type	0.012	2.98	1,123	0.088
Plateau vs. fall	1	Homorganicity, overlap	0.414	46.88	2,133	0.001
	2	Statistical properties	0.053	1.56	8,125	0.143
	3	Type	0.004	<1	1,124	

Table 4
Step-Wise Linear Regression Analysis of Responses in Experiments 1–2 Forcing Statistical Properties in the Last Step

Comparison	Step	Predictor	R^2 change	*F* change	*df*	*p* <
Response time						
All onsets	1	Homorganicity, overlap	0.222	25.38	3,267	0.001
	2	Type	0.015	5.20	1,266	0.030
	3	Statistical properties	0.034	1.52	8,258	0.160
Attested vs. rise	1	Homorganicity, overlap	0.325	31.74	2,132	0.001
	2	Type	0.006	1.17	1,131	0.290
	3	Statistical properties	0.134	3.85	8,123	0.001
Rise vs. plateau	1	Homorganicity, overlap	0.249	14.51	3,131	0.001
	2	Type	0.001	<1	1,130	
	3	Statistical properties	0.039	<1	8,122	
Plateau vs. fall	1	Homorganicity, overlap	0.094	6.92	2,133	0.001
	2	Type	0.020	2.98	1,132	
	3	Statistical properties	0.048	<1	8,124	
Accuracy						
All onsets	1	Homorganicity, overlap	0.407	61.11	3,267	0.001
	2	Type	0.000	<1	1,266	
	3	Statistical properties	0.061	3.67	8,258	0.001
Attested vs. rise	1	Homorganicity, overlap	0.406	45.18	2,132	0.001
	2	Type	0.035	8.10	1,131	0.006
	3	Statistical properties	0.092	3.04	8,123	0.005
Rise vs. plateau	1	Homorganicity, overlap	0.468	38.72	3,132	0.001
	2	Type	0.006	1.54	1,131	0.220
	3	Statistical properties	0.047	1.51	8,123	0.170
Plateau vs. fall	1	Homorganicity, overlap	0.414	46.89	2,133	0.001
	2	Type	0.002	<1	1,132	
	3	Statistical properties	0.055	1.61	8,124	0.130

experiments with printed words yielded reliable effects of onset type only relative to highly ill-formed onsets of falling sonority—comparisons involving only onsets of rising or level sonority (to which hearers in our previous experiments were highly tuned) did not reach significance with printed materials. Such differences could challenge the isomorphism of the representations assembled to printed and spoken language. Alternatively, the weaker effects of sonority with printed materials might be due to methodological factors. Unlike hearers, readers can perform the identity judgment by simply monitoring for the letter *e* (the pretonic vowel in the disyllabic forms, e.g., *lebif*), a strategy they could bring to perfection by attending to the accuracy feedback provided in the present experiments (but absent in previous research). Response accuracy in Experiments 1–2 was indeed far higher compared to the results with auditory materials (40%, see Berent et al., 2007; Experiment 3), and this might have attenuated the sensitivity of the task to fine-grained distinctions among adjacent sonority distances.

Regardless of whether the grammatical knowledge available to readers concerns sonority profile, broadly, or a narrow restriction against sonorant-initial onset, specifically, the results suggest that the representation available to readers is constrained by general phonological knowledge that appeals to sub-segmental regularities (see also Lukatela et al., 2007). Such phonological knowledge may well be grounded in the phonetic properties of the input (Hayes & Steriade, 2004): Forms like *lbif* might be grammatically ill-formed precisely because they are difficult to perceive and articulate (Wright, 2004). Once acquired, however, such grammatical constraints might apply irrespective of the phonetic characteristics of the input, and consequently, they could shape the representation of print. The finding that such knowledge is observed for onsets unattested in one's language, and mirrors the universal restrictions on such clusters, is consistent with the proposal that all speakers possess a universal set of grammatical phonological restrictions.

References

Berent, I. (2008). Are phonological representations of printed and spoken language isomorphic? Evidence from the restrictions on unattested onsets. *Journal of Experimental Psychology: Human Perception & Performance, 34,* 1288–1304.

Berent, I., Lennertz, T., Jun, J., Moreno, M. A., & Smolensky, P. (2008). Language universals in human brains. *Proceedings of the National Academy of Sciences, 105,* 5321–5325.

Berent, I., Lennertz, T., Smolensky, P., & Vaknin-Nusbaum, V. (2009). Listeners' knowledge of phonological universals: Evidence from nasal clusters. *Phonology, 26,* 75–108.

Berent, I., Steriade, D., Lennertz, T., & Vaknin, V. (2007). What we know about what we have never heard: Evidence from perceptual illusions. *Cognition, 104,* 591–630.

Blevins, J. (2004). *Evolutionary phonology* Cambridge, UK: Cambridge University Press.

Browman, C. P., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology, 6,* 201–251.

Buchwald, A. B., Rapp, B., & Stone, M. (2007). Insertion of discrete phonological units: An articulatory and acoustic investigation of aphasic speech. *Language and Cognitive Processes, 22,* 910–948.

Chomsky, N. (1965). *Aspects of the theory of syntax.* Cambridge, MA: MIT Press.

Chomsky, N. (1980). *Rules and representations.* New York: Columbia University Press.

Clements, G. N. (1990). The role of the sonority cycle in core syllabification. In J. Kingston & M. Beckman (Eds.), *Papers in laboratory phonology I: Between the grammar and physics of speech* (pp. 282–333). Cambridge, UK: Cambridge University Press.

Davidson, L. (2006). Phonotactics and articulatory coordination interact in phonology: Evidence from nonnative production. *Cognitive Science, 30,* 837–862.

Dupoux, E., Kakehi, K., Hirose, Y., Pallier, C., & Mehler, J. (1999). Epenthetic vowels in Japanese: A perceptual illusion? *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1568–1578.

Dupoux, E., Pallier, C., Kakehi, K., & Mehler, J. (2001). New evidence for prelexical phonological processing in word recognition. *Language and Cognitive Processes, 5,* 491–505.

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.

Fodor, J. (1983). *The modularity of mind.* Cambridge, MA: MIT Press.

Fowler, C., Treiman, R., & Gross, J. (1993). The structure of English syllables and polysyllables. *Journal of Memory and Language, 32,* 115–140.

Glushko, R. (1979). The organization and activation of orthographic knowledge in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 674–691.

Greenberg, J. H. (1978). Some generalizations concerning initial and final consonant clusters. In J. H. Greenberg, C. A. Ferguson, & E. A. Moravcsik (Eds.), *Universals of Human Language* (Vol. 2, pp. 243–279). Stanford, CA: Stanford University Press.

Hallé, P., Segui, J., Frauenfelder, U. H., & Meunier, C. (1998). The processing of illegal consonant clusters: A case of perceptual assimilation? *Journal of Experimental Psychology: Human Perception and Performance, 24,* 592–608.

Hallé, P. A., Dominguez, A., Cuetos, F., & Segui, J. (2008). Phonological mediation in visual masked priming: Evidence from phonotactic repair. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 177–192.

Hayes, B., & Steriade, D. (2004). A review of perceptual cues and cue robustness. In B. Hayes, R. M. Kirchner, & D. Steriade (Eds.), *Phonetically based phonology* (pp. 1–33). Cambridge, UK: Cambridge University Press.

Lindblom, B. (1998). Systemic constraints and adaptive change in the formation of sound structure. In J. R. Hurford, M. Studdert-Kennedy, & C. Knight (Eds.), *Approaches to the Evolution of Language-Social and Cognitive Bases* (pp. 242–263). Cambridge, UK: Cambridge University Press.

Lukatela, G., Eaton, T., Moreno, M. A., & Turvey, M. T. (2007). Equivalent inter- and intramodality long-term priming: Evidence for a common lexicon for words seen and words heard. *Memory & Cognition, 35,* 781–800.

Lukatela, G., & Turvey, M. T. (1990). Phonemic similarity effects and prelexical phonology. *Memory and Cognition, 18,* 128–152.

Lukatela, G., & Turvey, M. T. (1993). Similar attentional, frequency and associative effects for the pseudohomophones and words. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 166–178.

MacNeilage, P. F., & Davis, B. L. (2000). On the origin of internal structure of word forms. *Science,* 527–531.

Moreton, E. (2008). Analytic bias and phonological typology. *Phonology, 25,* 83–127.

Ohala, J. J. (1990). Alternatives to the sonority hierarchy for explaining segmental sequential constraints. *Papers from the Regional Meetings, Chicago Linguistic Society, 2,* 319–338.

Oudeyer, P. Y. (2005). The self-organization of speech sounds. *Journal of Theoretical Biology, 233,* 435–449.

Parker, S. (2002). *Quantifying the sonority hierarchy.* Unpublished doctoral dissertation, University of Massachusetts, Amherst, MA.

Perfetti, C. A., & Bell, L. (1991). Phonemic activation during the first 40 ms. of word identification. Evidence from backward masking and priming. *Journal of Memory and Language, 30,* 473–485.

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

Pitt, M. A. (1998). Phonological processes and the perception of phonotactically illegal consonant clusters. *Perception & Psychophysics, 60,* 941–951.

Prince, A., & Smolensky, P. (1993/2004). *Optimality theory: Constraint interaction in generative grammar.* Malden, MA: Blackwell.

Redford, M. A. (2008). Production constraints on learning novel onset phonotactics. *Cognition, 107,* 785–816.

Rumelhart, D. E., & McClelland, J. L. (1986). On learning past tense of English verbs: Implicit rules or parallel distributed processing? In J. L. McClelland, D. E. Rumelhart, & T. P. R. Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2, pp. 216–271). Cambridge MA: MIT Press.

Smolensky, P. (2006). Optimality in phonology II: Markedness, feature domains, and local constraint conjunction. In P. Smolensky & G. Legendre (Eds.), *The harmonic mind: From neural computation to optimality-theoretic grammar* (Vol. 2. Linguistic and Philosophical Implications, pp. 27–160). Cambridge, MA: MIT Press.

Smolensky, P., & Legendre, G. (2006). Harmony optimization and the computational architecture of the mind/brain. In P. Smolensky & G. Legendre (Eds.), *The harmonic mind: From neural computation to optimality-theoretic grammar* (Vol. 1: Cognitive architecture, pp. 59–61). Cambridge, MA: MIT Press.

Solso, R. L., & Juel, C. L. (1980). Positional frequency and versatility of bigrams for two- through nine-letter English words. *Behavior Research Methods & Instrumentation, 12,* 297–343.

Speech & Hearing Lab Neighborhood Database. Retrieved from the Washington University in St. Louis Web site: http://128.252.27.56/Neighborhood/Home.asp

Steriade, D. (1982). *Greek prosodies and the nature of syllabification* (Doctoral dissertation). MIT, Cambridge. Retrieved from MITWPL, Department of Linguistics and Philosophy, MIT.

Theodore, R. M., & Schmidt, A. M. (2003). Perceptual prothesis in native Spanish speakers. *Journal of the Acoustical Society of America, 113,* 256.

Treiman, R. (1984). On the status of final consonant clusters in English syllables. *Journal of Verbal Learning and Verbal Behavior, 23,* 343–356.

Treiman, R., Bowey, J., & Bourassa, D. (2002). Segmentation of spoken words into syllables by English-speaking children as compared to adults. *Journal of Experimental Child Psychology, 83,* 213–238.

Treiman, R., & Danis, C. (1988). Syllabification of intervocalic consonants. *Journal of Memory and Language, 27,* 87–104.

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

Wilson, C. (2006). Learning phonology with substantive bias: An experimental and computational study of Velar Palatalization. *Cognitive Science, 30,* 945–982.

Wright, R. (2004). A review of perceptual cues and robustness. In D. Steriade, R. Kirchner, & B. Hayes (Eds.), *Phonetically based phonology* (pp. 34–57). Cambridge, UK: Cambridge University Press.

Zec, D. (2007). The syllable. In P. de Lacy (Ed.), *The Cambridge handbook of phonology* (pp. 161–194). Cambridge, UK: Cambridge University Press.

Zuraw, K. (2007). The role of phonetic knowledge in phonological patterning: Corpus and survey eivdence from Tagalog infixation. *Language, 83,* 277–316.

(*Appendices follow*)

Appendix A

The Materials Used in Experiment 1

	Unattested omset		
Attested onset	Rise	Plateau	Fall
blif	bwif	bdif	lbif
brop	bnop	bdop	rgop
drif	dlif	dbif	rdif
drish	dnish	dgish	rbish
drof	dlof	dgof	rdof
drup	dnup	dbup	rdup
dwib	dmip	dgip	mdip
dwup	dmup	dgup	mdup
glep	gmep	gdep	lgep
glon	gmon	gbon	lfon
gref	gmef	gbef	rgef
gwid	gmit	gbit	mgit
klef	kmef	ktef	lketh
kraf	kmaf	kpaf	rgaf
plik	pnik	pkik	ltik
praf	pnaf	ptaf	rpaf
trap	tmap	tpap	rpap
tref	tnef	tpif	rtef
trok	tnok	tkok	rtok
truf	tluf	tkuf	rtuf
twaf	tmaf	tpaf	mtaf
twep	tlep	tkep	mtep
twog	tmok	tpok	mtok
twuk	tnuk	tguk	mguk
clim	cnim	cpim	lpim
clop	cmup	ctop	ltop
crek	cnek	cteg	rtek
crep	cmep	ctep	rkep
crik	cnik	ctig	rkik
cwug	cnuk	cpok	mcuk

Appendix B

The Materials Used in Experiment 2

	Unattested onset		
Attested onset	Rise	Plateau	Fall
blif	bwif	bdif	lbif
brop	bnop	bdop	rdop
drif	dlif	dbif	lpim
drof	dlof	dbof	rtek
dwib	dmip	dbip	rdif
dwup	dmup	dtup	mdip
drup	dnup	dbup	mdup
drish	dnish	dbish	rdup
dlep	dmep	bdep	rbish
dlon	tmon	dbon	ldep
dref	dmef	dbef	rdef
dwid	dmit	dpit	mdit
plik	pnik	pkik	rdaf
praf	pnaf	ptaf	ltik

(*Appendices continue*)

Appendix B (*continued*)

	Unattested onset		
Attested onset	Rise	Plateau	Fall
truf	tluf	tkuf	rpaf
twep	tlep	tkep	rtuf
trok	tnok	tkok	mtep
twaf	tmaf	tpaf	rtok
tref	tnef	tpif	mtaf
twuk	tnuk	tduk	rtef
trap	tmap	tpap	mduk
twog	tmok	tpok	rpap
clim	cnim	pcam	rcof
crek	cnek	tcog	lcon
cleth	cmef	tcof	lcoth
craf	cmaf	pcaf	rcak
crik	cnik	tcag	mcuk
cwug	cnuk	pcok	lcop
clop	cmup	tcop	rcup
crep	cmep	tcup	mcok
blim	dnim	ptam	rpof
prek	pnek	tdog	lton
dleth	tmef	tbof	ldoth
traf	dmaf	pdaf	rpak
drik	bnik	tpag	mbuk
pwug	pnuk	pdok	ldop
tlop	dmup	tbop	rdup
brep	tmep	tdup	mbok

Received October 26, 2007
Revision received July 29, 2009
Accepted August 6, 2009 ■