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Are Phonological Representations of Printed and Spoken Language Isomorphic? Evidence From the Restrictions on Unattested Onsets

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Are the phonological representations of printed and spoken words isomorphic? This question is addressed by investigating the restrictions on onsets. Cross-linguistic research suggests that onsets of rising sonority are preferred to sonority plateaus, which, in turn, are preferred to sonority falls (e.g., *bnif* $\succ$ *bdif* $\succ$ *lbif*). Of interest is whether these grammatical preferences constrain the recognition of auditory and printed words by speakers of English—a language in which such onsets are unattested. Five experiments compare phonological lexical decision responses to nonwords, including unattested onsets, through either aural or visual presentation. Results suggest that both hearers and readers are sensitive to the phonotactics of unattested onsets. However, the phonotactic generalizations of hearers and readers differ on their scope and source. Hearers differentiated all three types of onsets (e.g., *bnif, bdif,* and *lbif*), and their behavior implicated both grammatical and statistical constraints. In contrast, readers were able to differentiate only those structures similar to attested English onsets from dissimilar structures (i.e., *bnif* vs. *bdif* or *lbif*), and their preferences reflected statistical knowledge alone. These findings suggest that the phonological representations informing lexical decision to spoken and printed words are not isomorphic.

Keywords: phonology, markedness, sonority, reading, speech perception

Many complex cognitive skills are erected on domain-specific systems of core knowledge (Spelke, 2000). Reading is a case in point. Reading is the skill of mapping spelling onto phonological representations (Perfetti, 1985). There is ample evidence that readers routinely assemble phonological representations from print, and such representations specify various aspects of linguistic knowledge (e.g., Berent, Shimron, & Vaknin, 2001; Treiman, Fowler, Gross, Berch, & Weatherston, 1995). However, the nature of such knowledge and representations is not entirely clear. Is the computation of phonology from print shaped by the same knowledge available in the representation of spoken language?[1] Is the phonological representation from print isomorphic to the one computed on spoken language?

Understanding the linguistic phonological constraints on reading requires an account of linguistic knowledge and representations. These, however, are subject to an ongoing debate. Consider, for example, the restrictions on the structure of onset clusters (e.g., *bl* in *block*). Most English speakers would agree that *blif* is a possible English word whereas *lbif* is not. Although such intuitions are uncontroversial, the knowledge guiding these judgments is highly contentious. One view attributes phonological knowledge to a domain-general mechanism of statistical learning that tracks the co-occurrence of linguistic tokens (e.g., specific phonemes, such as *b* and *l*) in speakers' linguistic experience (e.g., Dell, Reed, Adams, & Meyer, 2000; Rumelhart & McClelland, 1986). For example, the preference for *blif* over *lbif* might be due to the fact that many English words begin with a *bl*, whereas none begin with *lb*. According to an alternative account, such intuitions might be due to grammatical knowledge that is potentially specific to language (Chomsky, 1980; Pinker, 1994). Grammatical knowledge encodes the constituent structure of mental variables (e.g., Fodor & Pylyshyn, 1988; Marcus, 2001; Pinker & Prince, 1988; Smolensky, 2006). Specifically, the grammatical knowledge of onset structure might concern two classes of segments, defined by the variables obstruents (e.g., *b, p*) and sonorants (e.g., *l, r*). Unlike statistical knowledge, grammatical knowledge extends to all members of a class equally, irrespective of their frequency in speakers' linguistic experience. For example, knowledge regarding the class of obstruents might apply equally to the frequent English phoneme *b* and to the foreign phoneme *x* (as in *ch*anukkah; see Berent, Marcus, Shimron, & Gafos, 2002). Moreover, several linguistic theories propose that all grammars include universal restrictions on language structure (e.g., Chomsky, 1980). Optimality theory (Prince & Smolensky, 2004) further predicts that speakers possess universal constraints regarding structures that may be unattested in their language. In the previous example, the dispreference for *lb* might reflect a universal grammatical constraint that identifies sonorant–obstruent onsets as dispreferred relative to obstruent–

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[1] Here I make the standard assumption that mental processes are computations on mental representations whose structure is shaped by knowledge (Fodor & Pylyshyn, 1988). Accordingly, differences in behavior (e.g., responses to spoken vs. printed stimuli) must reflect differences in the representation and, possibly, knowledge consulted during task performance.

sonorant onsets (Smolensky, 2006). Crucially, such universal preferences might be present even if *bl* and *lb* are both absent in the language.

Past research has attempted to probe for such universal preferences in the representation of spoken language (e.g., Berent, Steriade, Lennertz, & Vaknin, 2007; Davidson, 2006a; Moreton, 2002; Wilson, 2006; Zuraw, 2005). Here, I examine whether universal grammatical constraints on spoken language extend to the representation of print. My case study concerns the above-mentioned restrictions on onset clusters. Across languages, certain onsets are preferred to others: Onsets such as *bn* are preferred to onsets such as *bd*, which, in turn, are preferred to onsets such as *lb* (e.g., Smolensky, 2006). Previous research has shown that English speakers are sensitive to the entire hierarchy of onsets (e.g., *bn* ≻ *bd* ≻ *lb*) even though none of these onsets is attested in their lexicon (Berent et al., 2007). These findings suggest that speakers are equipped with broad preferences concerning onset structure. The goal here is determine whether such preferences constrain silent reading. This, in turn, might help to determine whether the representations of printed and spoken words are isomorphic.

The isomorphism of phonological representations computed across different modalities is potentially informative not only for reading research but also for phonological theory. Recent work in phonology underscores the articulatory and auditory basis of sound patterns (e.g., Browman & Goldstein, 1989; Hayes, Kirchner, & Steriade, 2004). The intimate link between phonology and phonetics raises the possibility that many phonological constraints are conditions relating to phonetic implementation factors: perceptibility, effort, or articulatory timing. Silent reading offers a unique opportunity to dissociate phonological knowledge from constraints that are strictly linked to phonetic processing. A convergence between the representation of spoken and printed language would strongly implicate a common representational system that is general with respect to stimulus properties. A divergence might indicate among other possibilities that certain phonological computations are contingent on the phonetic properties of auditory inputs.

Before describing the manipulation, it is first necessary to review the restrictions on onset structure (summarizing the discussion in Berent et al., 2007). The next sections proceed to test whether such restrictions shape the representation of print.

Sonority-Related Constraints on the Representation of Spoken Language

Many languages allow syllables that begin with a consonant cluster. However, the range of admitted clusters is strictly constrained. English, for example, allows combinations such as *bl* but disallows combinations like *lb*. The restrictions on the co-occurrence of consonants have been characterized in terms of their sonority (Blevins, 1995; Clements, 1990)—a scalar property that correlates with the loudness of a segment (Ladefoged, 1975). Louder segments (e.g., *l*) are more sonorous than quieter segments (e.g., *b*). Although the precise definition of sonority is debated (e.g., J. J. Ohala, 1990), most linguists agree that vowels and glides (e.g., *a* and *e* vs. *y* and *w*, respectively) are the most sonorous segments, followed by liquids (e.g., *l, r*), nasals (e.g., *n, m*), and obstruents (e.g., *s, sh, z, f, v, th, p, b, t, d, k, g*).

One can use the sonority scale to capture the properties of the clusters allowed by a given language. For example, English clusters such as *bl* manifest an abrupt, large rise in sonority from the obstruent *b* to the liquid *l*, whereas Russian allows even onsets of falling sonority (e.g., *rz*han "zealous," a liquid–obstruent cluster). Although languages differ on the sonority profiles they allow, the types of allowable profiles are systematically constrained. First, large sonority rises are more frequent than smaller ones (including plateaus and falls). Second, languages that tolerate small sonority rises tend to allow larger ones, but not vice versa (Berent et al., 2007).

Such distributional asymmetries are of interest because they might reflect universal grammatical restrictions. Prince and Smolensky (2004) proposed that there exists a set of universal markedness restrictions, present in the grammar of all individual speakers. Markedness restrictions are grammatical constraints that disfavor certain linguistic structures (e.g., syllables beginning with a complex onset, such as *pl*ay). Structures that violate markedness constraints are *marked*, that is, tagged by the grammar, in contrast to *unmarked* structures, which escape constraint violation and are consequently more frequent. In the present case, the grammar of all speakers might include statements that render onsets with sonority falls (e.g., *lb*) as more marked than onsets with sonority plateaus (e.g., *bd*), which are more marked than onsets with small rises (e.g., *bn*); small rises, in turn, are less marked than large rises (e.g., *bl*)—the least marked onset type on the sonority hierarchy.

Of interest, then, is whether the entire hierarchy of onset structure is, in fact, available to all speakers and whether it constrains reading. To address these questions, it is necessary to examine whether people are sensitive to the markedness of onsets that are unattested in their language. Although there has been much research investigating sonority-related preferences, most of the existing evidence concerns clusters that are attested in one's language (e.g., Gierut, 1999; D. K. Ohala, 1999; Romani & Calabrese, 1998; Treiman, 1984). The handful of studies investigating the production of unattested onsets suggests that onsets that are universally unmarked are judged as more frequent (Pertz & Bever, 1975) and are easier to produce (Broselow & Finer, 1991; Davidson, 2000). Other studies have compared the perception of unattested clusters with other clusters, either attested (Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Dupoux, Pallier, Kakehi, & Mehler, 2001; Hallé, Segui, Frauenfelder, & Meunier, 1998; Massaro & Cohen, 1983; Pitt, 1998) or unattested (Moreton, 2002). Their findings demonstrate that clusters that are both marked and unattested tend to be misperceived compared with less marked, typically attested clusters, but because markedness is typically covaried with familiarity and assessed by only a handful of items, it is unclear whether the misperception of such items is due to their sonority profile, their unfamiliar character, or some other idiosyncratic property.

A recent investigation (Berent et al., 2007) specifically links the misperception of marked clusters to their sonority profile. Berent and colleagues examined the perception of auditory clusters with a small sonority rise, plateau, or fall (e.g., *bnif, bdif,* and *lbif,* respectively) by speakers of English—a language in which these clusters are unattested. The results showed that speakers were more likely to misperceive marked clusters as disyllabic (e.g., *lbif* as *lebif*)[2] compared with relatively unmarked clusters (e.g., *bdif*). Specifically, in a syllable judgment task (e.g., participants had to decide whether *lbif* has one syllable or two), marked clusters were more likely to be classified as disyllabic. Likewise, marked clusters were misperceived as identical to their disyllabic counterparts in a task eliciting identity judgments (e.g., participants had to decide whether *lbif* is identical to *lebif*). Berent and colleagues attributed the misperception of marked onsets to a process that repairs illicit clusters by the epenthesis of a schwa (e.g., *lbif* → *lebif*)—a process seen also in inflection (*buss* + *s* → *busses*; see Anderson, 1974). Several aspects of the results suggest that the epenthetic representation of marked onsets is unlikely to result from an inability to encode their surface phonetic form. Moreover, the effect of markedness remained significant even after controlling for various statistical properties of the items by means of a regression analysis. Accordingly, the systematic misperception of marked clusters might reflect grammatical preferences (i.e., the ranking of the markedness constraints banning such clusters above constraints that ensure their faithful encoding; see also Gierut, 2004; Pater, 2004). Such preferences favor unmarked clusters over marked ones even when all clusters are unattested in the language.

Does Grammatical Sonority-Related Knowledge Constrain Silent Reading?

The present research seeks to determine whether the sensitivity to the structure of unattested onsets generalizes to silent reading. Readers' sensitivity to onset structure is gauged with the visual lexical decision task—a task that has been frequently used in reading research. To interpret the findings with printed words, however, it is necessary to evaluate them against a comparable task with aural material. Accordingly, the present investigation compared the sensitivity of English speakers to the markedness of auditory and visual nonwords by means of parallel experiments with visual and auditory materials. In each trial, participants were presented with a stimulus, either printed or spoken, and they were asked to determine whether this stimulus is an existing English word (for auditory stimuli) or sounds like one (for printed stimuli). To encourage the assembly of phonology from print, I used pseudohomophones (e.g., *klip*) for all visual targets. Of interest are the responses to nonword foils, especially those with unattested onsets. The following experiments investigate whether phonotactic preferences for novel onsets depend on input modality, examine the knowledge informing such preferences, gauge their scope, and probe their effect on the perception of marked onsets. In so doing, I address the following questions:

1. *Does the sensitivity to phonotactics depend on input modality?* The primary question of interest here is whether speakers' sensitivity to phonotactics is modulated by stimulus modality. If the phonological representation assembled from print is isomorphic to the one computed from the acoustic signal, then similar phonotactic preferences should emerge in the two modalities. Differences would suggest that responses to auditory and printed words in these experiments are informed by distinct phonological representations

2. *The nature of phonotactic knowledge*. A second question concerns the nature of phonotactic knowledge available to participants: Is the distinction among onset types determined by grammatical knowledge related to their sonority or by their statistical properties? Previous research (Berent et al., 2007) gauged the contribution of grammatical sonority-related knowledge by using tasks that require an explicit phonological judgment (e.g., syllable judgment, identity judgment). Of interest here is whether such knowledge constrains online responses to auditory and printed words in lexical decision. The following experimental investigation first probes for the scope of phonotactic preferences; their source (i.e., grammatical or statistical) will then be assessed by means of regression analyses presented in the General Discussion.

3. *The scope of sonority-related generalizations*. In view of the rapid, superficial discrimination required for lexical decision (e.g., Balota & Chumbly, 1984), it is conceivable that the scope of phonotactic knowledge tapped by this task is reduced compared with the tasks used in previous research (Berent et al., 2007), which elicited explicit judgments of onset structure. To quantify speakers' sensitivity to the phonotactic properties of novel onsets, the following experiments compare three types of unattested onsets that differ in their structural and statistical similarity to English onsets. One type of onset has a small sonority rise (e.g., *bnif*)—a profile similar to the structural and statistical properties of English onsets, which likewise rise in sonority (albeit to a larger extent) and include an obstruent and a sonorant in the first and second positions. The two other types of onsets have either a sonority plateau (e.g., *bdif*) or a fall in sonority (e.g., *lbif*). Not only are onsets with such sonority profiles disallowed in English,[3] but their statistical properties differ from those of onsets of rising sonority. A distinction among these clusters thus requires a broader generalization. Of interest is whether such generalizations are available to speakers and readers in the lexical decision task.

If lexical decision allows for the computation only of coarse phonotactic distinctions (either grammatical or statistical), then participants might exhibit a narrow preference for unattested onsets of rising sonority (onsets that resemble English clusters), but fail to distinguish among onsets with plateaus and falls (which are less similar to English onsets). To the extent that lexical decision responses are constrained by broad, fine-grained phonotactic distinctions, unattested onsets with a sonority plateau (e.g., *bdif*) should be favored over those with a sonority fall (e.g., *lbif*).

4. *The scope of repair*. The predictions so far have concerned speakers' preferences for novel clusters, but they have not specified how these preferences might modulate responses to such nonwords in the lexical decision task. It is well known that ill-formed foils are easier to reject (e.g., Stone & Van Orden, 1993), and it is also clear that marked onsets are inherently ill-formed. However, previous research has demonstrated that marked onsets are not represented faithfully. Instead, they are systematically repaired in perception as disyllabic forms with a simple onset (e.g., *lbif* → *lebif*; Berent et al., 2007)—forms that are preferred (i.e., grammatically less marked and statistically more frequent) relative to complex ones (Prince & Smolensky, 2004). Because the effect of markedness is modulated by repair, and

[2] In what follows, I use an orthographic transcription such as *lebif* to indicate the phonetic representation [ləbIf], with a reduced initial vowel.

[3] The only exception to this generalization is the class of *s-stop* onsets. Because these onsets present an exception to the sonority restrictions of many languages, they will not be discussed further (for discussions on their status, see Blevins, 1995; Selkirk, 1982; Wright, 2004).

because the use of repair in online lexical decisions is unknown a priori, I consider three general scenarios regarding the scope of repair and its effect on the markedness manipulation:

> No repair: One possibility is that lexical decision response is utterly unaffected by repair. If speakers are nonetheless sensitive to markedness, then nonwords with marked onsets should be perceived as less wordlike (i.e., easier to reject) than unmarked ones.

> Broad repair: A second possibility is that lexical decision is broadly sensitive to repair. As markedness increases, so, too, should the likelihood of repair. Because the repaired output is preferred to any type of onset cluster, marked clusters should be paradoxically harder to reject than unmarked clusters.

> Repairing the most marked: A third possibility is that lexical decision allows for repairing only the most marked onsets of falling sonority, a possibility discussed in detail below. For now, suffice it to note that such a scenario will result in a complex nonlinear relationship between markedness and rejection difficulty: Repaired onsets of falling sonority should be harder to reject than the unrepaired, less marked onsets with plateaus. Conversely, onsets with sonority plateaus should be easier to reject than less marked onsets of rising sonority, as both are unrepaired.

Although the direction of phonotactic effects cannot be determined a priori, their presence can be clearly discerned: To the extent that responses to marked items differ from those observed with unmarked items, one might conclude that speakers are sensitive to broad phonotactic preferences. Of interest is whether such preferences apply to both auditory and printed materials. Experiments 1 and 2 compare narrow generalization (e.g., *bnif* vs. *bdif*) for spoken and printed words, respectively. Experiments 3–5 extend this test to broader generalizations (e.g., *bdif* vs. *lbif*).

Narrow Generalizations

Experiment 1: Auditory Stimuli

In Experiment 1, I examined the sensitivity of English speakers to the phonotactics of novel onset clusters presented aurally. English manifests onset clusters with rising sonority, either obstruent–liquids (e.g., *play*) or obstruent–glides (e.g., *twin*). Of interest is whether English speakers generalize their phonotactic knowledge to unattested onsets with rising sonority—onsets whose statistical and structural properties are close to English onsets. To examine this question, in Experiment 1 I compared the acceptability of nonword foils with unattested onsets, either a sonority rise (e.g., *bnif*) or a plateau (e.g., *bdif*). If English speakers have productive knowledge of onset structure, and if the activation of such knowledge is sufficiently fast to constrain lexical decision, then responses to auditory clusters with a sonority rise should differ from onsets with a sonority plateau. The direction of this difference depends on the representation of those unattested clusters. To the extent that these clusters are represented faithfully, then marked onsets that are relatively dissimilar to English words (e.g., *bdif*) should be perceived as less wordlike and, hence, easier to reject than unmarked ones (e.g., *bnif*). To further probe into the effect of similarity, I included a third set of English words with attested onset clusters (e.g., *blif*) as well. If the rejection of nonwords reflects their (grammatical or statistical) similarity to English words, then nonwords with attested English onset clusters should be perceived as more wordlike, hence harder to reject than ones with unattested clusters.

Method

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

Materials. The materials comprised 90 English words and 90 nonword foils, presented aurally. Targets and foils were monosyllabic strings with an onset cluster. The foils had a consonant–consonant–vowel–consonant (CCVC) structure. They were composed of three matched types (see Appendix A), including either an attested English onset with a large sonority rise (e.g., *blif*) or an unattested onset—either with a smaller sonority rise (e.g., *bnif*) or with a sonority plateau (e.g., *bdif*). The three types were arranged in trios, matched for all phonemes except for the second onset consonant. To minimize the effect of lexicalization, I avoided using nonwords whose C_2VC_3 portion is an existing word (e.g., *bdish*, which includes the word *dish*). I also designed the stimuli to minimize the effects of phonotactic restrictions that are unrelated to sonority, such as the tendency of obstruent–obstruent onsets to agree on voicing and the tendency of all onsets to avoid the same place of articulation (Greenberg, 1978). Onsets with sonority plateaus invariably agreed on voicing. Likewise, most (80 out of 90) onsets comprised consonants with a different place of articulation.

The statistical properties of the nonwords with unattested onsets were estimated with three sets of measures. The first involved indices of phone co-occurrence computed over the entire word. These indices include the position-sensitive probability of each of the four segments (i.e., the probability that a given phoneme occurs at a specific word position, summed across the word's four phonemes), their position-sensitive biphone probability (i.e., the probability that any combination of adjacent two-phones occurs at a given word position, summed across those three biphones), the number of phonological neighbors (the number of words generated by substituting, deleting, or adding a single phoneme), and their summed frequency. The measures of phone and biphone probability were computed on the *Phonotactic Probability Calculator* (2004; Vitevitch & Luce, 2004), whereas neighborhood calculations were based on the *Speech & Hearing Lab Neighborhood Database* (http://128.252.27.56/Neighborhood/Home.asp). These phonotactic and neighborhood properties were calculated based on an electronic version of the Merriam-Webster Pocket Dictionary of 1964. Word frequencies are based on Kucera and Francis (1967).

A second set of statistical measures assessed statistical properties related to the onset cluster alone based on the Speech & Hearing Lab Neighborhood Database. These properties include the number of four-phoneme words that share the target's first consonant in the first position, the summed frequency of the above words, the number of four-phoneme words that share the target's second consonant in the second position, and the summed frequency of the above words.

A final set of statistical measures included the transitional probability of the item's phonemes (averaged across the word's

Table 1
Statistical Properties of the Auditory Nonwords With Unattested Onsets Used in Experiments 1 and 3

Statistical property	Onset type: Rise (e.g., *bnif*)	Plateau (e.g., *bdif*)	Fall (e.g., *lbif*)
Whole word properties			
Segment probability	.144[a,b] (.034)	.124 (.03)	.112 (.014)
Biphone probability	.0023[b] (0.0336)	.0018 (.0298)	.0018 (.0144)
Number of neighbors	1.00 (1.23)	1.03 (1.00)	0.73 (0.78)
Neighbors' frequency	16.63 (33.56)	21.80 (34.8)	20.00 (42.79)
Onset properties			
Number of C_1 words	183.53[b] (50.06)	183.53 (50.06)	120.57 (12.73)
Frequency of C_1 words	4,004.33 (1,413.69)	4,004.33 (1,413.69)	4,420.33 (1,938.88)
Number of C_2 words	82.43[b] (64.66)	37.8 (25.71)	35.87 (26.77)
Frequency of C_2 words	3,892.07[b] (2,448.67)	1,693 (1,174.94)	1,639.17 (1,347.15)
Additional measures			
Transitional probability (PS)	.0275 (.0161)	.0268 (.0117)	.027 (.0103)
C_1 probability (PI)	.0230[b] (.0221)	.023 (.0221)	.0544 (.0122)
C_2 probability (PI)	.0460[b] (.0102)	.0259 (.0191)	.0192 (.0188)
C_1C_2 biphone (PI)	.0002[b] (.0001)	.0003 (.0006)	.0009 (.0009)

Note. Values given are means, with standard deviations in parentheses. All significant differences reflect *p* values of .05 or better on a Scheffé post hoc test. C = consonant; PS = position sensitive; PI = position independent.
[a] Significant difference between the statistical property of a given onset type and the immediately more marked onset on the sonority hierarchy (i.e., between sonority rises and plateaus, and between plateaus and falls).
[b] Significant difference between the properties of sonority rises and falls.

four phonemes), the position-independent probability of the first and second phonemes, and the position-independent probability of the first bigram. The statistical properties for the nonwords with unattested sonority rises and plateaus (used in Experiment 1) as well as the set of onsets with sonority falls (used in Experiment 3) are provided in Table 1.

I conducted a series of one-way analyses of variance (ANOVAs) to determine whether the three types of unattested onsets differ on each of these statistical indices. The main effect of cluster type was significant for the measures of segment probability, $F_2(2, 58) = 20.92$, $p < .002$, $\eta^2 = .420$; biphone probability, $F_2(2, 58) = 3.98$, $p < .025$, $\eta^2 = .121$; number of C_1 words, $F_2(2, 58) = 41.20$, $p < .0002$, $\eta^2 = .587$; number of C_2 words, $F_2(2, 58) = 11.04$, $p < .0002$, $\eta^2 = .276$; frequency of C_2 words, $F_2(2, 58) = 15.29$, $p < .002$, $\eta^2 = .841$; position-independent C_1 probability, $F_2(2, 58) = 48.91$, $p < .0002$, $\eta^2 = .627$; position-independent C_2 probability, $F_2(2, 58) = 20.21$, $p < .0002$, $\eta^2 = .410$; and the position-independent C_1C_2 biphone probability, $F_2(2, 58) = 13.90$, $p < .0002$, $\eta^2 = .326$. These significant effects were next interpreted with Scheffé's tests. The results, summarized in Table 1, make it clear that the markedness of a cluster correlates with its frequency.[4]

The auditory materials used in Experiments 1 and 3 were recorded by a female native English speaker. Words and nonwords were recorded in separate lists. Words and nonwords with attested onsets were produced naturally. I generated nonwords with unattested onsets by splicing out the vowels from the recordings of their disyllabic counterparts (e.g., excising [bdIf] from [bədIf]) through visual and auditory scrutiny of their waveforms. The mean length of the nonwords with sonority rise, plateau, and fall is provided in Table 2. The spliced materials were inspected to ensure that the splicing procedure effectively eliminated the traces of the initial vowel in the disyllabic source. These items were also judged as monosyllabic by a group of seven speakers of Russian (whose language manifests a wide range of onset clusters with sonority rises, plateaus, and falls).[5]

Procedure. Participants wearing headphones were seated in front of a computer monitor. Each trial began with a fixation point and a message indicating the trial number, presented at the center of the screen. Participants initiated the trial by pressing the space

[4] The only exception is the position-independent probability of C_1, which yielded a higher estimate for the most marked onsets of falling sonority. Because most of the onsets of falling sonority began with a coronal consonant, this result probably reflects the overall frequency of coronal sonorants relative to labials and dorsals—which were the first consonants in onsets with plateaus and rises. However, the adequacy of position-independent measures as accounts of phonotactic knowledge is questioned by speakers' clear sensitivity to segment ordering.

[5] Participants were presented with a randomized list that included the 90 nonwords with unattested onset clusters used in the present experiment (the 60 nonwords with a sonority rise or plateau used in Experiment 1 and the additional 30 nonwords with a sonority fall from Experiment 3) mixed with their disyllabic counterparts. Participants were asked to determine whether each stimulus had one syllable or two. The mean response accuracy for monosyllabic and disyllabic words was 86% and 88%, respectively. Furthermore, the mean response accuracy for the monosyllabic words whose clusters had a sonority rise (82%), plateau (89%), and fall (88%) did not differ significantly, $F_1(2, 12) = 1.02$, $MSE = .011$, $p < .39$; $F_2(1, 58) = 1.76$, $p < .19$, *ns*.

Table 2
Measurements (in ms) of the Auditory Nonwords With Unattested Clusters in Experiments 1 and 3

Segment	Onset type: Rise	Plateau	Fall
Consonant 1	74 (35)	118 (28)	135 (29)
Silence	0 (0)	0 (0)	16 (14)
Consonant 2	135 (25)	101 (34)	88 (27)
Vowel	259 (91)	262 (91)	246 (61)
Consonant 3	328 (73)	330 (77)	260 (85)
Total length	796 (95)	812 (99)	745 (111)

Note. Values given are means, with standard deviations in parentheses.

bar. Their response triggered a delay of 500 ms followed by the presentation of an auditory stimulus. The auditory stimulus was presented until participants had responded (or after a maximum of 3,500 ms). Participants were asked to determine whether the stimulus was a real English word and to indicate their response by pressing the appropriate key (1 = yes, 2 = no) as fast and accurately as possible. Slow (responses slower than 3,000 ms from the stimulus onset) or incorrect responses triggered negative feedback from the computer. The order of trials was random. To familiarize participants with the experimental task, I presented them with a practice session of twelve trials (six words and six nonwords) that did not appear in the experimental session. Participants were tested in small groups of up to 3 people at a time. The experiment was conducted with MEL software (Schneider, 1990) on Dell 5100 personal computers.

Results and Discussion

Correct responses falling 2.5 standard deviations above or below the mean (2.4% of the correct responses) were eliminated from the analyses of response latency. Mean correct response time and response accuracy are presented in Table 3. In this and all subsequent experiments, the analyses of response accuracy were conducted on the proportion of correct responses. Response times are reported from the onset of the stimulus.

As a preliminary test of participants' sensitivity to the properties of onset clusters, I first compared responses to attested and unattested onsets (collapsing over the distinction between sonority rise and plateau) in a one-way ANOVA using participants (F_1) and items (F_2) as random variables. As expected, responses to attested onsets were significantly slower—$F_1(1, 21) = 107.46$, $MSE = 2{,}216$, $p < .0002$, $\eta^2 = .837$; $F_2(1, 29) = 45.73$, $MSE = 9{,}287$, $p < .0002$, $\eta^2 = .612$—and less accurate—$F_1(1, 21) = 47.75$, $MSE = .0055$, $\eta^2 = .694$, $p < .0002$; $F_2(1, 29) = 17.76$, $MSE = .019$, $p < .0003$, $\eta^2 = .380$—relative to unattested onsets. To determine whether participants were also sensitive to the phonotactics of unattested onsets, I next compared responses to unattested onsets with sonority plateaus and rises. Response accuracy to onsets with sonority rises did not differ from those with sonority plateaus ($F < 1$). However, the two onsets significantly differed on their response time: Participants took longer to reject nonwords with an unattested sonority rise compared with a plateau, $F_1(1, 21) = 9.32$, $MSE = 1{,}693$, $p < .007$, $\eta^2 = .307$; $F_2(1, 29) = 10.68$, $MSE = 2{,}325$, $p < .003$, $\eta^2 = .269$. These results suggest that unattested onsets with sonority rises were preferred to onsets with sonority plateaus. In Experiment 2, I examined whether these preferences generalize to printed words.

Experiment 2: Printed Stimuli

Method

The materials were printed letter strings, including 90 targets and 90 foils (see Appendix B). The targets were pseudohomophones (e.g., *klip*; see Appendix C), whereas the foils corresponded to the auditory nonwords used in Experiment 1. As in Experiment 1, I computed several statistical measures of wordwise letter co-occurrence, including Coltheart *N* (the number of neighbors—words that match the item's length and differ from it on one letter), the summed frequency of those neighbors, bigram count (the number of words that share the item's bigrams—combinations of two consecutive letters at the same word position), and bigram frequency (the summed frequency of the words that share the item's bigrams). A second set of statistical measures captures several characteristics of the onset consonants, including the number of four-letter words that share an item's initial consonant, the summed frequency of those words, the number of four-letter words sharing the item's second consonant, and their summed frequency. The neighborhood counts were based on the Speech & Hearing Lab Neighborhood Database (http://128.252.27.56/Neighborhood/Home.asp), whereas the bigram calculations were based on Kucera and Francis (1967). These statistical properties are listed in Table 4.

An ANOVA assessing the statistical properties of these materials across the three types of sonority profiles (sonority rise, plateau, and falls) yielded significant main effects of bigram count, $F_2(2, 58) = 4.138$, $p < .03$, $\eta^2 = .124$; bigram frequency, $F_2(2, 58) = 3.32$, $p < .05$, $\eta^2 = .103$; the number of C_1 words, $F_2(2, 58) = 11.84$, $p < .0002$, $\eta^2 = .290$; the number of C_2 words, $F_2(2, 58) = 15.06$, $p < .0002$, $\eta^2 = .342$; and the summed frequency of C_2 words, $F_2(2, 58) = 21.95$, $p < .0002$, $\eta^2 = .431$. Significant main effects were next interpreted via Scheffé post hoc tests. The outcomes, indicated in Table 4, suggest that the markedness of a cluster is inversely related to its statistical frequency.

The procedure was as in Experiment 1 with the exception that participants were now asked to determine whether the printed letter string sounded like an English word. As in Experiment 1, at the beginning of the trial, participants saw a fixation point (+)

Table 3
Mean Response Time and Response Accuracy to the Nonwords in Experiment 1

Onset type	Response time (ms) *M*	Response time (ms) *SD*	Response accuracy (% correct) *M*	Response accuracy (% correct) *SD*
Attested onsets				
Large rise (e.g., *blif*)	1,229	121	80.1	10.8
Unattested onsets				
Rise (e.g., *bnif*)	1,101	108	95.9	5.2
Plateau (e.g., *bdif*)	1,063	121	95.1	5.4
Mean unattested onsets	1,182	111.1	95.5	10.8

Table 4
Statistical Properties of the Visual Nonwords With Unattested Onsets Used in Experiments 2, 4, and 5

Statistical property	Onset type: Rise (e.g., *bnif*)	Plateau (e.g., *bdif*)	Fall (e.g., *lbif*)
Whole word properties			
Bigram count	13.37[b] (15.18)	11.07 (14.99)	10.83 (13.64)
Bigram frequency	424.80 (620.43)	345.23 (634.23)	321.57 (588.21)
Number of neighbors	0.20 (0.55)	0.13 (0.35)	0.30 (0.60)
Neighbors' frequency	0.23 (0.68)	4.43 (23.91)	8.30 (28.19)
Onset properties			
Number of C_1 words	98.33 (21.82)	98.33[a,b] (21.82)	76.20 (23.64)
Summed frequency of C_1 words	11,171 (11,004)	11,171 (11,004)	9,768 (9,502)
Number of C_2 words	32.33[a,b] (26.16)	13.90 (6.08)	12.73 (5.14)
Summed frequency of C_2 words	5,165[a,b] (5,632)	459 (369)	320 (276)

Note. Values given are means, with standard deviations in parentheses. All significant differences reflect *p* values of .05 or better on a Scheffé post hoc test. C = consonant.
[a] Significant difference between the statistical property of a given onset type and the immediately more marked onset on the sonority hierarchy (i.e., between sonority rises and plateaus, and between plateaus and falls).
[b] Significant differences between the properties of sonority rises and falls.

presented at the center of the screen. Participants initiated the trial by pressing the space bar, resulting in the immediate presentation of a fixation point (a series of eight *X*s) for a duration of 500 ms, followed by the presentation of the visual letter string. Response times are reported from the onset of the visual stimulus. Slow (responses slower than 1,800 ms) or incorrect responses triggered negative feedback from the computer.

Results and Discussion

Correct responses falling 2.5 standard deviations above the mean or faster than 200 ms (2.9% of the total correct responses) were excluded from the analyses of response time. Mean correct response times and response accuracy are presented in Table 5.

An inspection of the means suggests that responses to printed words follow the same pattern observed with their auditory counterparts. As in Experiment 1, nonwords with attested clusters yielded slower responses—$F_1(1, 21) = 51.79$, $MSE = 1{,}957$, $p < .0002$, $\eta^2 = .712$; $F_2(1, 29) = 65.02$, $MSE = 3{,}001$, $p < .0002$, $\eta^2 = .692$—and less accurate—$F_1(1, 21) = 80.40$, $MSE = .009$, $p < .0002$, $\eta^2 = .793$; $F_2(1, 29) = 42.27$, $MSE = .023$, $p < .0002$, $\eta^2 = .593$—compared with unattested clusters. However, readers were also sensitive to the phonotactics of unattested clusters: Unattested onsets with sonority rises (e.g., *bnif*) elicited slower responses—$F_1(1, 21) = 22.02$, $MSE = 980.52$, $p < .0002$, $\eta^2 = .512$; $F_2(1, 29) = 21.14$, $MSE = 1{,}532$, $p < .0002$, $\eta^2 = .422$—and less accurate—$F_1(1, 21) = 11.27$, $MSE = .004$, $p < .004$, $\eta^2 = .352$; $F_2(1, 29) = 14.33$, $MSE = .004$, $p < .0008$, $\eta^2 = .329$—compared with onsets with sonority plateaus (e.g., *bdif*). These findings suggest that onsets of rising sonority are more acceptable compared with more marked onsets with level sonority.

Table 5
Mean Response Time and Response Accuracy to the Nonwords in Experiment 2

Onset type	Response time (ms) *M*	Response time (ms) *SD*	Response accuracy (% correct) *M*	Response accuracy (% correct) *SD*
Attested onsets				
Large rise (e.g., *blif*)	847.7	91.6	64.0	19.7
Unattested onsets				
Rise (e.g., *bnif*)	773.8	100.4	86.3	14.8
Plateau (e.g., *bdif*)	729.5	77.4	92.5	8.5
Mean unattested onsets	751.65	86.87	89.4	11.2

Broad Generalizations

The results of Experiments 1 and 2 demonstrate that not all unattested onsets are perceived alike: Unattested onsets with a sonority rise are preferred to those with a plateau, and this preference was independent of stimulus modality. However, unattested onsets of rising sonority are rather similar to English onsets on both their sonority profile and their statistical properties. Experiments 3 and 4 probe for broader generalizations of phonotactic preferences by examining whether onsets with a sonority plateau (e.g., *bdif*) are preferred to onsets with a sonority fall (e.g., *lbif*). For comparison with previous experiments, I also included unattested onsets of rising sonority (e.g., *bnif*).

Replicating Experiments 1 and 2, onsets with sonority rises (e.g., *bnif*) should be preferred and, hence, harder to reject compared with plateaus (e.g., *bdif*) with either auditory or visual materials. Of main interest are the plateaus and the falls. If English speakers possess only coarse phonotactic preferences (either grammatical or statistical) for sonority rises, then they might ignore the difference between such onsets. Conversely, if English speakers prefer plateaus to falls, then nonwords with sonority plateaus (e.g., *bdif*) should be preferred to those with sonority falls (e.g., *lbif*). The effect of such preferences on behavior depends on how marked clusters are represented. If highly marked onsets are encoded faithfully (i.e., without repair), then they should be less acceptable and, hence, easier to reject compared with clusters with sonority plateaus. Alternatively, the strong markedness of onsets with sonority falls might trigger their selective repair (e.g., *lbif* → *lebif*). This might happen either because their repair is mandatory or because it is faster to emerge and, hence, more likely to affect a fast response. Either way, onsets of falling sonority would be selectively repaired. Because the resulting simple onset is preferred to any complex onset (Prince & Smolensky, 2004), such repair would paradoxically result in difficulty in rejecting sonority falls compared with plateaus. In Experiment 3, I examine these predictions with auditory words. In Experiment 4, I extend the investigation to printed materials.

Experiment 3: Auditory Stimuli

Method

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

Materials. The materials consisted of the 90 words used in Experiment 1 and 90 nonword foils with unattested onset clusters. The nonwords were arranged in trios (see Appendix A). One trio member had an onset with a sonority rise (e.g., *bnif*); a second member had an onset with a sonority plateau (e.g., *bdif*); the third member had an onset of falling sonority (e.g., *lbif*). The members with sonority rises and plateaus were used in Experiment 1. Within each trio, members had identical rhymes. Their statistical properties and sonority profiles are listed in Table 1. The procedure was the same as in Experiment 1.

Results

Correct responses that fell 2.5 standard deviations above or below the mean (2.7% of the correct responses) were eliminated from the analysis of response latency. Mean correct response time and response accuracy are given in Table 6.

The one-way ANOVAs (3 cluster type: unattested rise, plateau, fall) yielded a significant effect of cluster type in response time, $F_1(2, 42) = 9.67$, $MSE = 2{,}140$, $p < .0005$, $\eta^2 = .315$; $F_2(2, 58) = 12.48$, $MSE = 2{,}600$, $p < .0002$, $\eta^2 = .301$. The effect of cluster type was not significant in the analyses of response accuracy, $F_1(2, 42) < 1$, $MSE = .0115$, $\eta^2 = .014$; $F_2(2, 58) < 1$, $MSE = .0018$, $\eta^2 = .014$. Narrow and broad generalizations were next tested by means of planned comparisons.

In agreement with the findings of Experiment 1, results showed that participants were slower to reject unattested onsets with sonority rises compared with those with plateaus, $F_1(1, 42) = 15.73$, $p < .0003$; $F_2(1, 58) = 20.24$, $p < .0001$. These results suggest that participants (narrowly) extended the English preference for a sonority rise to novel clusters: Unattested onsets of rising sonority were considered more wordlike compared with clusters with sonority plateaus.

Of interest is whether phonotactic preferences generalize broadly to favor sonority plateaus over sonority falls—onsets whose statistical and grammatical properties are further from attested English onsets. Response time to onsets with sonority plateaus differed significantly from onsets with sonority falls, $F_1(1, 42) = 13.05$, $p < .0008$; $F_2(1, 58) = 17.07$, $p < .0002$. However, onsets with sonority falls were harder to reject, suggesting that they were perceived as more wordlike than sonority plateaus. Responses to onsets with sonority falls did not differ from sonority rises (all *F*s < 1).

Table 6
Mean Response Time and Response Accuracy to the Nonwords in Experiment 3

	Response time (ms)		Response accuracy (% correct)	
Onset type	*M*	*SD*	*M*	*SD*
Rise (e.g., *bnif*)	985	120	96.5	4.8
Plateau (e.g., *bdif*)	930	127	97.3	4.3
Fall (e.g., *lbif*)	980	107	96.7	5.6

Discussion

In Experiment 3, I examined the ability of English speakers to generalize phonotactic preferences concerning onset structure. The results suggest that hearers extend their phonotactic preferences not only to unattested, rising sonority onsets, onsets whose profile is similar to the ones attested in English (narrow generalizations), but also to clusters that are quite distant from the English inventory—a broad generalization of phonotactic knowledge. In particular, speakers exhibit distinct preferences for onsets with sonority plateaus compared to those with sonority falls. Remarkably, the relatively unmarked onsets with sonority plateaus (e.g., *bdif*) were easier to reject (i.e., dispreferred) compared with the falling sonority onsets (e.g., *lbif*). This inverse relation between markedness and speakers' preference could indicate the epenthetic repair of highly marked onsets. The insertion of a vowel yields a simple onset (e.g., *lbif* → *lebif*), so the repaired output (e.g., *lebif*) is less marked and more frequent than any complex onset.[6] Consequently, such foils are harder to reject.

To evaluate the repair account, it is necessary to seek empirical support for its predictions and to compare it against alternative interpretations. In what follows, I offer converging evidence that the auditory materials used in these experiments are repaired in perception. I next demonstrate that the representation of marked onsets as disyllabic is a reliable phenomenon that cannot be explained by stimulus artifacts. I finally show that highly marked onsets are indeed preferred to their less marked counterparts.

Are marked onsets perceived as disyllabic? Previous research has directly demonstrated that highly marked onsets are misperceived as disyllabic (Berent et al., 2007). In the lexical decision

[6] The finding that the repaired output (e.g., *lebif*) is not preferred to clusters with sonority rise (e.g., *bnif*) suggests that speakers register the presence of the cluster (possibly due to the encoding of its phonetic traces), rendering the repaired outputs less optimal than true disyllabic inputs.

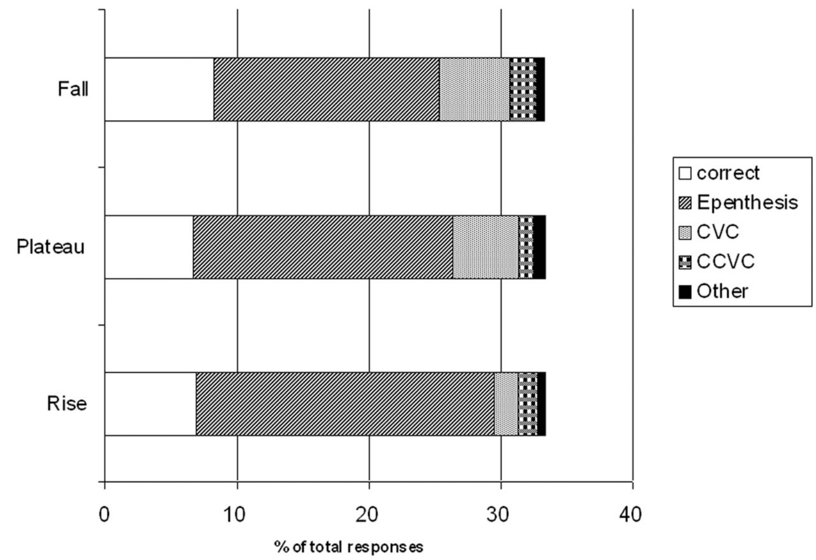

Figure 1. The distribution of correct and erroneous responses in the spelling task. Erroneous responses include (a) epenthesis (e.g., *lbif* → *lebif*); (b) responses that omit one of the clusters' consonants (e.g., *lbif* → *bif*—that is, consonant–vowel–consonant responses); (c) responses that maintain the skeletal structure of the input but change one of its segments (e.g., *lbif* → *blif,* or consonant–consonant–vowel–consonant responses); and (d) others, either omissions or responses that vastly distort the input. Means reflect the percentage relative to the total number of responses across all items. CVC = consonant–vowel–consonant; CCVC = consonant–consonant–vowel–consonant.

task, however, repair is expressed indirectly, in the difficulty to reject nonwords with clusters of falling sonority. To show that perceptual repair specifically applies to the materials used here, I asked a group of 16 participants (Florida Atlantic University students who were native English speakers) to transcribe the auditory materials using English spelling. If marked onsets are repaired by epenthesis, then most erroneous responses should reflect the epenthesis of a vowel. An inspection of the transcription data (see Figure 1) supports this prediction. Most responses (59% of the total responses) manifested the epenthesis of a vowel, and in most cases (97% of the epenthetic responses), the vowel was inserted between the two initial consonants (e.g., *lbif* → *lebif*). Note, however, that in the spelling task, epenthetic repair was not limited to onsets of falling sonority. In fact, such repair was the most frequent response to each of the three types of unattested clusters. The high rate of epenthesis might be due to the greater memory demands of the spelling task: The need to maintain the transcribed input in phonological working memory might have prompted its repair. Although the demands of the spelling task differ from online lexical decision, its results converge with previous research (Berent et al., 2007) to show that marked, unattested onsets are subject to epenthetic repair.

Why lbif is perceived as lebif—the role of stimulus artifacts. The discussion so far has attributed the misperception of highly marked onsets to a phonological process that perceptually recodes them as disyllabic. But according to an alternative explanation, this misperception is due to stimulus artifacts. Because the materials were generated by splicing (e.g., *lbif* was spliced from the recording of *lebif*), it is possible that the traces of the vowels were not fully eliminated from onsets with sonority falls. As reported in the Experiment 1 *Method* section, the three types of clusters were considered (equally) monosyllabic by Russian speakers (whose grammar tolerates sonority plateaus and falls). Nonetheless, it is useful to demonstrate that the findings do not depend on this particular set of materials. To this end, I conducted two replications of Experiment 3. The first used another set of newly recorded and spliced items that largely overlap with those used in Experiment 3. The results ($N = 16$ participants; see Table 7 for response time and accuracy) remain unchanged: Unattested onsets with sonority rises were harder to reject compared with those with sonority plateaus, $F_1(1, 30) = 11.13$, $p < .003$; $F_2(1, 58) = 12.22$, $p < .001$. Conversely, onsets with sonority plateaus were rejected significantly more quickly compared with those with sonority falls— $F_1(1, 30) = 6.29$, $p < .02$; $F_2(1, 58) = 5.92$, $p < .02$—suggesting that onsets with sonority falls are repaired.

A second replication used unspliced materials recorded by a native Russian speaker.[7] The results ($N = 28$ participants) are presented in Table 7. Once again, the responses of English speakers to clusters with sonority falls were slower compared with clusters with sonority plateaus, $F_1(1, 54) = 19.93$, $p < .0002$; $F_2(1, 28) = 14.99$, $p < .0006$. In addition, speakers had more errors in the rejection of unattested onsets with sonority rises compared with sonority plateaus, $F_1(1, 30) = 64.12$, $p < .0001$; $F_2(1, 28) = 2.66$, $p < .12$. These findings suggest that the

[7] The materials corresponded to a subset of 15 trios selected from the set of 30 nonword trios used in Experiment 3. This subset excludes clusters that begin with *r* because the trill in the Russian pronunciation might offer participants with an obvious phonetic cue for the classification of these items as foreign to English.

Table 7
Mean Response Time and Response Accuracy to the Nonwords Used in the Replications of Experiment 3 With Spliced and Naturally Recorded Materials

Onset type	Response time (ms) *M*	Response time (ms) *SD*	Response accuracy (% correct) *M*	Response accuracy (% correct) *SD*
Spliced materials				
Rise (e.g., *bnif*)	1,035	81.1	95.5	5.0
Plateau (e.g., *bdif*)	979	106.4	95.8	4.8
Fall (e.g., *lbif*)	1,021	94.8	94.8	4.4
Naturally recorded materials				
Rise (e.g., *bnif*)	859	77.7	89.5	4.4
Plateau (e.g., *bdif*)	865	72.0	97.8	4.1
Fall (e.g., *lbif*)	920	88.4	97.1	4.3

difficulty in rejecting onsets of falling sonority is not due to stimulus artifact.

Do speakers prefer lbif to bdif? The persistent difficulty in rejecting nonwords with sonority falls is attributed to their repair as more preferred (i.e., less marked and more frequent) structures (e.g., *lbif* as *lebif*). To directly show that (the repaired representations of) marked onsets are preferred to their (unrepaired) less marked counterparts, I next asked a group of native English speakers to compare the onsets with plateaus versus falls. In each trial, participants were presented with two auditory nonwords, corresponding to a matched pair of unattested onsets that differed on their sonority profile (with order counterbalanced). They were asked to determine which stimulus sounded better as an English word. When comparing sonority rises with sonority plateaus (e.g., *bnif* vs. *bdif*), participants favored clusters with sonority rises (i.e., the relatively unmarked option) on 56% of the trials, a preference that was significantly higher than chance, $t_1(47) = 4.58$, $p < .0001$; $t_2(29) = 3.64$, $p < .002$. Conversely, when clusters with sonority plateaus were compared with those with sonority falls (e.g., *bdif* vs. *lbif*), participants favored clusters with sonority falls (i.e., the most marked option) on 56% of the trials, a preference that was significantly greater than chance in the analysis by participants, and marginally so by items, $t_1(47) = 3.31$, $p < .002$; $t_2(29) = 1.93$, $p < .07$. These results demonstrate that nonwords with sonority falls are preferred to less marked onsets with sonority plateaus. Past research (Berent et al., 2007) has shown that such items are repaired in perception. It thus appears that the paradoxical difficulty to reject the most marked items reflects a process of repair, triggered by the dispreference for such clusters.[8]

Before moving to examine readers' sensitivity to such broad generalizations, I should briefly comment on the modulation of repair by task demands. Using syllable and identity judgment of auditory materials, past researchers have observed a linear relationship between markedness and repair: As the markedness of the onset cluster increased, participants were more likely to judge them as disyllabic (Berent et al., 2007). In contrast, the present lexical decision task implicates repair only of extremely marked onsets of falling sonority. The divergence might well reflect differences in task demands. Syllable- and identity-judgment tasks require explicit evaluation of the structure of the auditory stimulus, whereas lexical decision elicits a fast discrimination between words and nonwords. The temporal properties of the lexical decision task could have either attenuated its sensitivity to the (slower, but presumably automatic) repair of less marked onsets or reduced the scope of repair, eliminating it in all but the most marked onsets of falling sonority. Despite these divergent manifestations, both tasks implicate sensitivity to broad phonotactic preferences. In Experiment 4, I examined whether such broad preferences extend to reading by replicating Experiment 3 with printed materials.

Experiment 4: Printed Stimuli

Method

The materials corresponded to the same items used in Experiment 3. The procedure, a phonological lexical decision task, is as described in Experiment 2.

Results and Discussion

Correct responses falling 2.5 standard deviations above the mean and responses faster than 200 ms (3.6% of the correct responses) were excluded from the analysis of response latency. Mean correct response time and response accuracy are presented in Table 8.

An inspection of the means suggests that participants were once again sensitive to the distinction between onsets of sonority rise and plateaus. But unlike the responses to auditory words, there was no evidence that nonwords with falling sonority were harder to reject. The ANOVA yielded a significant effect of onset type in response accuracy—$F_1(2, 42) = 7.01$, $MSE = .002$, $p < .003$, $\eta^2 = .248$; $F_2(2, 58) = 3.36$, $MSE = .007$, $p < .05$, $\eta^2 = .104$—and a marginally significant effect in response time—$F_1(2, 42) = 3.16$, $MSE = 1{,}602$, $p < .06$, $\eta^2 = .131$; $F_2(2, 58) = 4.96$, $MSE = 2{,}060$, $p < .02$, $\eta^2 = .146$. Planned comparisons suggested that unattested onsets with rising sonority elicited significantly slower responses—$F_1(1, 42) = 4.15$, $p < .05$; $F_2(1, 58) = 5.0$, $p < .03$—compared with onsets with sonority plateaus. A similar trend was observed in the analysis of response accuracy, $F_1(1, 42) = 4.28$, $p < .05$; $F_2(1, 58) = 2.11$, $p < .17$. However, responses to onsets with sonority plateaus and falls did not differ reliably: in response time, $F < 1$; in response accuracy, $F_1(1, 42) = 2.78$, $p < .12$; and $F_2(1, 58) = 1.25$, $p < .27$.

Experiment 5: Printed Stimuli

The contrast in the findings of Experiment 3 versus Experiment 4 implies differences between the phonological representations

[8] According to an alternative explanation, the distinction between sonority falls and plateaus could be informed by the linguistic experience of English speakers. As noted earlier (see footnote 3), English tolerates *s*-obstruent onsets, onsets that, on some accounts, reflect a fall in sonority (Kiparsky, 1979). The difficulty experienced by participants in rejecting onsets of falling sonority could thus reflect the effect of familiarity, rather than of repair. However, this account fails to explain why onsets of falling sonority are perceived as disyllabic (Berent et al., 2007). The hypothesis that such onsets are repaired in perception explains both their misperception as disyllabic and their preference.

Table 8
Mean Response Time and Response Accuracy to the Nonwords in Experiment 4

Onset type	Response time (ms) M	Response time (ms) SD	Response accuracy (% correct) M	Response accuracy (% correct) SD
Rise (e.g., *bnif*)	727.1	98.5	87.6	11.4
Plateau (e.g., *bdif*)	702.5	101.9	90.6	9.0
Fall (e.g., *lbif*)	699.4	124.9	93.1	8.5

assembled to spoken and printed words. Unlike the representation of spoken language, the representation of printed words appears to be insensitive to broad phonological generalizations. Because this conclusion is based on a null result, it is important to demonstrate the consistency of this finding and its generality. For example, one might worry that the failure to distinguish items with sonority plateaus and falls might be due to the overall phonological illegality of this set of nonwords. This could have allowed for a fast discrimination between printed targets and foils and reduced the specificity of phonological computation. To address this concern, Experiment 5 reexamines responses to foils with sonority plateaus and falls (e.g., *bdif, lbif*) in the context of foils with attested onset clusters (e.g., *blif*). Because the phonological structure of such foils is similar to existing English words, their inclusion is expected to slow down the discrimination and to encourage attention to phonotactics. If readers in the phonological lexical decision task access the full range of (grammatical or statistical) phonotactic constraints on spoken language, then the distinction between sonority plateaus and falls might emerge when attention to phonology is encouraged. In contrast, if readers are unable to broadly generalize their knowledge of onset structure, then they should remain insensitive to the distinction between onsets of level and falling sonority despite greater attention to the phonological structure of the stimuli.

Method

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

Materials. The materials were identical to Experiment 4, the only exception being that the group of foils with unattested sonority rises was replaced by the group of items with attested onset clusters used in Experiment 2. All other aspects of the procedure remained unchanged.

Results and Discussion

Outliers (correct responses slower than 2.5 standard deviations from the mean or faster than 200 ms) were removed from the analyses of response time. This procedure resulted in the exclusion of 2.8% of the total correct responses. Mean response times and response accuracy are given in Table 9.

An inspection of the means confirms that responses in Experiment 5 were slower and less accurate compared with Experiment 4, suggesting that the presence of foils with attested onsets rendered the discrimination task more difficult. Nonetheless, the pattern of results remains unchanged. An ANOVA yielded a significant effect in both response time—$F_1(2, 54) = 21.48$, $MSE = 3{,}923$, $p < .0002$, $\eta^2 = .443$; $F_2(2, 58) = 69.20$, $MSE = 1{,}777$, $p < .0002$, $\eta^2 = .705$—and accuracy, $F_1(2, 54) = 103.01$, $MSE = .011$, $p < .0002$, $\eta^2 = .792$; $F_2(2, 58) = 122.87$, $MSE = .01$, $p < .0002$, $\eta^2 = .809$. In agreement with previous experiments, foils with attested clusters were more difficult to reject than were those with unattested clusters, either clusters with sonority plateaus—$F_1(1, 54) = 30.91$, $p < .0001$; $F_2(1, 58) = 97.51$, $p < .0001$; $F_1(1, 54) = 143.77$, $p < .0001$; $F_2(1, 58) = 171.55$, $p < .0001$ (in response time and accuracy, respectively)—or falls—$F_1(1, 54) = 33.41$, $p < .0001$; $F_2(1, 58) = 109.62$, $p < .0001$; $F_1(1, 54) = 164.35$, $p < .0001$; $F_2(1, 58) = 169.19$, $p < .0001$ (in response time and accuracy, respectively). Crucially, responses to clusters with sonority plateaus did not differ from clusters of falling sonority (all Fs < 1). This finding converges with the outcome of Experiment 4 to suggest that the phonotactic preferences of readers in these experiments are narrower than those of hearers.

General Discussion

This research investigated whether the phonological representation of print is isomorphic to that of spoken language. As a case study, I examined the restrictions on onset structure. Previous research (Berent et al., 2007) has suggested that, across languages, onsets with small sonority rises are preferred to onsets of level sonority, which, in turn, are preferred to onsets of falling sonority (e.g., *bnif* $\succ$ *bdif* $\succ$ *lbif*). Such universal preferences further constrain the identification of auditory words by speakers of English despite the absence of such sonority profiles in their language. The goal here was to test whether similar phonotactic preferences constrain the representation of printed words online, in silent reading. To address this question, I compared responses to auditory and printed nonwords presented as foils in the lexical decision task.

The results of five experiments demonstrate that English speakers manifest preferences regarding unattested onsets and such preferences are found with either spoken or printed materials. However, the scope of those preferences was modulated by the modality of the input—visual or auditory. The results of Experiments 1 and 2 showed that hearers and readers had greater difficulties rejecting nonword foils of rising sonority compared with plateaus, suggesting that onsets with sonority rises are preferred irrespective of stimulus modality. Input modality, however, did

Table 9
Mean Response Time and Response Accuracy to the Nonwords in Experiment 5

Onset type	Response time (ms) M	Response time (ms) SD	Response accuracy (% correct) M	Response accuracy (% correct) SD
Attested (e.g., *blif*)	813.9	134.9	55.0	20.2
Plateau (e.g., *bdif*)	720.8	108.8	89.7	10.9
Fall (e.g., *lbif*)	717.2	81.6	92.11	15.0

modulate the distinction between sonority plateaus and falls—profiles that are markedly dissimilar from English onsets. When presented with spoken stimuli (in Experiment 3), nonword foils with marked onsets of falling sonority were rejected more slowly (i.e., preferred) than onsets with sonority plateaus, a finding attributed to the repair of marked onsets as disyllabic (e.g., *lbif* as *lebif*). In contrast, no difference between onsets with plateaus and falls was observed when the materials were presented visually (in Experiments 4 and 5).

The contrast between the scope of phonotactic distinctions available to hearers and readers raises the possibility that the phonological representations mediating responses in the two modalities are not isomorphic. As noted in the introduction, the three types of unattested onsets under investigation differ on both their grammatical and statistical properties. The difference between the scope of the generalizations with spoken and printed words could thus reflect the differential contribution of statistical and grammatical constraints to the representation of printed and spoken materials in these experiments. To address this possibility, I next compare the sensitivity of hearers and readers to grammatical knowledge related to sonority. The initial set of analyses examines the effect of grammatical constraints with auditory words; subsequent parallel analyses are conducted for the printed materials. The final section discusses some explanations for the distinct behaviors of hearers and readers.

Are Hearers Sensitive to Grammatical Sonority-Related Knowledge?

The first set of analyses examines hearers' sensitivity to grammatical sonority-related knowledge by means of several stepwise multiple regression analyses using hierarchical procedures (i.e., forced entry of predictors in steps). To control for the contribution of statistical knowledge, I first forced into the model several indices of whole-word segment co-occurrence (position-specific phoneme frequency, biphone frequency, the number of neighbors, and their frequency, listed in Table 1). These analyses also assessed the possibility that the distinction between unattested onsets might be due to phonological factors unrelated to sonority. Greenberg (1978) noted the tendency of onset consonants to avoid sharing the same place of articulation (i.e., onsets containing homorganic consonants are dispreferred), and this constraint appears to modulate the perception of unattested clusters in laboratory tasks (Hallé et al., 1998). Accordingly, homorganicity was forced as a second predictor into the regression model. The effect of sonority was entered as the third and last predictor. As shown in Table 10, the effect of sonority was marginally significant in Experiment 1 and significant in Experiment 3 after controlling for these factors.

A second analysis examined the possibility that the effect of sonority might be specifically due to the statistical properties of onset consonants. To this end, the regression analysis was repeated while first forcing into the model the onset properties listed in Table 1 (the number of four-phoneme words sharing the cluster's first and second consonants and their frequency); homorganicity was forced as a second predictor, whereas sonority was entered as the third and last predictor. Once again, the effect of sonority was significant after controlling for the clusters' statistical properties and homorganicity (see Table 11).

A third analysis examined whether hearers' knowledge of phonotactics reflects the frequency of specific features at onset clusters. This possibility is far more difficult to assess, as there are no widely available statistical databases of feature co-occurrence. To make a first approximation, I thus focus on the frequency of a single feature that is characteristic of English onsets. Most (27 of the 36) biconsonantal onsets in English include a coronal segment as their second consonant. The next most frequent place of articulation for the second consonant—labial—is far less frequent (8 cases), and the mean biphone probability of consonant-labial onsets (.0025) is less than half the probability of onsets whose second consonant is a coronal (.0051). If the preference for onsets of rising sonority reflects only the statistical frequency of features in the English lexicon, then the effect of markedness should be modulated (or even subsumed) by the effect of feature frequency. However, a comparison of the responses to items including either coronals or noncoronals as the second onset consonant did not yield a significant effect of feature frequency in either Experiment

Table 10
Stepwise Linear Regression Analyses of Responses to Auditory Stimuli (Experiments 1 and 3)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 1			
Rises vs. plateaus					
1	Whole-word statistical properties	.054	4, 55	<1	*ns*
2	Homorganicity	.003	1, 54	<1	*ns*
3	Sonority	.060	1, 53	3.63	.07
		Experiment 3			
Rises vs. plateaus					
1	Whole-word statistical properties	.156	4, 55	2.54	.06
2	Homorganicity	.004	1, 54	<1	*ns*
3	Sonority	.107	1, 53	7.78	.008
Plateaus vs. falls					
1	Whole-word statistical properties	.117	4, 55	1.82	.15
2	Homorganicity	.02	1, 54	<1.1	*ns*
3	Sonority	.271	1, 53	24.09	.001

Table 11
Stepwise Linear Regression Analyses of Responses to Auditory Stimuli (Experiments 1 and 3)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 1			
Rises vs. plateaus					
1	Frequency of onset phonemes	.147	4, 55	2.37	.07
2	Homorganicity	.000	1, 54	<1	*ns*
3	Sonority	.063	1, 53	4.24	.05
		Experiment 3			
Rises vs. plateaus					
1	Frequency of onset phonemes	.268	4, 55	5.02	.002
2	Homorganicity	.000	1, 54	<1	*ns*
3	Sonority	.096	1, 53	7.97	.007
Plateaus vs. falls					
1	Frequency of onset phonemes	.212	4, 55	3.69	.01
2	Homorganicity	.001	1, 54	<1	*ns*
3	Sonority	.210	1, 53	19.23	.001

1 or 3—$F_2(1, 56) < 1$, $\eta^2 = .001$; $F_2(1, 84) = 1.2$, $p < .28$, *ns*, $\eta^2 = .014$ (for Experiments 1 and 3, respectively)—nor did feature frequency interact with cluster type—$F_2(1, 56) < 1$, $\eta^2 = .014$; $F_2(1, 84) = 1.45$, $p < .24$, $\eta^2 = .033$, *ns* (for Experiments 1 and 3, respectively).

Finally, I considered the possibility that the experimental findings reflect the co-occurrence of consonants in fast speech. English speakers are known to reduce pretonic schwas (e.g., *believe* → *b'lieve*). Such reductions could potentially give rise to onset clusters that are otherwise unattested in their lexicon (e.g., *beneath* → *b'neath; debate* → *d'bate*). However, the rate of reduction does not agree with the preferences implicated by the present results. For example, the results suggest that stop–nasal sequences are preferred to stop–stop sequences, but the rate of reduction for stop–schwa–nasal and stop–schwa–stop sequences approaches zero (Davidson, 2006b).

The experimental results suggest that hearers possess productive grammatical knowledge that is irreducible to various statistical measures of segment and feature co-occurrence either in their lexicon or in fast speech. It is important to note that the contribution of the grammar is inferred from the failure of a specific set of statistical indices to account for the findings. Such a failure, however, cannot rule out the possibility that some other statistical indices could capture the results. But even if the findings were compatible with either statistical or grammatical optimality theoretic explanations, the grammatical account is arguably preferable for its ability to offer a principled explanation of the statistical properties of the typology, in general, and the linguistic experience of English speakers, in particular. Note, however, that hearers' putative sensitivity to grammatical phonological constraints does not negate their demonstrable sensitivity to statistical structure (Dell et al., 2000; Frisch, Large, & Pisoni, 2000; Luce & Pisoni, 1998; Vitevitch, Luce, Pisoni, & Auer, 1999). A final regression analysis (see Table 12) indeed suggests that statistical properties uniquely account for the auditory lexical decision results in Experiment 3 even after controlling for the grammatical properties of the materials in the initial steps. The conclusion that hearers are sensitive to the statistical properties of spoken language is indeed uncontroversial. The novel contribution of the present findings is

Table 12
Stepwise Linear Regression Analyses of Responses to Auditory Stimuli (Experiments 1 and 3)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 1			
Rises vs. plateaus					
1	Homorganicity	.005	1, 58	<1	*ns*
2	Sonority	.093	1, 57	5.86	.019
3	Frequency of onset phonemes	.112	4, 53	1.88	.13
		Experiment 3			
Rises vs. plateaus					
1	Homorganicity	.019	1, 58	1.1	*ns*
2	Sonority	.166	1, 57	11.64	.001
3	Frequency of onset phonemes	.179	4, 53	3.72	.010
Plateaus vs. falls					
1	Homorganicity	.009	1, 58	<1	*ns*
2	Sonority	.206	1, 57	14.92	.001
3	Frequency of onset phonemes	.207	4, 53	4.75	.002

in showing that the online representation of spoken words might also be shaped by grammatical constraints related to sonority.

Do Readers Constrain the Sonority of Printed Words?

In view of the grammatical constraints on the representation of spoken language, one wonders whether such constraints shape the representation of print. Because participants in these experiments were explicitly required to determine whether an item sounded like a real word, and because all targets (i.e., "yes" responses) consisted of pseudohomophones (e.g., *klip*), readers must have assembled some phonological structure for these items. Of interest is whether this representation is isomorphic to the one computed by hearers. Readers' insensitivity to the distinction between sonority plateaus and falls—a distinction that constrains the processing of spoken language—could suggest that the phonotactic knowledge available to them is more limited than the broad grammatical distinctions consulted by hearers.

To determine whether readers are sensitive to the grammatical structure of novel onsets, I conducted two sets of regression analyses. The initial analysis probed for the contribution of grammatical knowledge after controlling for the whole-word statistical properties listed in Table 4 (bigram count, bigram frequency, number of neighbors, and neighbor frequency). These statistical properties were forced as the first predictor. As in the analyses of auditory items, I also assessed the possibility that the dispreference for marked onsets might be due to the homorganicity of a few of the items by entering this factor as a second predictor. In each case, the effect of sonority (entered last) remained significant after controlling for the statistical properties of onsets with rises versus plateaus (see Table 13).

This unique effect of sonority could reflect the effect of grammatical constraints on reading. Alternatively, this result might be due to a failure to fully control the statistical properties of these items. Indeed, the measure of bigram frequency disregards the frequency of individual C_1 and C_2 letters. For example, the bigram measure renders the onsets *bn* and *bd* equally frequent (a bigram frequency of zero) even though they differ considerably on the frequency of their second letter: *n* frequently occurs second in four-letter English words (there are 33 such words), whereas *d* is far less frequent (13 such words). To control for the frequency of the onset consonants, I conducted a second analysis that considers the indices of C_1 and C_2 frequency in four-letter words, listed in Table 4. This additional control changed the results quite dramatically: Once the frequency of onset consonants was accounted for, the grammatical effect of sonority was no longer significant in any of the visual experiments (see Table 14). Conversely, a final regression analysis in which the grammatical properties of the items were entered first yielded a reliable effect of statistical properties as the last predictor (see Table 15).

These findings suggest some principled differences in the knowledge and representations available to hearers and readers in these experiments. Hearers were sensitive not only to the statistical structure of novel spoken words but also to grammatical constraints that extend to all three types of novel onsets studied in the present experiments, including the distinction between sonority plateaus and falls—onsets that greatly differ from attested English onsets on both their grammatical and statistical properties. Unlike hearers, readers considered only the statistical properties of the items, and they were insensitive to the broad grammatical distinctions between sonority plateaus and falls.

Phonological Representations of Spoken and Printed Words: Why Do They Differ?

What is the source of the differences between the representations of printed and spoken language? Consider two replies to this

Table 13
Stepwise Linear Regression Analyses of Responses to Printed Stimuli (Experiments 2, 4, and 5)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 2			
Rises vs. plateaus					
1	Whole-word statistical properties	.475	4, 55	12.42	.001
2	Homorganicity	.038	1, 54	4.21	.05
3	Sonority	.079	1, 53	10.25	.003
		Experiment 4			
Rises vs. plateaus					
1	Whole-word statistical properties	.243	4, 55	4.40	.004
2	Homorganicity	.004	1, 54	<1	*ns*
3	Sonority	.062	1, 53	4.78	.04
Plateaus vs. falls					
1	Whole-word statistical properties	.194	4, 55	3.32	.02
2	Homorganicity	.007	1, 54	<1	*ns*
3	Sonority	.002	1, 53	<1	*ns*
		Experiment 5			
Plateaus vs. falls					
1	Whole-word statistical properties	.139	4, 55	2.22	.08
2	Homorganicity	.022	1, 54	1.4	.23, *ns*
3	Sonority	.004	1, 53	<1	*ns*

question. One answer attributes the divergent outcomes with printed and spoken words to systematic differences between the representations computed by readers and hearers—differences that generalize beyond the particular circumstances of the present experiments. In this view, the representations assembled to print do not support grammatical generalizations related to sonority. This could happen for two different reasons. One is that the relevant grammatical constraints concern only the phonetic properties of various onset cluster (e.g., their perceptibility; see Wright, 2004) rather than their sonority profile. In the absence of phonetic input, readers might be unable to extend these constraints to print. Conversely, the grammar might include phonological knowledge regarding the markedness of sonority profiles, but such knowledge might be inaccessible in reading. Regardless of why readers are unable to consult grammatical knowledge related to sonority, the first set of explanations assumes that such knowledge invariably does not constrain the representation of print.

As an alternative explanation, the representations of printed and spoken words are potentially isomorphic. Readers' insensitivity to grammatical knowledge is caused by the different temporal characteristics of responses to aural and printed stimuli, rather than by stimulus modality per se.[9] A comparison of Experiments 1 and 3 with Experiments 2 and 4 clearly shows that responses to auditory words were slower than responses to visual materials. The faster time course of visual lexical decisions could have either attenuated grammatical phonological computation or merely reduced the sensitivity of the task to presumably mandatory but slower-emerging grammatical constraints. If this explanation is correct, then the effect of grammatical sonority-related constraints on reading could emerge under conditions that encourage the assembly of a detailed phonological representation to print (e.g., when readers attempt to maintain information in phonological working memory). Whether some future experimental conditions might allow for the computation of isomorphic representations for spoken and printed words remains to be seen. In the present experimental conditions, the scope of phonotactic preferences and their nature depends on stimulus modality. Well-established links between reading and spoken language notwithstanding, the phonological representations computed in the two modalities are not always isomorphic.

Table 14
Stepwise Linear Regression Analyses of Responses to Printed Stimuli (Experiments 2, 4, and 5)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 2			
Rises vs. plateaus					
1	Onset frequency	.257	4, 55	4.74	.002
2	Homorganicity	.022	1, 54	1.67	.20
3	Sonority	.019	1, 53	1.47	.23
		Experiment 4			
Rises vs. plateaus					
1	Onset frequency	.237	4, 55	4.27	.0074
2	Homorganicity	.010	1, 54	<1	*ns*
3	Sonority	.009	1, 53	<1	*ns*
Plateaus vs. falls					
1	Onset frequency	.081	4, 55	1.21	.32
2	Homorganicity	.037	1, 54	2.27	.14
3	Sonority	.052	1, 53	3.35	.08
		Experiment 5			
Plateaus vs. falls					
1	Onset frequency	.060	4, 55	<1	*ns*
2	Homorganicity	.041	1, 54	2.47	.122
3	Sonority	.000	1, 53	<1	*ns*

Table 15
Stepwise Linear Regression Analyses of Responses to Printed Stimuli (Experiments 2, 4, and 5)

Comparison and step	Predictor	ΔR^2	*df*	*F*	*p*
		Experiment 2			
Rises vs. plateaus					
1	Homorganicity	.074	1, 58	4.66	.04
2	Sonority	.081	1, 57	5.43	.02
3	Onset frequency	.143	4, 53	2.71	.04
		Experiment 4			
Rises vs. plateaus					
1	Homorganicity	.000	1, 58	<1	
2	Sonority	.06	1, 57	3.67	.06
3	Onset frequency	.196	4, 53	3.49	.01
Plateaus vs. falls					
1	Homorganicity	.017	1, 58	1.0	.31
2	Sonority	.003	1, 57	<1	*ns*
3	Onset frequency	.150	4, 53	2.40	.07
		Experiment 5			
Plateaus vs. falls					
1	Homorganicity	.013	1, 58	<1	.31
2	Sonority	.002	1, 57	<1	*ns*
3	Onset frequency	.086	4, 53	1.26	.29

[9] Differences between the behaviors of readers and speakers could potentially reflect the contribution of spelling to reading. Because spelling provides readers with unambiguous cues for presence of a cluster, it could have attenuated the repair of marked onsets in reading even if the phonological constraints on reading and spoken language were isomorphic. Such an account, however, incorrectly predicts that, like speakers, readers should have been sensitive to the effect of grammatical markedness—a prediction that is inconsistent with the present results.

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Appendix A

Auditory Nonwords Used in Experiments 1 and 3

	Unattested		
Attested	Sonority rise	Sonority plateau	Sonority fall
blɪf	bwɪf	bdɪf	lbɪf
brœp	bnœp	bdœp	rgœp
klɪm	knɪm	kpɪm	lpɪm
krɛg	knɛg	ktɛg	rtɛg
drɪf	dlɪf	dbɪf	rdɪf
drœf	dlœf	dgœf	rdœf
dwɪb	dmɪb	dgɪb	mdɪb
dwʌp	dmʌp	dgʌp	mdʌp
drʌp	dnʌp	dbʌp	rdʌp
drɪʃ	dnɪʃ	dgɪʃ	rbɪʃ
glɛb	gmɛb	gdɛb	lgɛb
glœn	gmœn	gbœn	lfœn
grɛf	gmɛf	gbɛf	rgɛf
gwɪd	gmɪd	gbɪd	mgɪd
klɛθ	kmɛθ	ktɛθ	lkɛθ
krœf	kmœf	kpœf	rgœf
krɪg	knɪg	ktɪg	rkɪg
kwʌg	knʌg	kpœg	mkʌg
klœb	kmʌb	ktœb	ltœb
krɛp	kmɛp	ktɛp	rkɛp
plɪg	pnɪg	pkɪg	ltɪg
prœf	pnœf	ptœf	rpœf
trʌf	tlʌf	tkʌf	rtʌf
twɛp	tlɛp	tkɛp	mtɛp
trœg	tnœg	tkœg	rtœg
twœf	tmœf	tpœf	mtœf
trɛf	tnɛf	tpɪf	rtɛf
twʌk	tnʌk	tgʌk	mgʌk
trœb	tmœb	tpœb	rpœb
twœg	tmœg	tpœg	mtœg

Note. Experiment 1 used the attested, unattested-rise, and plateau clusters; Experiment 3 used the unattested clusters with sonority rise, plateau, and fall.

Appendix B

Nonword Foils Used in ɛxperiments 2, 4, and 5

	Unattested		
Attested	Rise	Plateau	Fall
blif	bwif	bdif	lbif
brop	bnop	bdop	rbop
clim	cnim	cpim	lkim
creg	cneg	cteg	rkeg
drif	dlif	dbif	rdif
drof	dlof	dgof	rdof
dwib	dmib	dgib	wdib
dwup	dmup	dgup	wdup
drup	dnup	dbup	rdup
drish	dnish	dgish	rdish
glɛb	gmeb	gdeb	lgeb
glon	gmon	gbon	lgon
gref	gmef	gbef	rgef
gwid	gmid	gbid	wgid
kleth	kmeth	kteth	lketh
kraf	kmaf	kpaf	rkaf
crig	cnig	ctig	rkig
cwug	cnug	cpug	wcug
clob	cmob	ctob	lcob
crep	cmep	ctep	rkep
plig	pnig	pkig	lpig
praf	pnaf	ptaf	rpaf
truf	tluf	tpuf	rtuf
twep	tlep	tkep	wtep
trog	tnog	tkog	rtog
twaf	tmaf	tkaf	wtaf
tref	tnef	tpif	rtef
twuk	tnuk	tpuk	wtuk
trab	tmab	tpab	rtab
twog	tmog	tpog	wtog

Note. Experiment 2 used the attested, unattested-rise, and plateau clusters; Experiment 4 used the unattested clusters with sonority rise, plateaus, and falls; Experiment 5 used the attested, unattested-plateau, and unattested-fall clusters.

Appendix C

The Pseudohomophonic Targets Used in Experiments 2, 4, and 5

blaid, blaiz, brane, braik, braiv, bryde, brite, brode, klam, klap, klash, klass, klick, kliff, klip, klock, klog, klot, klutch, krack, krash, krip, kross, drane, dreem, drout, phlag, phlake, phlame, phlat, phlesh, phlip, phreeze, phresh, phrog, glair, glaiz, glyde, glume, gloo, graid, grane, graip, graf, graiv, fraze, playt, pleez, praze, preech, pryce, pryde, pryme, pryze, proon, kwake, kweer, kween, kwest, kwick, kwill, skail, skan, skar, skeem, skope, skore, skrap, skreem, skreen, skript, scirt, slaiv, smyle, snale, snaik, spyce, spyne, stane, staik, stail, stayr, steem, strayt, strype, thryve, trale, trane, trate, trybe

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