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People's knowledge of phonological universals: evidence from fricatives and stops

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PEOPLE'S KNOWLEDGE OF PHONOLOGICAL UNIVERSALS:
EVIDENCE FROM FRICATIVES AND STOPS

A dissertation presented

by

Tracy Jordan Lennertz

to

The Department of Psychology

In partial fulfillment of the requirements for the degree of
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ABSTRACT OF DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Psychology
in the Graduate School of Arts and Sciences of
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Abstract

Do people have knowledge concerning universal restrictions on the sound structure of language? Optimality Theory (Prince & Smolensky, 1994/2006) predicts that people's knowledge about phonology includes universal, grammatical restrictions. Such restrictions are active in the grammars of all speakers, irrespective of whether the particular structures occur in one's language. The present research tests this prediction using the sonority of fricatives (e.g., *f*) and stops (e.g., *p*) as a case study.

Past research examined people's sensitivity to universal constraints on the sonority distance of onset clusters (the co-occurring consonants at the beginning of the syllable, e.g., *pl* in *please*). The frequency of onset clusters across languages is constrained: onsets such as *pl* are more frequent than onsets such as *pn*, which, are more frequent than onsets such as *pt*. Least frequent are onsets such as *lp*. Moreover, if a language allows an infrequent onset to occur, it also tends to allow more frequent ones, but not vice versa. Sonority, an abstract phonological property, can account for these observations. Glides are the most sonorous consonants (e.g., *w, y*), followed by liquids (e.g., *l, r*), nasals (e.g., *m, n*), and obstruents—a group comprising both fricatives (e.g., *f, z*) and stops (e.g., *p, t*). The sonority distance between two consonants can be computed with these levels. An onset like *pl* consists of a large rise in sonority—starting with the less sonorous *p* and rising to the more sonorous *l*, *pn* is a small rise, *pt* is a sonority plateau, including two consonants from the same level, and lastly *lp* falls in sonority. Languages vary in their minimum sonority distance. For example, English requires onsets have a large rise (e.g., *pl*), whereas Russian allows onsets with falling sonority (e.g., *lp*). But, languages that allow small distances tend to also admit larger ones, whereas languages that allow large distances do not necessarily admit smaller ones (Greenberg, 1978; Berent, Steriade, Lennertz, & Vaknin, 2007). Such cross-linguistic regularities

might reflect a universal grammatical constraint that favors onsets with large sonority distance over onsets with smaller sonority distance (e.g., $pl > pn > pt > lp$; “>” denotes grammatical well-formedness). If this restriction is, in fact, active in the grammars of all speakers, then people should favor better-formed onsets over ill-formed ones even if all onset types are unattested in their language.

Previous experimental results by Berent and colleagues (2007; 2008; 2009) are consistent with this possibility. Berent et al. (2007) demonstrated that English speakers are sensitive to the sonority distance of onset clusters that are absent in English (e.g., $pn > pt > lp$). Speakers’ sensitivity was inferred from their tendency to systematically misidentify illicit onset clusters. Past research has shown that illicit onsets are often misidentified to conform to native language restrictions (e.g., $tila \rightarrow tela$; Pitt, 1998). Berent et al. observed that people’s rate of misidentification is systematically modulated by sonority distance—monosyllables whose onsets comprise small sonority distances are more likely to be misidentified as disyllabic (e.g., $lpik \rightarrow lepik$) relative to monosyllables whose onsets comprise larger sonority distances (e.g., $pnik$). This pattern cannot be attributed to an inability to correctly perceive the phonetic form of the onset (similar results obtain with printed materials; Berent & Lennertz, 2010), nor is it explicable by the statistical properties of the onsets. Accordingly, Berent et al. interpreted such misidentification as evidence for the ill-formedness of onsets with small sonority distances. The finding that misidentification was systematically modulated by the sonority distance of onsets that are all unattested in the speakers’ language further suggests that the grammar includes universal restrictions on sonority distance.

This dissertation extends this past research to investigate whether people possess knowledge of fine-grained distinctions among the sonority levels that are unattested in their language. Specifically, I investigate the whether people encode the putatively universal

distinction between the sonority levels of fricatives and stops. Across languages, fricatives and stops differ in their sonority levels. Fricatives (e.g., *f*) are more sonorous than stops (e.g., *p*; Dell & Elmedlaoui, 1985). Productive phonological alternations in English, however, do not make this distinction. The present research examines whether English speakers nonetheless consider fricatives more sonorous than stops. To the extent that English speakers are sensitive to this distinction, and this distinction cannot be explained by their linguistic experience, such finding would provide evidence for the universality of the distinction between the sonority levels of fricatives and stops.

The following research infers the sonority levels of fricatives and stops from their sonority distance. If English speakers consider fricatives more sonorous than stops, then the rise in a fricative-nasal onset (e.g., *fn*) should be *smaller* than the rise in a stop-nasal one (e.g., *pn*). Consequently, the sonority distance between fricative-initial onsets with rising (e.g., *fn*) and level (e.g., *fs*) sonority should be attenuated relative to the distance between stop-initial onsets with rising (e.g., *pn*) and level (e.g., *pt*) sonority. To gauge English speakers' knowledge of the sonority levels of fricatives and stops, onsets with rising sonority (e.g., *fn*, *pn*) were thus compared to matched onsets with level sonority (e.g., *fs* or *pt*). Given that English speakers misidentify ill-formed monosyllables with small sonority distances as disyllabic (Berent et al., 2007), and that the rise in fricative-nasal onsets is smaller than the rise in stop-nasals ones, one would expect the rate of misidentification for rises and plateaus to be more similar for fricative-initial monosyllables compared to stop-initial ones. Therefore, when compared to matched sonority plateaus, stop-nasal monosyllables should be identified more accurately than fricative-nasal ones: people should identify them more readily as monosyllables, and more accurately distinguish them from disyllabic counterparts.

Four experiments compared English speakers' perception of sonority distance in onsets composed of either stops or fricatives. Materials comprised CCVC non-words (e.g., *pnik*) and their matched disyllabic counterparts (e.g., *penik*). The critical manipulation concerned two aspects of the monosyllables: 1) the sonority distance of the onset—a small rise (e.g., *pn*), plateau (e.g., *pt*), or fall (e.g., *lp*) and 2) whether the onset comprised a stop (e.g., *p*) or a fricative (e.g., *f*). In Experiments 1-2, participants determined if an auditory non-word (e.g., *fnik*; *fenik*) had one syllable or two. Monosyllables with a stop-initial onset of rising sonority (e.g., *pnik*) yielded more accurate responses than stop-initial monosyllables with a sonority plateau (e.g., *ptik*). In contrast, responses to fricative-initial monosyllables with rising (e.g., *fnik*) and level (e.g., *fsik*) sonority did not differ. In Experiment 3, participants determined if a pair of auditory stimuli (e.g., *pnik-penik*; *fnik-fenik*) was identical. Non-identical trials with sonority rises elicited faster responses than plateaus given items comprising stop-initial, but not with fricative-initial onsets. These results are consistent with the prediction that the sonority distance between fricative-initial onsets is attenuated relative to stop-initial ones, and consequently, English speakers consider fricatives more sonorous than stops. It is possible, however, that such misidentifications reflect an inability to perceive the phonetic properties of stop-onsets relative to fricative-ones. But, the results from Experiment 4 with printed materials countered this interpretation. In this experiment, people remained sensitive to the sonority level of the onset—a stop or a fricative—even when presented with printed monosyllables, inputs that carry no phonetic information. In particular, the identification of printed stop-initial items was modulated by sonority distance, whereas no such effect was observed for fricative-initial ones.

Overall, the results are consistent with the prediction that English speakers consider fricatives more sonorous than stops. If the ranking of the sonority levels of fricatives and stops cannot be learned from experience in English, then the English findings would suggest that

speakers universally represent fricatives as more sonorous than stops. To gauge universality, additional analyses examined evidence for the distinction between fricatives and stops in the English lexicon. The results showed that the sonority distinction between fricatives and stops cannot be captured by the co-occurrence of features in English, as performance was selectively modulated by sonority-relevant distinctions. Specifically, people were indifferent to the co-occurrence of features irrelevant to sonority (e.g., place), but sensitive to the co-occurrence of features relevant to sonority (e.g., manner). Nonetheless, the English results do not necessarily require that the ranking of the sonority levels of fricatives and stops be universally specified. Additional analyses showed that, if the grammar was equipped with substantive knowledge related to sonority (including knowledge that sonorants are more sonorous than obstruents, knowledge that obstruents comprise both fricatives and stops, and a preference for onsets with large sonority distances), then English speakers could potentially use their lexical experience to infer that fricatives are *more* sonorous than stops. While the ranking of these sonority levels could be learned, such inference presupposes knowledge that fricatives and stops comprise *different* sonority levels, and such knowledge appears to be unlearnable from lexical experience. Thus, while the English results cannot inform the origins of the ranking of fricatives as more sonorous than stops, they do suggest that distinction between their sonority levels might be universal.

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Table of Contents

Abstract.....	3
Acknowledgements	8
Table of Contents	10
Introduction.....	11
Experiment 1	19
Method.....	20
Results	25
Discussion.....	29
Experiment 2	33
Method.....	35
Results	35
Discussion.....	37
Experiment 3	38
Method.....	39
Results	41
Discussion.....	46
Experiment 4	47
Method.....	50
Results	52
Discussion.....	56
General Discussion	58
References	74
Appendices	84

Introduction

English speakers agree that *plik* could be a possible word whereas *lpik* could not be—despite never encountering *plik* or *lpik* before (cf. Chomsky & Halle, 1965). Such observations suggest that people have productive knowledge about the sound structure of language. But what is the source of such knowledge? On one account, people’s knowledge about phonology is *only* constrained by their experience with a particular language. For example, English has words that begin with *pl-* as in *please*, but no words begin with *lp-*. English speakers may prefer *plik* to *lpik* because it has a familiar sequence (Chambers, Onishi, & Fisher, 2003; Dell, Reed, Adams, & Meyer, 2000; McClelland & Plaut, 1999; Onishi, Chambers, & Fisher, 2002; Saffran, Aslin, & Newport, 1996) that is easier to perceive (Blevins, 2004, 2006; Ohala, 1990; Ohala & Kawasaki-Fukumori, 1997; Wright, 2004) and produce (Locke, 2000; MacNeilage & Davis, 2000; Redford, 2008).

On another account, people’s linguistic preferences reflect broad knowledge of grammatical phonological principles that go beyond their language-particular experience. People may have knowledge of phonological universals—grammatical restrictions on the sound structure of language (Chomsky, 1965, 1980; Pinker, 1994; Prince & Smolensky, 1993/2004). Such grammatical restrictions, for example, could disfavor syllables like *lpik* relative to *plik*. Optimality Theory (Prince & Smolensky, 1993/2004; Smolensky & Legendre, 2006)—a theory of generative grammar—predicts that such restrictions are active in the grammars of all speakers, even if the relevant linguistic structures are absent in their language.

The present research tests this prediction. We investigate whether speakers have knowledge of putatively universal restrictions on phonology. Our specific case concerns people’s knowledge of sonority, a phonological feature that correlates with intensity. Across languages, fricatives (e.g., *f*, *s*, *v*) and stops (e.g., *p*, *t*, *g*) differ with respect to sonority: fricatives are more

sonorous than stops. Productive phonological alternations in English, however, provide no evidence for the distinction between the sonority of fricatives and stops (Giegerich, 1992). Here, we examine whether English speakers are sensitive to this distinction. To the extent that English speakers lack any experience relevant for this distinction, their sensitivity to the distinction between the sonority levels of stops and fricatives would provide evidence for the universality of this distinction. The issue of whether such experience is in fact present in English will be considered in detail in the General Discussion.

Evidence for phonological universals: Onset clusters as a case study

Our present investigation of the sonority levels of fricatives and stops forms part of a broader research program that examines speakers' sensitivity to universal grammatical constraints on the sonority structure of onset clusters (Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Berent, Lennertz, Smolensky, & Vaknin, 2009; Berent, Steriade, Lennertz, & Vaknin, 2007). Onset clusters are strings of consonants occurring at the beginning of the syllable (e.g., *pl* in *please*). Although many languages allow onset clusters, not all clusters are treated alike: onsets such as *pl* are more frequent across languages compared to onsets such as *pn*, which in turn are more frequent than onsets such as *pt*. Least frequent across languages are onsets such as *lp*. Moreover, if a language permits an infrequent onset (e.g., *lp*) it also tends to allow the more frequent ones (e.g., *pl*), but not vice versa (Greenberg, 1978). Sonority can account for this cross-linguistic restriction (Clements, 1990). Sonority is an abstract, phonological property of sounds correlated with intensity (Clements, 1990; Ladefoged, 2001; Parker, 2002, 2008). Glides are the

most sonorous consonants (e.g., *y*, *w*), followed by liquids (e.g., *l*, *r*), nasals (e.g., *n*, *m*), and obstruents—a group of sounds that includes both stops (e.g., *p*, *b*, *t*, *k*) and fricatives (e.g., *f*, *z*, *sh*)¹.

Using these sonority levels, one can compute the sonority distance between any two consonants. For example, the onset *pl* begins with an obstruent, *p*, and rises positively in sonority to *l*, a liquid. An onset such as *pn* manifests a smaller rise, *pt* has a sonority plateau—it comprises two sounds from the same level—and lastly, *lp* falls in sonority. Languages vary in the minimum sonority distance that they tolerate. English requires that onsets have a large sonority rise (e.g., *pl*), whereas Russian even allows onsets with falling sonority (e.g., *lp*). Despite this cross-linguistic diversity, the sonority profile within a language is systematically constrained: if a language allows an onset with a small sonority distance (e.g., *lp*), it also tends to allow larger sonority distances (e.g., *pt*, *pn*, *pl*). But, languages that allow large sonority distances do not necessarily tend to tolerate smaller ones (Greenberg, 1978; reanalyzed in Berent et al., 2007). The cross-linguistic preference (indicated by $>$) is thus $pl > pn > pt > lp$.

Optimality Theory (Prince & Smolensky, 1994/2006) attributes such typological facts to a set of universal grammatical constraints. Specifically, the $pl > pn > pt > lp$ preference reflects a universal, grammatical constraint that favors onsets with large sonority distances over small ones: a large sonority rise (e.g., *pl*) is preferred to a smaller sonority rise (e.g., *pn*), which is preferred to a sonority plateau (e.g., *pt*). Least preferred are onsets with a sonority fall (e.g., *lp*; Smolensky, 2006). While these grammatical restrictions may not be arbitrary—a preference for large sonority distance may indeed have several phonetic explanations (Gordon, 2007; Hayes, 2004; Hayes & Steriade, 2004)—such constraints are algebraic and abstract. Moreover, these

¹ For ease of exposition, orthography is frequently used to specify phonetic representations (e.g., /ʃ/ is transcribed as “sh” and /ə/ as “e”).

constraints are active in the grammars of all speakers, regardless of whether the particular onsets occur in one's language.

Are speakers sensitive to the sonority distance of onset clusters?

A large body of research suggests that people are sensitive to the sonority distance of onset clusters that are attested in their language. Ill-formed onsets with small sonority distances are more difficult to produce in first-language acquisition (Barlow, 2001a, 2005; Gierut, 1999; Gnanadesikan, 2004; Ohala, 1999; Pater & Barlow, 2003) and are less likely to be retained in aphasic speech (Bastiaanse, Gilbers, & van der Linde, 1994; Christman, 1992; Code & Ball, 1994; Romani & Calabrese, 1998; Stenneken, Bastiaanse, Huber, & Jacobs, 2005). Moreover, sonority distance appears to constrain performance in lexical decision tasks (Alonzo & Taft, 2002), and word games (Fowler, Treiman, & Gross, 1993; Moreton, Feng, & Smith, 2005; Treiman, 1984; Treiman, Bowey, & Bourassa, 2002; Treiman & Cassar, 1997; Treiman & Danis, 1988; Treiman & Zukowski, 1990; Yavas & Gogate, 1999). However, the findings of studies that examine sonority restrictions using attested onset clusters are inconclusive. Indeed, unattested onsets are not only ill-formed but also unfamiliar. Accordingly, the preference for better-formed onsets may be due to familiarity, not grammatical constraints. Fewer studies have investigated speakers' sensitivity to sonority distance using only unattested onset clusters. Results suggest that ill-formed unattested clusters are more difficult to accurately produce than better-formed ones (Broselow & Finer, 1991; Davidson, 2006; Eckman & Iverson, 1993) and are judged as less likely to occur in one's native language (Pertz & Bever, 1975).

Building on this past research, Berent and colleagues (2007; 2008; 2009) systematically examined speakers' preferences concerning the sonority distance of unattested onset clusters. In particular, Berent et al. (2007) examined English speakers' perception of highly ill-formed onsets

with a sonority fall (e.g., *lp*), less ill-formed onsets with a sonority plateau (e.g., *pt*), and better-formed onsets with a small sonority rise (e.g., *pn*). People's knowledge about onset clusters was inferred from the phenomenon of misidentification. Related work in speech perception has observed that ill-formed clusters are often misidentified to conform to native-language phonotactics (Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Dupoux, Pallier, Kakehi, & Mehler, 2001; Hallé, Segui, Frauenfelder, & Meunier, 1998; Kabak & Idsardi, 2007; Massaro & Cohen, 1983; Moreton, 2002; Pitt, 1998). In particular, Pitt (1998) demonstrated that a speaker's knowledge of permissible phoneme sequences triggers perceptual illusions: English speakers judged monosyllables with unattested onsets, such as *tla*, as disyllabic (e.g., as *tela*). Berent et al. (2007) suggested that these perceptual illusions might be due to the grammatical ill-formedness of such clusters. Accordingly, if people are sensitive to the sonority distance of unattested onset clusters (e.g., $pn > pt > lp$) and if ill-formedness results in misidentification (e.g., *lpa* → *lepa*), then the rate of misidentification should be modulated by universal sonority restrictions. That is, monosyllables with an ill-formed onset (e.g., *lpik*) may be more likely to be misidentified as having two syllables (e.g., *lepik*) compared to monosyllables with a better-formed onset (e.g., *ptik*).

In accord with this prediction, Berent et al. (2007) found that the rate of misidentification is inversely related to the sonority profile of the onset: as the sonority distance of an onset decreased (e.g., $pn > pt > lp$), people were more likely to misidentify the onset consonants as separated by a vowel (e.g., *lpik* → *lepik*). Specifically, in a syllable count task (e.g., “does *lpik* have one or two syllables?”), speakers more often misidentified monosyllabic non-words with onsets manifesting a fall in sonority (e.g., *lpik*) as having two syllables compared to monosyllabic non-words with onsets manifesting a sonority plateau (e.g., *ptik*), which in turn, were more often misidentified as disyllabic compared to monosyllabic non-words with onsets manifesting a

sonority rise (e.g., *pmik*). Similarly, in an auditory AX identity judgment task² (e.g., “is *lpik* identical to *lepik*?”) monosyllables with onsets manifesting a fall or plateau in sonority were more often misjudged as identical to their disyllabic counterparts compared to monosyllables with onsets manifesting a sonority rise.

Additional results rule out the possibility that the misidentification of ill-formed onsets is caused by their statistical or phonetic properties. A statistical account—the possibility that better-formed onsets (e.g., *pn*) are preferred because they resemble onsets attested in the English lexicon (e.g., *snack*)—is challenged by the demonstration of similar preferences among speakers of Korean, a language whose lexicon lacks onset clusters altogether (Berent et al., 2008). Other findings preclude a phonetic explanation. In the phonetic view, the misidentification of ill-formed onsets reflects not a grammatical repair, but rather the inability to encode the phonetic properties of such onsets from the acoustic input. However, this possibility is countered by the replication of the original findings with printed materials (Berent & Lennertz, 2010). Taken together, the findings suggest that people share grammatical preferences regarding the sonority distance of onset clusters that do not occur in their language, and these preferences converge with the distribution of onset clusters across languages.

A new case study: The sonority levels of fricatives and stops

The results described so far suggest that people have knowledge concerning sonority distances that are unattested in their language (e.g., sonority plateaus vs. falls). In all these cases,

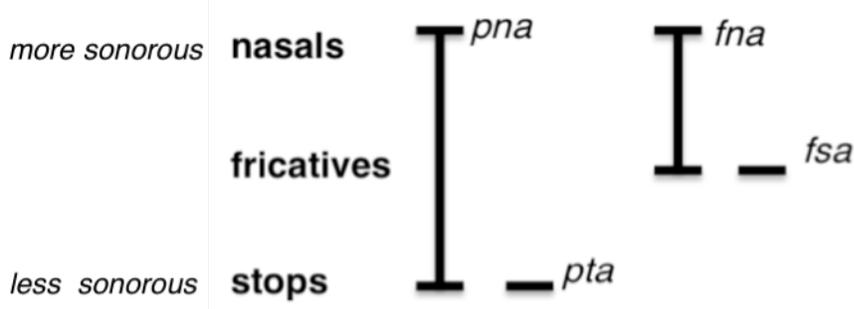
² In this task, participants were not explicitly instructed on what counts as “identical” - whether it refers to token- or type-identity. Throughout the experiment, however, identical items comprised identical tokens, whereas non-identical items comprised different types. Participants were provided with a practice session including several such trials. Given this practice and the clear distinction between identical and non-identical trials, the nature of the task was made amply clear.

however, sonority distances invariably comprised of segments whose sonority levels can be discerned from active phonological alternations in speakers' language. For example, despite not having encountered sonority falls (e.g., *lb*), English speakers have ample experience that could attest to the fact that the liquid *l* is more sonorous than the stop *b*. While those earlier findings suggest that the ranking of sonority distances might be universal (e.g., sonority plateaus are preferred to falls), they do not address the question of whether knowledge of sonority levels (e.g., liquids are more sonorous than stops) might be likewise universally shared. The present work examines this question. As we next demonstrate, linguistic evidence suggests that fricatives and stops differ on their sonority level, but the grammar of English treats them alike. Our question is whether English speakers are nonetheless sensitive to this distinction.

The possibility that fricatives are universally more sonorous than stops is supported by various types of evidence. Cross-linguistically, these two types of obstruents manifest different patterns of syllabification (Dell & Elmedlaoui, 1985; Hankamer & Aissen, 1974; Rose, 2000; Steriade, 1982, 1988). For example, in Imdlawn Tashlhiyt Berber (a language spoken in Morocco), any segment can act as the syllable nucleus. More sonorous segments, however, are preferred as syllable nuclei compared to less sonorous ones, and, notably, fricatives are preferred as syllable nuclei over stops (e.g., the word *'tʃikt'* is syllabified as *'tʃ.tkt'* not *'tʃT.kt'*; with a period marking the syllable boundary and capitalization denoting the nucleus; Dell & Elmedlaoui, 1985). Additional linguistic evidence for the distinction between the sonority levels of fricatives and stops comes from first language-acquisition (Barlow, 2003; Gnanadesikan, 2004; Ohala, 1999; Pater & Barlow, 2003; Stoel-Gammon, 1985), performance in language-games (Barlow, 2001b), co-occurrence restrictions (Coetzee & Pater, 2008), and patterns of loan-word adaptation (Gouskova, 2001).

The distinction between the sonority levels of fricatives and stops should also have a direct measurable effect on the sonority profile of obstruent-onsets. If fricatives are more sonorous than stops, then the sonority rise in fricative-nasal onsets (e.g., *fn*) should be *smaller* than stop-nasal combinations (e.g., *pn*). To gauge the sonority distance of such rises, we can use sonority plateaus as a baseline. If fricatives are more sonorous than stops, then the distance between sonority rises and plateaus should be attenuated for fricative-initial onsets (e.g., *fn-fs*) compared to stop-initial ones (e.g., *pn-pt*; see Figure 1). Assuming, further, that small sonority distances are ill-formed, we should predict that, compared to plateaus, stop-onsets with a small rise (e.g., *pn*) should be preferred relative to fricative-onsets with a small rise (e.g., *fn*).

Figure 1. A comparison of the sonority distance between stop- and fricative-onsets with rising and level sonority.



Past research (Berent et al., 2007; Berent et al., 2008; Berent & Lennertz, 2010) has examined people's knowledge of sonority distances comprising sonorants and stops. Although these results establish that English speakers are sensitive to sonority distances that are unattested in their language (i.e., small rise, plateau, fall), they do not address the possibility that English speakers might further distinguish between the sonority levels of these two categories of obstruents (i.e., fricatives and stops).

The present research addresses this question. In four experiments, we examine whether the sonority of onsets comprising fricatives differs from those comprising stops. To this end, we compare the sonority distance of obstruent-onsets that include either stops or fricatives. Our materials are monosyllabic CCVC non-words with onsets that are unattested in English (e.g., *pnik*) and their matched CeCVC counterparts (e.g., *penik*). The critical manipulation concerns two aspects of the monosyllables: (a) the sonority distance of the onset—either small rises, plateaus or falls; and (b) the nature of the obstruent consonant in the onset—either a stop (e.g., *p*, *t*) or a fricative (e.g., *f*, *sh*). Replicating past research, we expect participants will be sensitive to sonority distance: as the sonority distance of a monosyllabic non-word decreases, people will be more likely to misidentify the non-word as disyllabic (e.g., *lpik* → *lepik*). Of interest is whether people further differentiate between the sonority levels of fricatives and stops.

In Experiments 1-2, participants determine if an auditory non-word has one syllable or two; Experiment 3 uses an identity judgment task (e.g., “is *fnik* identical to *fenik*?”). If small sonority distances are ill-formed, then as sonority distance decreases, people will be more likely to misidentify CCVC items as disyllabic (in Experiments 1-2) and they will misjudge them as identical to their disyllabic counterparts (in Experiment 3). It is conceivable, however, that such misidentifications are due not to the phonological ill-formedness of certain onsets but rather to their phonetic properties. To address this possibility, Experiment 4 replicates Experiment 3 using *printed* materials. If the misidentification of ill-formed onsets reflects a grammatical process, then this process should emerge in all experiments, irrespective of input modality.

Experiment 1

Experiment 1 used the syllable-count task to examine whether English speakers are sensitive to the universal distinction between the sonority levels of fricatives and stops. In each

trial, participants heard a single auditory stimulus, either a monosyllable or a disyllable (e.g., *fnik*, *fenik*), and indicated whether it included one syllable or two. Two critical aspects of the monosyllables were manipulated: the sonority distance of the onset cluster (i.e., small rise, plateau, or fall) and the type of the obstruent consonant in the onset (i.e., fricative or stop).

If English speakers consider fricatives as more sonorous than stops, then the sonority rise in fricative-nasal onsets (e.g., *fn*) should be smaller compared to stop-nasal ones (e.g., *pn*). Accordingly, the difference between rises and plateaus should be attenuated for fricative-initial onsets (e.g., *fn* vs. *fs*) compared to stop-initial ones (e.g., *pn* vs. *pt*). This difference should be evident in the susceptibility of fricative- vs. stop-initial onsets to misidentification. Recall that English speakers misidentify onsets with small sonority distances, such that the onset consonants are separated by a vowel (*pt* → *pet*), and the rate of misidentification is monotonically related to sonority distance. In particular, previous research with stop-initial onsets showed that onsets of rising sonority (e.g., *pn*) are typically less likely to undergo misidentification compared to onsets with level sonority (e.g., *pt*), and we expect this pattern to replicate with the present stop-initial onsets as well. But if the sonority rise in fricative-nasal onsets is attenuated, then their propensity for misidentification should be more similar to that of sonority plateaus. Accordingly, when compared to sonority plateaus, onsets of rising sonority should yield more accurate monosyllabic responses for stop- compared to fricative-initial items.

Method

Participants. Twenty-four native English speakers, undergraduate students at Northeastern University, participated in Experiment 1 in partial fulfillment of a course requirement.

Materials. The experimental materials consisted of 48 pairs of non-words presented aurally. In each pair, one non-word was monosyllabic (e.g., CCVC, /fnik/) and the other was disyllabic (e.g., CəCVC, /fənik/).

All monosyllables had an unattested onset cluster that included an obstruent consonant. Two properties of the onset were manipulated: sonority distance and obstruent type. The sonority distance manipulation contrasted three types of onsets: Onset with small rises, comprised of an obstruent followed by a nasal; sonority plateaus, comprised of two obstruents (either two stops or two fricatives), and sonority falls, including a sonorant (e.g., either a liquid or nasal) followed by an obstruent. The second critical manipulation concerned the nature of the obstruent consonant in the onset—either a stop (e.g., *p*, *t*) or a fricative (e.g., *f*, *sh*).

These two variables were crossed and manipulated within items. To this end, the items were arranged in triplets that were matched for their rhyme, and differed only on their sonority distance (i.e., small rise, plateau, fall). In half of the triplets, the onset included a fricative (e.g., *f*, *sh*), and in the other half, the onset had a stop (e.g., *p*, *t*).

The monosyllabic items were subject to three sets of restrictions. The first set of restrictions matched items within a triplet (i.e., small rise, plateau, fall) on several linguistic dimensions. First, the consonants within an onset never shared the same place of articulation; this is because onsets with consonants sharing the same place of articulation are less preferred across languages than onsets with differing places of articulation (Kreitman, 2006). Second, we matched the triplet members for place of articulation—in half of the triplets, onsets comprised labial-coronal sequences (e.g., /fnik/-/fsik/-/msik/) whereas the other half comprised coronal-labial sequences (e.g., /fmik/-/ffik/-/lfik/). This restriction controlled for fronting—the preference for place of articulation to move from front-to-back over back-to-front (cf. Byrd,

1992). Because English lacks labial liquids, sonority-falls beginning with a labial consonant were invariably nasal-initial (e.g., /msik/). Finally, we matched triplet members on voicing and restricted plateaus to two voiceless consonants, as sonority plateaus that disagree on voicing are less frequent across languages (Greenberg, 1978). Sonority plateaus were likewise matched for the manner of articulation—either two fricatives (e.g., /fs/) or two stops (e.g., /pt/), but *not* a fricative-stop combination (e.g., /ft/).

A second set of restrictions matched the triplets with a fricative-onset to those with a stop-onset. First, both fricative- and stop-triplets included only voiceless obstruents. Second, fricative-triplets and stop-triplets were matched for their place of articulation: One-half of the triplets for each obstruent-type included an onset with a labial-coronal sequence and one-half included an onset with a coronal-labial sequence.

A final set of restrictions matched the stop- and fricative-triplets for their rhyme. First, each stop-triplet was matched with a fricative-triplet that had the same nucleus (i.e., vowel) in the rhyme. Second, each stop-triplet and fricative-triplet was matched for their coda with the following restrictions: the choice of the coda for each triplet was limited by the place of articulation of both the first and second consonants and whether the obstruent was a fricative or a stop. A fricative was not used as a coda for fricative-triplets and a stop was not used as a coda for stop-triplets; therefore, the coda was not matched identically across fricative- and stop-triplets. These restrictions were placed on the coda to avoid violation of the obligatory contour principle: adjacent phonemes did not share identical features (Berent, Vaknin, & Shimron, 2004; McCarthy, 1986). The phoneme /k/—a voiceless velar stop—was chosen as an ideal coda for both fricative- and stop-triplets because it did not overlap in place of articulation with any of the consonants in the onset regardless of obstruent-type. This coda was used for fricative- and stop-triplets with both a labial-coronal and coronal-labial place of articulation. In addition, triplets

with a labial-coronal onset also had a voiceless coronal as the coda—/t/ for fricative-triplets and /ʃ/ for stop-triplets. These additional codas were chosen to provide variation in the monosyllabic items.

The materials also included 48 disyllabic non-words. Each such disyllable was matched to a monosyllable—the two were identical on all segments except for the presence of an epenthetic schwa between the two initial consonants (e.g., CəCVC; /fənik/). Likewise, the monosyllabic and disyllabic pair members were matched as closely as possible in their pitch contour and overall acoustic quality.

In addition to the 48 pairs of experimental items described above, the experiment also included 16 pairs of filler items, composed of monosyllabic non-words with a large sonority rise and their disyllabic counterparts (e.g., /flik/-/fəlik/). The monosyllabic pair member had an onset that is attested in English—an obstruent followed by a sonorant. One-half of the obstruents were fricatives (e.g., /flik/) and one-half of the obstruents were stops (e.g., /plik/). These fillers were included to encourage participants to treat the unattested items as permissible English words. Since the perception of these items may be constrained by either their sonority distance or familiarity, they were not included in the data analyses and were not subject to the stringent linguistic controls placed on the experimental items. Appendix A lists all monosyllabic experimental and filler items.

A female native Russian speaker recorded the materials, as all onsets are permissible in Russian. The speaker read the items from a pseudo-randomized list presented in Cyrillic. The items were read in the context of “X raz” (i.e., X once) and the monosyllabic item from each pair always preceded the disyllabic one. The speaker had a clear Russian accent. Participants in this

and subsequent experiments were familiarized to her voice by listening to her read a brief recorded passage prior to the practice trials.³

Stimuli validation. In line with previous research, we predict that onsets with small sonority distances should be misidentified as disyllabic more often than onsets with larger sonority distances. To assure that such misidentifications are not simply due to artifacts related to the articulation of the materials by the Russian talker, we presented the same items to a group of six Russian speakers. If the ill-formed monosyllabic items are tainted by phonetic cues that invariably signal disyllabicity, then these items should be identified as disyllabic by all listeners, irrespective of their linguistic experience. The performance of Russian participants, however (see Table 1) suggests otherwise. Russian participants identified the monosyllables with high accuracy ($M = 96.18\%$). A 2 obstruent-type X 2 sonority-distance (plateaus and falls only, performance for small rises was nearly at ceiling) ANOVA yielded no significant effects (all $F < 3.51$, $p = 0.10$). Although the interpretation of such null effects based on a small number of participants requires caution, the results do suggest that our monosyllabic items are indeed representable as such. No significant effects were obtained with disyllables (all $F < 1.37$, $p = 0.30$).

³ An additional 48 pairs of non-words comprised of voiced obstruents constructed in the same manner as described above were also recorded. An inspection of the voiced onsets determined that our Russian speaker systematically produced a schwa-like event following the initial consonant. In pilot research, we observed that such items consistently elicited a disyllabic perception, and English speakers even had difficulty perceiving some of the attested monosyllabic items correctly (e.g., *bluk*). As such, the voiced items were not included in this and subsequent experiments.

Table 1. Mean response accuracy to monosyllables in the Russian syllable count task as a function of obstruent-type and sonority distance (N = 6).

	Small Rise	Plateau	Fall
Fricative	100.0	97.9	93.8
Stop	93.8	97.9	93.8

Procedure. Participants, wearing headphones, were seated in front of a computer. Each trial began with a fixation point (“*”) and a message indicating the trial number. The participant pressed the space bar key to initiate the trial, triggering the presentation of a 500 ms silence, followed by the auditory stimulus. The participant entered his/her response using the numeric keypad (1 = one syllable, 2 = two syllables). Participants were instructed to respond quickly and were told that it was important for their response to be accurate.

Prior to the experimental trials, participants were familiarized with the procedure with practice trials on real English words (e.g., *drive-derive*). Feedback on response accuracy was provided in the practice trials only. Feedback on response time was not provided in either the practice or experimental trials. Each participant responded to all mono- and disyllabic items, a total of 128 experimental trials: 2 syllables (monosyllabic, disyllabic) X 2 obstruent-types (fricative, stop) X 4 sonority distances (fillers, small rise, plateau, fall) X 8 items. Trial order was randomized for each participant and the entire procedure took about 20 minutes.

Results

In this and all subsequent experiments, outliers were defined as correct responses falling 2.5 SD above the mean or faster than 200 ms and removed from the analysis of response time. We considered a response accurate if it matched the talker’s intended production (e.g.,

monosyllabic responses produced by the talker given monosyllabic printed inputs). In Experiment 1, outliers amounted to 3.62 % of the total correct responses. We next inspected responses to monosyllabic and disyllabic items separately.

Responses to monosyllabic items

Figure 2 displays the effect of sonority distance and obstruent-type on response accuracy (the corresponding response times are provided in Table 2). In this and all figures, error bars reflect confidence intervals constructed to the difference between the sonority distances of a given obstruent type (e.g., between stop-items with sonority rises, plateaus and falls).

The effect of obstruent-type and sonority distance was investigated by means of 2 obstruent-type X 3 sonority distance ANOVAs conducted on response accuracy and response time for subjects (F1) and items (F2). These analyses yielded a significant main effect of obstruent-type in response accuracy ($F(1, 23) = 57.58$, $MSE = 0.033$, $p < 0.0001$; $F(1, 7) = 51.87$, $MSE = 0.012$, $p < 0.0002$; in response time: both $F < 3.43$, $p = 0.10$) and sonority distance in response accuracy and time (response accuracy: $F(2, 46) = 145.66$, $MSE = 0.032$, $p < 0.0001$; $F(2, 14) = 83.71$, $MSE = 0.018$, $p < 0.0001$; in response time: $F(2, 16) = 24.56$, $MSE = 20792$, $p < 0.0001$; $F(2, 12) = 25.95$, $MSE = 17093$, $p < 0.0001$). Planned contrasts showed that participants responded significantly more accurately ($t(46) = 3.01$, $p < 0.005$; $t(14) = 2.28$, $p < 0.04$; in response time, both $p > 0.4$) to onsets of rising sonority compared to sonority plateaus, which, in turn, produced more accurate ($t(46) = 13.05$, $p < 0.0001$; $t(14) = 9.89$, $p < 0.0001$) and faster ($t(16) = 5.57$, $p < 0.00005$; $t(12) = 5.75$, $p < 0.0001$) responses compared to onsets of falling sonority. Lastly, participants responded more accurately ($t(46) = 16.06$, $p < 0.0001$; $t(14) = 12.17$, $p < 0.0001$) and faster ($t(16) = 6.47$, $p < 0.0001$; $t(12) = 6.63$, $p < 0.0001$) to onsets of rising compared to onsets of falling sonority. Crucially, the analysis

of response accuracy produced a significant interaction ($F_1(2, 46) = 17.78$, $MSE = 0.020$, $p < 0.0001$; $F_2(2, 14) = 14.46$, $MSE = 0.008$, $p < 0.0004$).⁴

We next turned to examine the effect of sonority distance on response accuracy to monosyllables with stop- and fricative-onsets separately. An analysis of stop-onsets yielded a reliable simple main effect of sonority distance ($F_1(2, 46) = 38.21$, $MSE = 0.036$, $p < 0.0001$; $F_2(2, 14) = 31.44$, $MSE = 0.015$, $p < 0.0001$). Planned contrasts showed that onsets with a small sonority rise elicited more accurate responses compared to plateaus ($t_1(46) = 3.13$, $p < .004$; $t_2(14) = 2.84$, $p < 0.02$), which, elicited more accurate responses compared to sonority falls ($t_1(46) = 5.50$, $p < 0.0001$; $t_2(14) = 4.99$, $p < 0.0002$).

A similar analysis of fricative-onsets also yielded a significant simple main effect of sonority distance ($F_1(2, 46) = 225.42$, $MSE = 0.016$, $p < 0.0001$; $F_2(2, 14) = 99.07$, $MSE = 0.012$, $p < 0.0001$). Like their stop-initial counterparts, fricative-initial onsets of rising and level sonority each yielded more accurate responses compared to sonority falls (*rises*: $t_1(46) = 18.99$, $p < 0.0001$; $t_2(14) = 12.59$, $p < 0.0001$; *plateaus*: $t_1(46) = 17.71$, $p < 0.0001$; $t_2(14) = 11.74$, $p < 0.0001$). But unlike their stop-counterparts, responses to fricative-initial onsets of rising sonority did not differ from plateaus (both $p > 0.21$). Thus, sonority rises differed from plateaus given stop, but not fricative-initial onsets.

⁴ This interaction in Experiment 1 was largely confirmed by a mixed logit model: a 2 obstruent-type X 3 sonority distance model yielded a significant interaction ($\beta = 0.298$, $SE = 0.062$, $\zeta = -4.839$, $p < 0.0001$). The 2 obstruent-type X 2 sonority distance (small rises and plateaus only) model failed to reach significance, but was in the predicted direction ($\beta = 0.124$, $SE = 0.101$, $\zeta = 1.22$, $p < 0.23$).

Figure 2. Mean response accuracy in Experiment 1 as a function of syllabicity, sonority distance, and the nature of the obstruent in the onset (N = 24). Error bars represent the confidence intervals constructed for the difference among the means.

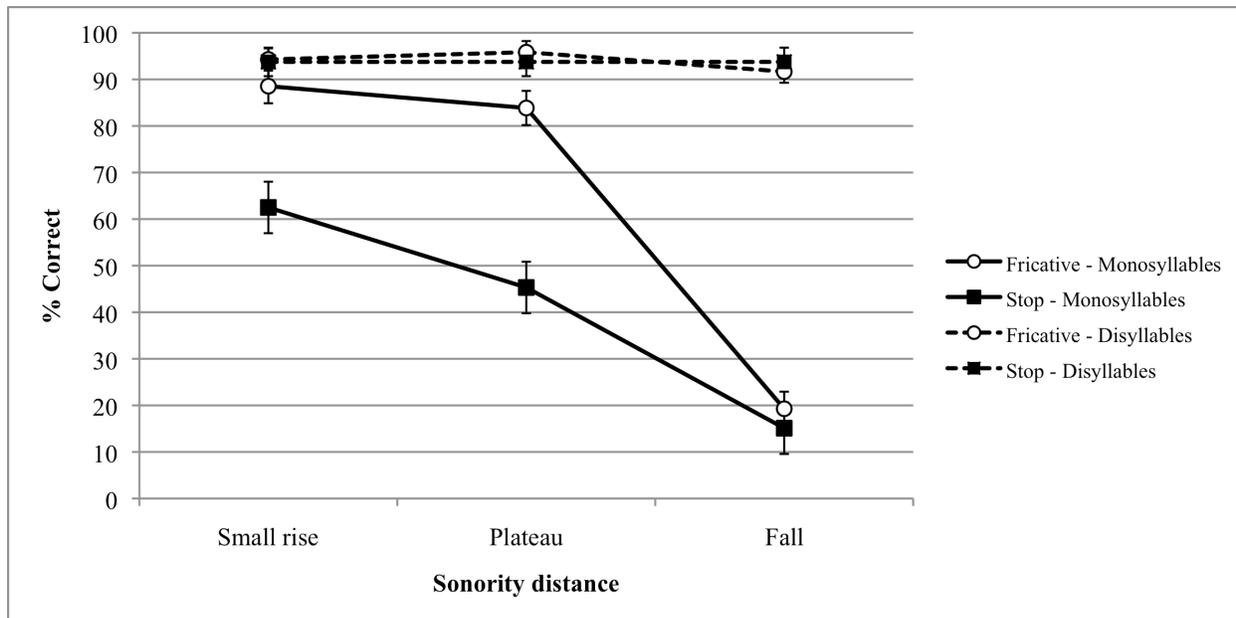


Table 2. Mean correct response time (ms) to monosyllables in Experiment 1 as a function of sonority distance and obstruent type. Standard deviations are indicated in parentheses. Note participants with missing data are excluded from the subject analyses (N = 9).

	Small Rise	Plateau	Fall
Fricative	1185 (140)	1211 (220)	1476 (272)
Stop	1103 (180)	1165 (125)	1435 (330)

Responses to disyllabic items

Mean response accuracy to disyllables is shown in Figure 2. A 2 obstruent-type X 3 sonority distance ANOVA on response accuracy to disyllables did not yield any significant effects (all $F < 1$). Similar ANOVAs conducted on response time yielded a reliable main effect of

obstruent type (F1 (1, 23) = 11.29, MSE = 18674, $p < 0.003$; F2 (1, 7) = 58.37, MSE = 1115, $p < 0.0002$) and a significant interaction (F1 (2, 46) = 4.21, MSE = 16909, $p < 0.03$; F2 (2, 14) = 3.53, MSE = 8983, $p < 0.058$).⁵ The effect of sonority distance was next examined separately for the disyllabic counterparts of fricative- and stop-onsets.

An analysis of the disyllabic counterparts of stop-onsets yielded a simple main effect of sonority distance (F1 (2, 46) = 5.26, MSE = 13105, $p < 0.009$; F2 (2, 14) = 4.49, MSE = 6728, $p < 0.04$). As shown in Table 3, responses to the disyllabic counterparts of sonority falls were significantly slower compared to the counterparts of both rises (t_1 (46) = 3.10, $p < 0.004$; t_2 (14) = 2.78, $p < 0.02$) and plateaus (t_1 (46) = 2.38, $p < 0.03$; t_2 (14) = 2.36, $p < 0.04$), which, in turn, did not differ (both $p > 0.5$). A similar analysis of the disyllabic counterparts of fricative-onsets did not yield a simple main effect of sonority distance (both $F < 2.42$, $p = 0.10$).

Table 3. Mean correct response time (ms) to disyllables in Experiment 1 as a function of sonority distance and obstruent-type. Standard deviations are indicated in parentheses (N = 24).

	Small Rise	Plateau	Fall
Fricative	1265 (184)	1204 (194)	1214 (219)
Stop	1109 (173)	1133 (226)	1211 (200)

Discussion

The results of Experiment 1 suggest that English speakers differentiate between the sonority levels of fricatives and stops. Replicating previous research, stop-initial onsets of rising

⁵ A mixed linear model confirmed the interaction in response time: a 2 obstruent-type X 3 sonority distance model yielded a significant interaction ($\beta = -0.019$, $SE = 0.005$, $t = -3.8$). The 2 obstruent-type X 2 sonority distance (small rises and plateaus only) model in response time also yielded a marginally significant interaction ($\beta = -0.015$, $SE = 0.009$, $t = -1.8$).

sonority yielded more accurate responses compared to sonority plateaus. In contrast, responses to fricative-initial onsets of rising and level sonority did not differ. People's indifference to the sonority rise in fricative-initial onsets is in line with the hypothesis that fricatives are more sonorous than stops. Because the sonority cline between an obstruent and a nasal is attenuated for fricative-initial onsets, their well-formedness is more similar to plateaus, and consequently, they are just as likely to result in misidentification—a reflex of ill-formedness.

On an alternative account, the similar rate of misidentification of fricative-initial onsets with rising and level sonority may reflect a ceiling effect caused by the overall higher level of accuracy associated with the identification of fricatives. To evaluate this possibility, we split the participants into two groups based on their overall mean accuracy for both mono- and disyllabic items. If the pattern of misidentification for fricative-initial monosyllables reflects a ceiling effect, then this pattern should be absent in the low-accuracy group. A 2 group X 2 obstruent-type X 3 sonority distance ANOVA yielded a significant three-way interaction ($F_1(2, 44) = 8.78$, $MSE = 0.02$, $p < 0.0007$; $F_2(2, 28) = 7.23$, $MSE = 0.01$, $p < 0.003$), but this effect was solely due to the identification of monosyllables with falling sonority only (means are provided in Table 4).

Indeed, a test of the simple 2 group X 2 obstruent-type X 2 sonority distance (small rises and plateaus) interaction did not approach significance ($F_1 < 2.09$, $p = 0.16$; $F_2 < 2.00$, $p = 0.18$).

Moreover, a separate analysis of the low-accuracy group mirrored the omnibus pattern.

Specifically, the 2 obstruent-type X 3 sonority distance ANOVA yielded a significant interaction ($F_1(2, 22) = 22.53$, $MSE = 0.02$, $p < 0.0001$; $F_2(2, 14) = 21.40$, $MSE = 0.01$, $p < 0.0001$). The simple main effect of sonority distance was significant for both fricative-initial monosyllables ($F_1(2, 22) = 77.93$, $MSE = 0.02$, $p < 0.0001$; $F_2(2, 14) = 53.36$, $MSE = 0.02$, $p < 0.0001$) and stop-initial ones ($F_1(2, 22) = 8.81$, $MSE = 0.02$, $p < 0.002$; $F_2(2, 14) = 8.12$, $MSE = 0.02$, $p < 0.005$). Planned comparisons confirmed that sonority falls produced lower accuracy than

sonority rises for either fricative- ($t_1(22) = 11.43, p < 0.0001, t_2(14) = 9.46, p < 0.0001$) or stop-initial items ($t_1(22) = 4.20, p < 0.0004, t_2(14) = 4.03, p < 0.002$). However, while stop-initial items produced higher accuracy for sonority rises compared to plateaus ($t_1(22) = 2.10, p < 0.05, t_2(14) = 2.02, p < 0.064$), this contrast was not significant for fricative-initial items (both $p > 0.18$). The convergence of the omnibus findings with those of the low-accuracy group counters the possibility of a ceiling effect. These results suggest that English speakers might, in fact, distinguish between the sonority levels of fricatives and stops.

Table 4. Mean response accuracy in Experiment 1 as a function of overall accuracy, obstruent-type and sonority distance (N = 12 per accuracy-group).

		Small Rise	Plateau	Fall
High Accuracy	Fricative	96.9	95.8	28.1
	Stop	87.5	66.7	19.8
Low Accuracy	Fricative	80.2	71.9	10.4
	Stop	37.5	24.0	10.4

This possibility, however, also raises a puzzle. If fricatives are more sonorous than stops, then one might have expected sonorant-stop onsets (e.g., *lp*) with a larger fall to elicit less accurate responses compared to sonorant-fricative ones (e.g., *lf*). This, however, was not observed, possibly because this subtle distinction was overshadowed by the overwhelming propensity of sonority falls to elicit disyllabic responses. Further evidence for the great difficulty in the identification of sonority falls is seen in the responses to their disyllabic counterparts. Participants were significantly slower responding to the counterparts of sonority falls (e.g., *lepik*) compared to the counterparts of sonority rises and plateaus (e.g., *penik, petik*). Because disyllables do not differ

in terms of their sonority distance, this must be a carry-over effect from their monosyllabic counterparts. Specifically, the great difficulty in the identification of monosyllables of falling sonority could have led participants to exercise caution with any sonorant-initial item, as such items are potentially monosyllables of falling sonority. Consequently, sonorant-initial items, both monosyllables and disyllables, produced slower responses compared to obstruent-initial ones.

Sonority-independent factors could likewise explain the main effect of obstruent type. Across sonority distance, fricative-initial onsets produced higher accuracy relative to their stop-initial counterparts, for both small rises ($F_1(1, 23) = 27.28$, $MSE = 0.030$, $p < 0.00003$; $F_2(1, 7) = 30.60$, $MSE = 0.009$, $p < 0.0009$) and plateaus ($F_1(1, 23) = 54.76$, $MSE = 0.033$, $p < 0.0001$; $F_2(1, 7) = 89.50$, $MSE = 0.007$, $p < 0.00004$). Because the sonority cline of fricative-initial onsets is smaller than stop-initial onsets, sonority-related factors should have only increased the ill-formedness of fricative-initial onsets, thereby increasing the propensity of such items to disyllabic repair. The opposite was observed and must be therefore due to some other factors. The acoustic properties of stop consonants could capture this effect. The speech signal of stop-, but not fricative-consonants, is discontinuous (Stevens, 1989)—following the release burst of a stop consonant, there is a reduction in the energy of all formants, which breaks the speech signal. Previous research (Berent, Balaban, Lennertz, & Vaknin, in press) found that acoustic discontinuities in the speech signal promote the identification of the speech input as disyllabic. The discontinuity of stops in the present experiment could have likewise elevated the disyllabic misidentification of stop-initial monosyllables (both sonority rises and plateaus), putting them at a disadvantage relative to fricative-initial monosyllables.

Although performance in this experiment was clearly modulated by non-phonological factors, the main finding concerns the effect of sonority profile. Not only were people sensitive to the sonority distance of onsets unattested in their language, but this effect was further sensitive to

the status of the initial obstruent—fricative vs. stop. This finding is consistent with our hypothesis that people differentiate between the sonority levels of stops and fricatives.

Experiment 2

In Experiment 1, English speakers were sensitive to the putatively universal distinction between the sonority levels of stops and fricatives. Replicating past research, stop-initial onsets of rising sonority elicited more accurate responses compared to stop-initial onsets comprised of a sonority plateau. In contrast, fricative-initial onsets yielded no reliable differences between sonority rises and plateaus. These findings are consistent with the hypothesis that English speakers consider fricatives more sonorous than stops, thereby attenuating the sonority rise in fricative-initial onsets.

On an alternative account, however, the observed difference between fricatives and stops reflects not genuine differences in their sonority levels, but rather artifacts of our experimental design. Our experimental logic infers the sonority levels of fricatives and stops from their tendency to elicit disyllabic repair. Tacit in our approach is the assumption that, other things being equal, ill-formed onsets are repaired by inserting an epenthetic vowel between the two initial consonants—the greater the ill-formedness, the higher the tendency of epenthetic repair. It is conceivable, however, that fricative- and stop-initial onsets might undergo different types of repair (for similar concerns see Fleischhacker, 2001; Peperkamp, 2007): Stop-initial onsets could be repaired by inserting a schwa between the consonants (*epenthesis*, e.g., *pta* → *peta*), whereas fricative-initial onsets could be repaired by inserting a schwa before the onset cluster (*prothesis*, e.g., *fsa* → *efsa*).

Consider, now, how this possibility would affect performance in the syllable count task. Although the task does not explicitly elicit a comparison of monosyllables with their disyllabic

counterparts, it is conceivable that participants might rely on such a heuristic. Essentially, participants could make their syllable count response by deciding whether a monosyllabic input (e.g., *fsik*) is distinct from the default disyllabic alternative (e.g., *fesik*). The representation of the input, however, might depend on the sonority distance of the onset (sonority plateaus are more likely to elicit repair, irrespective of obstruent-type) and obstruent-type—stops are repaired epenthetically (e.g., *ptik* → *petik*); fricatives are repaired prothetically (e.g., *fsik* → *efsik*). But despite being equally likely to undergo repair, stop- and fricative-initial plateaus may not be equally likely to elicit a monosyllabic response. Because the encoding of stop initial-plateaus (e.g., *ptik* → *petik*) resembles the disyllables in our experiment (which are all epenthetic), they will be difficult to discriminate from disyllables hence accuracy will decline. In contrast, fricative-initial plateaus, encoded prothetically (e.g., *fsik* → *efsik*), will be quite distinct from disyllables (e.g., *fesik*), so they should be easy to discriminate from their monosyllabic counterparts—perhaps just as easy as rises. This scenario correctly predicts that sonority plateaus will produce lower accuracy than rises for stop- but not fricative-initial items despite no differences in the sonority levels of fricatives and stops. If so, the differential effects of sonority-distance for fricatives and stops might occur for reasons unrelated to their sonority.

Experiment 2 was designed to evaluate this possibility. In Experiment 2, participants were once again asked to indicate whether an auditory stimulus included one syllable or two, but disyllables were now prothetically-related to their monosyllabic counterparts (e.g., *fnik* vs. *efnik*). If the results of Experiment 1 are only due to use of epenthetic items for disyllables, then prothetic disyllables should yield the opposite outcomes: fricative-initial onsets with rising sonority should now elicit more accurate responses than onsets with level sonority, whereas no such effect should be found with stop-initial items. On the other hand, if English speakers consider fricatives more sonorous than stops, then the pattern of Experiment 1 should replicate: fricative-initial onsets of

rising and level sonority will elicit similar response accuracy, whereas stop-initial onsets of rising sonority will elicit more accurate responses than stop-initial onsets of level sonority.

Method

Participants. Sixteen native English speakers, undergraduate students at Northeastern University, participated in Experiment 2 in partial fulfillment of a course requirement. None of the participants had taken part in Experiment 1.

Materials. The materials were of the same design as Experiment 1, except disyllables included a prothetic (e.g., *efnik*) instead of an epenthetic vowel (e.g., *fenik*). The same female native Russian speaker recorded the materials. To ensure that all triplets matched in intonation and acoustic quality, both the monosyllables and disyllables were obtained from the same recording.

Procedure. The procedure was the same as Experiment 1, however the practice trials included prothetically-related real English words (e.g., *scribe-ascibe*).

Results

Correct responses falling 2.5 SD above the mean or faster than 200 ms (about 3.03 % of the total observations) were excluded from the analysis of response time. Responses to monosyllabic and disyllabic items were examined separately.

The analysis of disyllabic items yielded no significant effects (in response time, all $F < 2.97$, $p = 0.08$; in response accuracy, all $F < 1.83$, $p = 0.20$). In contrast, responses to monosyllabic items were strongly modulated by both sonority distance and obstruent type (see Figure 3). An ANOVA (2 obstruent-type X 3 sonority distance) on response accuracy yielded a

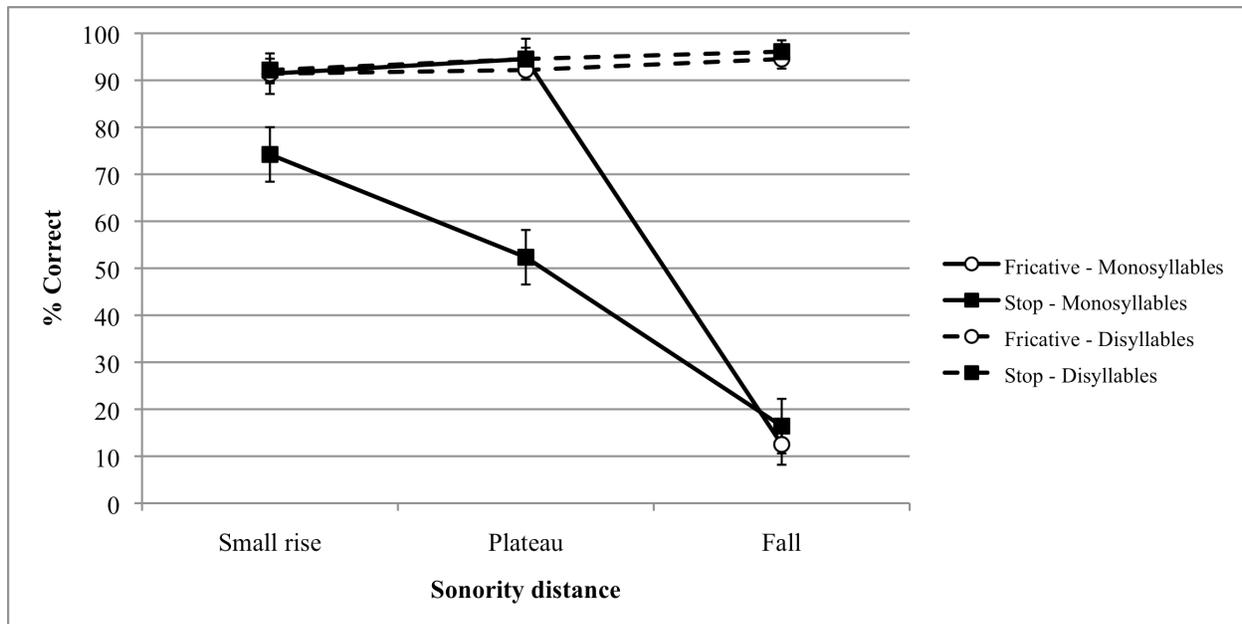
significant main effect of obstruent-type ($F_1(1, 15) = 47.29$, $MSE = 0.017$, $p < 0.0001$; $F_2(1, 7) = 16.91$, $MSE = 0.024$, $p < 0.005$) and sonority distance ($F_1(2, 30) = 168.27$, $MSE = 0.026$, $p < 0.0001$; $F_2(2, 14) = 112.57$, $MSE = 0.020$, $p < 0.0001$). Importantly, the interaction was significant in response accuracy ($F_1(2, 30) = 30.50$, $MSE = 0.014$, $p < 0.0001$; $F_2(2, 14) = 14.15$, $MSE = 0.015$, $p < 0.0005$).⁶ Similar analysis of response time yielded no significant effects ($F < 1.46$, $p = 0.27$).

The effect of sonority distance on response accuracy was next examined separately for monosyllables with stop- and fricative-onsets. An analysis of stop-onsets yielded a simple main effect of sonority distance ($F_1(2, 30) = 52.88$, $MSE = 0.026$, $p < 0.0001$; $F_2(2, 14) = 24.03$, $MSE = 0.028$, $p < 0.00004$). Planned contrasts demonstrated that onsets with a small rise yielded more accurate responses than plateaus ($t_1(30) = 3.85$, $p < 0.0006$; $t_2(14) = 2.60$, $p < 0.03$), which yielded more accurate responses than sonority falls ($t_1(30) = 6.33$, $p < 0.0001$; $t_2(14) = 4.27$, $p < 0.0008$).

An analysis of fricative-onsets also yielded a simple main effect of sonority distance ($F_1(2, 30) = 241.75$, $MSE = 0.014$, $p < 0.0001$; $F_2(2, 14) = 278.45$, $MSE = 0.006$, $p < 0.0001$). As in Experiment 1, fricative-initial onsets of rising and level sonority elicited more accurate responses than sonority falls (*rises*: $t_1(30) = 18.66$, $p < 0.0001$; $t_2(14) = 20.03$, $p < 0.0001$; *plateaus*: $t_1(30) = 19.40$, $p < 0.0001$; $t_2(14) = 20.82$, $p < 0.0001$). Crucially, however, response accuracy to fricative-initial onsets of rising sonority did not differ from plateaus (both $p > 0.4$).

⁶ This interaction in Experiment 2 was confirmed using a mixed logit model: a 2 obstruent-type X 3 sonority distance model yielded a significant interaction ($\beta = -0.459$, $SE = 0.084$, $\zeta = -5.481$, $p < 0.0001$). The 2 obstruent-type X 2 sonority distance (small rises and plateaus only) model also yielded a significant interaction ($\beta = 0.423$, $SE = 0.154$, $\zeta = 2.79$, $p < 0.01$).

Figure 3. Mean response accuracy in Experiment 2 as a function of syllabicity, sonority distance, and the nature of the obstruent consonant (N = 16). Error bars represent confidence intervals constructed for the difference between the means.



Discussion

The results of Experiment 2 replicate the main finding of Experiment 1: participants are sensitive to the sonority difference between sonority rises and plateaus only for stop-, but not for fricative-initial items. The persistent indifference to the sonority rise of fricative-nasal onsets, irrespective of the choice of the disyllables—with either epenthetic disyllables (e.g., *fenik*) in Experiment 1) or prothetic disyllables (e.g., *efnik*; in Experiment 2)—rules out the possibility that the differences between stop- and fricative-onsets are an artifact of a particular choice of disyllables in the experiment. In fact, our findings question the contention that the disyllabic counterpart affected syllable count. Had participants performed syllable count by comparing monosyllables to their disyllabic counterparts, then the rate of monosyllabic responses to stop-initial onsets should have been higher in the presence of prothetic disyllables, as previous

research (Berent et al., 2007) has shown that such items are typically repaired by epenthesis. Accordingly, an item such as *ptik* (recoded as *petik*) should be more readily discriminable from *eptik*, in Experiment 2, relative to *petik* (in Experiment 1). The comparable levels of performance across the two experiments are inconsistent with this possibility⁷.

Taken together, the results suggest that people's sensitivity to the distinction between the sonority levels of stops and fricatives is robust. Regardless of the disyllabic context, people consider fricatives more sonorous than stops, and consequently, the sonority distance between fricatives and nasals is attenuated relative to stop-nasal combinations. The smaller rise in sonority in *fn*-type items renders them more comparable to plateaus, resulting in a similar rate of misidentification.

Experiment 3

Our investigation of sonority distance, in general, and the sonority levels of stops and fricatives, specifically, gauges sonority distance from the tendency of an onset cluster to elicit repair. We have reasoned that small sonority distances trigger epenthetic repair, and consequently, the likelihood of epenthetic repair indicates sonority distance: the similar rate of repair for sonority rises and plateaus comprising fricative-initial onsets (e.g., *fn* vs. *fs*) was thus

⁷ A 2 group X 2 obstruent-type X 3 sonority distance ANOVA did not yield a significant three-way interaction (both $F < 1$), and a separate analysis of the low-accuracy group mirrored the omnibus pattern. Specifically, the 2 obstruent-type X 3 sonority distance ANOVA yielded a significant interaction ($F_1(2, 14) = 12.25$, $MSE = 0.02$, $p < 0.0009$; $F_2(2, 14) = 8.26$, $MSE = 0.03$, $p < 0.005$). The simple main effect of sonority distance was significant for both fricative-initial monosyllables ($F_1(2, 14) = 74.56$, $MSE = 0.02$, $p < 0.0001$; $F_2(2, 14) = 85.02$, $MSE = 0.02$, $p < 0.005$) and stop-initial ones ($F_1(2, 14) = 12.78$, $MSE = 0.03$, $p < 0.0007$; $F_2(2, 14) = 9.90$, $MSE = 0.04$, $p < 0.003$). Planned comparisons confirmed that sonority falls produced lower accuracy than sonority rises for either fricative- ($t_1(14) = 10.21$, $p < 0.0001$, $t_2(14) = 10.90$, $p < 0.0001$) or stop-initial items ($t_1(14) = 5.03$, $p < 0.0002$; $t_2(14) = 4.42$, $p < 0.0006$). While stop-initial items tended to elicit higher accuracy for sonority rises compared to plateaus ($t_1(14) = 2.05$, $p < 0.06$; $t_2(14) = 1.80$, $p < 0.094$), this contrast did not even approach significance for fricative items (both $p > 0.5$).

interpreted to suggest that their sonority distances are similar, more similar than stop-initial onsets (e.g., *pn* vs. *pt*). Those previous experiments, however, gauged repair by the tendency of monosyllables with ill-formed onsets to elicit a disyllabic syllable count. Experiment 3 presents a stronger test of this hypothesis. Here, people are asked to discriminate monosyllables from their disyllabic alternatives—a task that typically allows for more accurate performance than identification procedures. In each trial, participants heard two stimuli, either identical (e.g., *fnik-fnik*, *fenik-fenik*) or non-identical and epenthetically-related (e.g., *fnik-fenik*, *fenik-fnik*), and they were asked to indicate whether the two items were identical. Two questions are of interest. The first concerns sonority distance—Are monosyllables with ill-formed onsets still misidentified when people are directly asked to compare them to their disyllabic counterparts? The second question concerns the nature of the obstruent in the onset—Are responses modulated by whether the onset is comprised of a fricative or a stop?

If English speakers consider fricatives more sonorous than stops, then the sonority distance between sonority rises and plateaus should be attenuated for fricative-initial monosyllables relative to their stop-initial counterparts. Consequently, the advantage of sonority rises over plateaus (i.e., the faster and more accurate discrimination) should be larger for stop- compared to fricative-initial items.

Method

Participants. Thirty-six native English speakers, undergraduate students at Northeastern University, participated in Experiment 3 in partial fulfillment of a course requirement. None of the participants took part in the previous experiments.

Materials. The materials were the same as in Experiment 1. The materials were arranged in pairs. In one-half of the trials, pair members were token-identical, either monosyllabic (e.g., *fnik-fnik*) or disyllabic (e.g., *fenik-fenik*). In the other half of the trials, the pair members were non-identical and epenthetically-related (e.g., *fnik-fenik*, *fenik-fnik*). Next, the pairs were arranged in two counterbalanced lists: Each list included an equal number of identical and non-identical trials matched for sonority distance (i.e., small rise, plateau, fall), obstruent-type (i.e., fricative, stop), and presentation-order (i.e., non-identical trials were balanced for the occurrence of the monosyllabic item as either the first or second pair member). Within a list, a single item (e.g., *fnik*) was presented in either the identical trials or non-identical trials, but not in both. An additional 16 pairs of attested non-words (e.g., *flik-felik*) were included as fillers to encourage participants to treat the unattested items as permissible English words. Each list thus comprised 128 experimental trials: 2 identity (identical, non-identical) X 2 presentation-order (the monosyllable occurred in either the first or second position) X 2 obstruent-type (fricative, stop) X 4 sonority distance (fillers, small rise, plateau, fall) X 4 items. Each participant responded to both lists, presented in counterbalanced blocks.

Procedure. Participants, wearing headphones, were seated in front of a computer. Each trial began with a fixation point (“*”) and a message indicating the trial number. The participant initiated the trial by pressing space bar, triggering the presentation of a pair of auditory stimuli, with the second stimulus following the onset of the first by 1500 ms. Participants indicated if the stimuli were identical using the numeric keypad (1 = identical, 2 = non-identical). One-half of the trials included an identical pair, and the other half included a non-identical pair. Participants were instructed to respond quickly and were told that it was important for their response to be accurate.

Prior to the experimental trials, participants completed a short practice with real English words (e.g., *drive-derive*). Feedback on response accuracy was provided during the practice trials only; however, feedback on response time was provided during both the practice and experimental trials. To motivate participants to respond quickly, responses longer than 2500 ms, irrespective of their accuracy, triggered a warning message from the computer (“TOO SLOW”). Trial order was randomized. The entire procedure took about 30-minutes.

Results

Responses to identical trials were generally fast ($M = 988$ ms) and accurate ($M = 97.05\%$). Response accuracy and response time to identical trials are shown in Tables 5 and 6, respectively. Our interest is in responses to non-identical trials. Correct non-identical responses that were 2.5 SD above the mean or faster than 200 ms were excluded in the analysis of response time (about 3.02 % of the total observations).

Table 5. Mean response accuracy to identical trials in Experiment 3 as a function of syllabicity, obstruent-type and sonority distance ($N = 36$).

		Small Rise	Plateau	Fall
Fricative	CC-CC	95.5	93.1	96.9
	CeC-CeC	97.9	97.6	98.6
Stop	CC-CC	96.9	98.3	97.6
	CeC-CeC	96.9	98.6	96.9

Table 6. Mean response time (ms) to identical trials in Experiment 3 as a function of syllabicity, obstruent-type and sonority distance (N = 36). Standard deviations are indicated in parentheses.

		Small Rise	Plateau	Fall
Fricative	CC-CC	1036 (130)	1038 (141)	979 (134)
	CeC-CeC	1071 (112)	1059 (121)	1027 (143)
Stop	CC-CC	915 (116)	937 (131)	995 (131)
	CeC-CeC	905 (118)	927 (132)	983 (122)

Before turning to examine the main effects of interest, we conducted preliminary analyses designed to assure that performance was not contaminated by fatigue or learning across the two blocks of trials. We assessed the effects of block-order by means of 2 block X 2 obstruent-type X 3 sonority distance ANOVAs on response time and accuracy. Block did not interact with either obstruent-type or sonority distance (in response time, the block X sonority distance interaction approached significance by items only, $F_2 = 3.47$, $p = 0.06$, the interaction was likely driven by a decrease in response time to non-identical trials with sonority falls in the second block only; in accuracy, the three-way interaction approached significance by items only, $F_2 = 3.50$, $p = 0.06$, this interaction appears to be driven by a decrease in response accuracy to non-identical trials comprising stop-onsets with plateaus and falls relative to small rises in the second block only)⁸. Armed with the conclusion that block does not interact with sonority distance or obstruent-type, we next proceeded to examine effect of obstruent-type and sonority distance on response accuracy and response time, collapsing across block-order.

⁸ Despite the marginal significance of these interactions, the pattern of behavior was qualitatively identical across the two blocks. In response accuracy, people were more accurate with small rises compared to plateaus for both fricative- and stop-items. In response time, people took longer to correctly respond to non-identical trials with a plateau compared to small rises when the onset comprises a stop, but not a fricative.

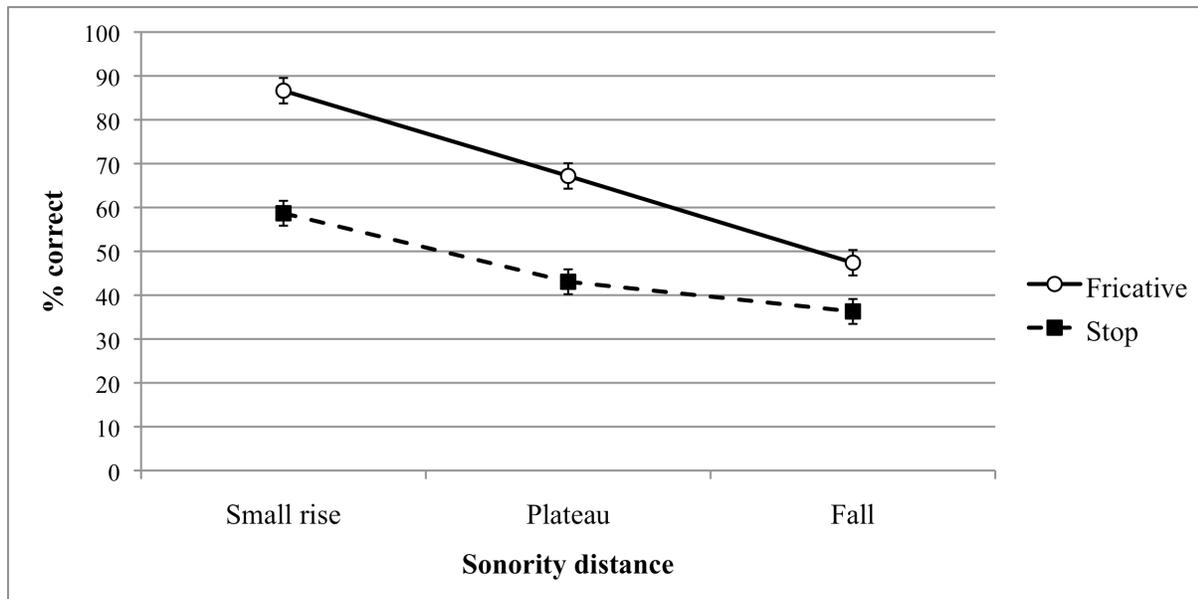
Response accuracy

Mean response accuracy to non-identical trials is shown in Figure 4. A 2 obstruent-type X 3 sonority distance ANOVA yielded a significant interaction ($F_1(2, 70) = 9.70$, $MSE = 0.014$, $p < 0.0002$; $F_2(2, 14) = 4.49$, $MSE = 0.007$, $p < 0.04$).⁹

The simple main effect of sonority distance was significant for both stop ($F_1(2, 70) = 32.55$, $MSE = 0.015$, $p < 0.0001$; $F_2(2, 14) = 7.13$, $MSE = 0.015$, $p < 0.008$) and fricative items ($F_1(2, 70) = 91.53$, $MSE = 0.015$, $p < 0.0001$; $F_2(2, 14) = 23.58$, $MSE = 0.013$, $p < 0.00004$). Planned contrasts demonstrated that sonority rises yielded more accurate responses compared to sonority falls for either stop ($t_1(70) = 7.89$, $p < 0.0001$; $t_2(14) = 3.68$, $p < 0.003$) or fricative items ($t_1(70) = 13.52$, $p < 0.0001$; $t_2(14) = 6.87$, $p < 0.00002$). Similarly, responses to plateaus tended to be more accurate compared to falls (for stop items: $t_1(70) = 2.38$, $p < 0.03$; $t_2, p > 0.3$; for fricative items: $t_1(70) = 6.82$, $p < 0.0001$; $t_2(14) = 3.46$, $p < 0.004$). Crucially, however, responses to sonority rises were significantly more accurate compared to sonority plateaus with both stop ($t_1(70) = 5.49$, $p < 0.0001$; $t_2(14) = 2.57$, $p < 0.03$) and fricative items ($t_1(70) = 6.70$, $p < 0.0001$; $t_2(14) = 3.40$, $p < 0.005$). Moreover, A 2 obstruent-type X 2 sonority distance (small rises and plateaus only) ANOVA did not yield a significant interaction (both $F < 1.04$, $p = 0.32$). Thus, the accuracy data provide no evidence for the attenuation of the sonority rise for fricative-initial items.

⁹ A mixed 2 obstruent-type X 3 sonority distance logit model confirmed the interaction in response accuracy from Experiment 3 ($\beta = -0.147$, $SE = 0.027$, $\zeta = -5.432$, $p < 0.0001$). The 2 obstruent-type X 2 sonority distance (small rises and plateaus only) model also yielded a significant interaction in response accuracy ($\beta = -0.138$, $SE = 0.051$, $\zeta = -2.731$, $p < 0.01$).

Figure 4. Mean response accuracy to non-identical trials in Experiment 3 as a function of sonority distance and the nature of the obstruent in the onset (N = 36). Error bars reflect confidence intervals constructed for the difference between the means.



Response time

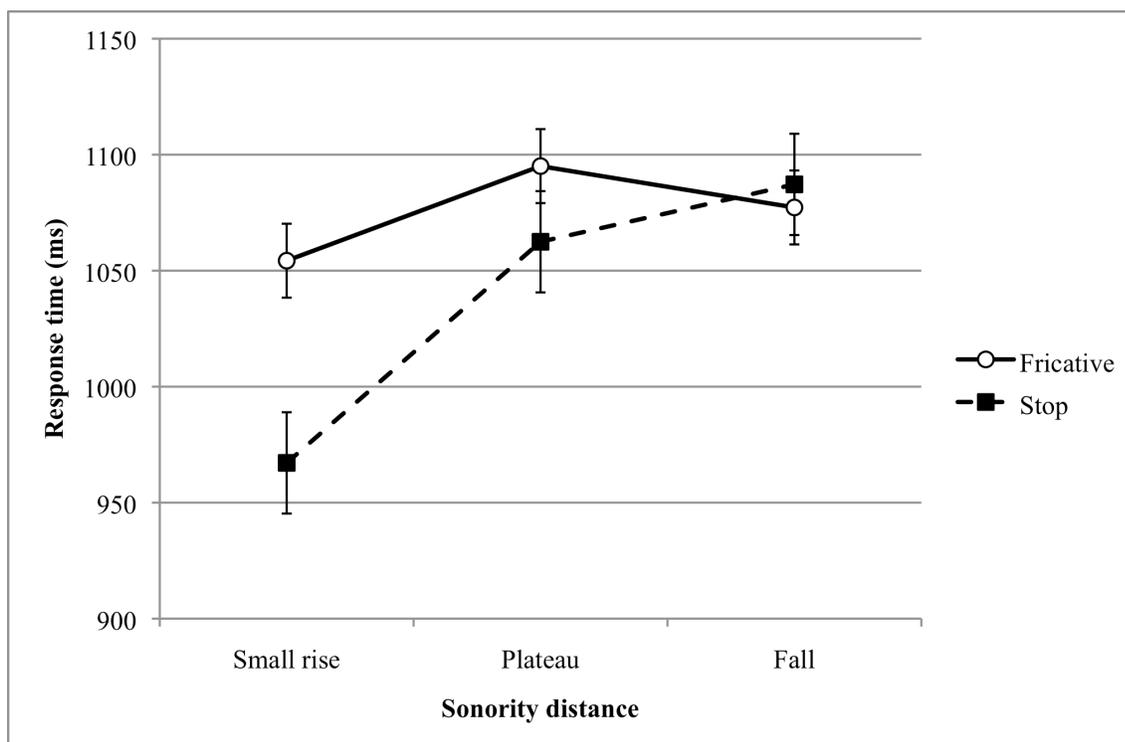
Mean correct response time for non-identical trials as a function of sonority distance and obstruent-type is presented in Figure 5. An inspection of the means suggests that the difference in sonority distance between sonority rises and plateaus was smaller for fricative-initial onsets compared to stop-initial ones. These conclusions are supported by the significance of the interaction in a 2 obstruent-type X 3 sonority distance ANOVA ($F_1(2, 68) = 6.19$, $MSE = 6699$, $p < 0.004$; $F_2(2, 14) = 5.45$, $MSE = 1444$, $p < 0.02$).¹⁰

Responses to non-identical trials with stop- and fricative-onsets were next examined separately. The analysis of fricative items did not yield a reliable simple effect of sonority

¹⁰ A mixed a 2 obstruent-type X 3 sonority distance linear model confirmed the interaction in response time in Experiment 3 ($\beta = -0.015$, $SE = 0.004$, $t = -3.8$). The 2 obstruent-type X 2 sonority distance (small rises and plateaus only) model in response time also yielded a significant interaction ($\beta = -0.012$, $SE = 0.006$, $t = -2.1$).

distance (both $F < 2.54$, $p = 0.09$). In contrast, sonority distance reliably modulated responses to stop items ($F_1(2, 68) = 16.82$, $MSE = 8362$, $p < 0.0001$; $F_2(2, 14) = 20.42$, $MSE = 1665$, $p < 0.0001$). Planned contrasts showed that onsets of falling sonority yielded reliably slower responses compared to sonority rises ($t_1(68) = 5.49$, $p < 0.0001$; $t_2(14) = 6.39$, $p < 0.00003$), and marginally so compared to plateaus ($t_1, p > 0.26$; $t_2(14) = 3.07$, $p < 0.009$). Crucially, however, responses to sonority plateaus were also slower than sonority rises ($t_1(68) = 4.36$, $p < 0.0001$; $t_2(14) = 3.32$, $p < 0.006$). Thus, participants were sensitive to the different sonority distance of rises and plateaus for stops, but not for fricative items.

Figure 5. Mean correct response time for non-identical trials in Experiment 3 as a function of sonority distance and the nature of the obstruent in the onset ($N = 35$). Error bars reflect confidence intervals constructed for the difference between the means.



Discussion

Experiment 3 examined the representation of sonority-distance using a discrimination task. Of interest was whether people would still misidentify ill-formed monosyllables with small sonority distances despite being able to compare them with their disyllabic counterparts. Replicating previous findings (Berent et al., 2007), the results yielded reliable effects of sonority distance in both response time and response accuracy: As sonority distance decreased, people were less accurate and slower to distinguish monosyllables from their disyllables counterparts, a finding consistent with the hypothesis that ill-formed onsets with small sonority distance are encoded epenthetically. Moreover, sonority distance was modulated by the type of obstruent—stop or fricative. This effect, however, acquired different forms in response time and response accuracy.

The analysis of response accuracy yielded no evidence that the rise in sonority from an obstruent to a nasal was smaller for fricative- compared to stop-initial onsets. This finding, which counters the results from syllable count, could be due to the change in task demands. Specifically, the explicit comparison of monosyllables with their disyllabic counterparts could have allowed participants to discriminate among them even when the sonority rise was attenuated for fricative-initial onsets. Doing so, however, incurred a cost in response time. Indeed, responses to fricative-initial onsets were overall slower than responses to stop-initial onsets. Moreover, the advantage of sonority rises compared to plateaus was smaller for fricative-initial onsets compared to stop-initial ones. This finding is consistent with our previous experiments, in which the effect of sonority distance was attenuated for fricative-initial onsets. These results suggest that people differentiate between the sonority levels of stops and fricatives, but the consequences of this distinction may be modulated by task demands.

Experiment 4

Why do people treat *fna* as more similar to *fsa*? One possibility is that this finding reflects people's knowledge of sonority—an abstract phonological feature. In this view, English speakers consider fricatives more sonorous than stops. Since the sonority rise between an obstruent and a nasal is attenuated for fricatives—fricative-nasal onsets of rising sonority are more similar to sonority plateaus than stop-nasal ones, and consequently, *fn-* and *fs-*type onsets elicit a more similar rate of repair.

On an alternative account, the more similar propensity of fricative-initial onsets to repair could be solely due to their phonetic properties. Fricatives are generally more perceptible than stops (Wright, 2004): they tend to be more intense (Parker, 2002, 2008) and longer in duration (Kent & Read, 1992). Relative to stops, fricatives also include stronger internal cues for place of articulation (Wright, Frisch, & Pisoni, 1999). Such cues might allow people to distinguish fricative-initial monosyllables (e.g., *fsa*) from their disyllabic counterparts (e.g., *fesa*) more readily than stop-initial pairs (e.g., *pta-peta*). Accordingly, the different patterns obtained with stop- and fricative-initial items reflect only their different phonetic properties, rather than their different sonority profiles.

To adjudicate between these possibilities, we next examine whether this pattern generalizes to *printed* onsets, when the input carries no phonetic information. A large body of research suggests that graphemes are mapped onto phonemes during silent reading (Lukatela & Turvey, 1993; Van Orden, 1987; Van Orden, Pennington, & Stone, 1990). The assembly of phonology from print is a fast (Berent & Perfetti, 1995; Perfetti & Bell, 1991) and automatic process that occurs even when phonological decoding is detrimental to task demands (e.g., the *Stroop* task; (Berent & Marom, 2005; Marom & Berent, 2010). Moreover, the phonological representations assembled from print are shaped by phonological constraints, including

constraints on sonority profiles that are unattested in one’s language (Berent et al., 2009; Berent & Lennertz, 2010). Experiment 4 thus uses printed materials to examine whether speakers’ phonological knowledge differentiates between the sonority levels of stops and fricatives.

In each trial, English speakers were presented with a succession of two printed non-words and determined if the non-words were identical; one half of the trials included graphemically identical items (e.g., *fsik-fsik*; *fesik-fesik*) and the other half of the trials included epenthetically-related non-identical items (e.g., *fsik-fesik*; *fesik-fsik*). Our interest concerns responses to non-identical trials. If the distinction between the sonority levels of fricatives and stops reflects only their phonetic structure, then this distinction should be eliminated given printed materials. On the other hand, if people possess phonological knowledge concerning the sonority levels of fricatives and stops, then responses to fricative-initial and stop-initial onsets should diverge even when no phonetic information is present. As in previous experiments, we expect that the difference between sonority rises and plateaus should be attenuated in fricative-initial onsets compared to stop-initial ones.

To ensure that participants base their response on the phonological, rather than the orthographic structure of the materials, Experiment 4 also included two sets of control conditions designed to gauge the assembly of phonology from print. One such condition—the phonological control—compared two types of non-identical trials that varied in the consistency of grapheme-phoneme mapping: inconsistent items (e.g., *clup-celup*) and consistent items (e.g., *blup-belup*). Both sets of items were matched on their number of shared graphemes, but differed on their number of shared phonemes. In the inconsistent items, the monosyllable and the disyllable members differ on the pronunciation of the “c” grapheme (e.g., /klup/ vs. /səlup/), and consequently, pair members differ by two phonemes. In contrast, consistent items differ only by a single phoneme (e.g., /blup/ vs. /bəlup/), so their phonemic difference is attenuated. If phonology is assembled

during silent reading, then participants should potentially be faster or more accurate at determining that a pair of inconsistent printed non-words (e.g., *clup-celup*) is not identical relative to a pair of consistent printed non-words (e.g., *blup-belup*).

A second test of the assembly of phonology from print is obtained by examining the effect of presentation order. Recall that in our non-identical trials, the monosyllabic pair member was presented either first (e.g., *fsik-fesik*) or second (e.g., *fesik-fsik*). In view of the long stimulus-onset asynchrony (SOA) between the two items—3000 ms—their comparison is likely to require the commitment of the first item to phonological working memory, and since phonology assembly is harder for monosyllables, the cost of holding the first item in memory should be higher for monosyllables. Phonology encoding should thus manifest itself as an order effect: responses to monosyllables should be impaired (i.e., slower and less accurate) when they are presented first compared to second.

Given that participants could engage in either phonological encoding or visual detection to respond correctly, we expect sonority effects to be less robust with printed materials compared to auditory stimuli, an expectation confirmed by past research (Berent & Lennertz, 2010). To maximize the sensitivity of our manipulation, the following experiment includes two counter-balanced blocks of trials—unlike previous research, in which only a single list of items was presented to each participant. Although this approach has the advantage of maximizing power, it runs the risk of promoting complex interactions due to learning or fatigue. To protect from such artifacts, we test for block effects before proceeding with our main analysis.

Method

Participants. Thirty-six native English speakers, undergraduate students at Northeastern University, participated in Experiment 4 in partial fulfillment of a course requirement. None of the participants took part in the previous experiments.

Materials. The materials comprised printed onsets identical to the onsets used in Experiment 3. In most cases (12/16), the same coda was used in Experiment 3 and 4. To constrain the number of letters in the orthographic representation, the vowel in the rhyme sometimes differed between the two sets of materials (e.g., /u/ was written as “u” instead of “oo”). Across the three sonority distances, however, the items were matched for their vowel, their coda and the number of letters. In the disyllables, the epenthetic schwa was written with the grapheme “e”. The only other change relative to the auditory version was the change in one of the triplets from “u” to “a” in order to avoid swear words. The experimental materials were arranged in two counterbalanced lists as described in Experiment 3. The monosyllabic materials are provided in Appendix B.

An additional subset was included to examine whether phonology is assembled from print in the non-identity condition. In this subset, one-half of the non-identical pair members differed by two phonemes (*inconsistent*; e.g., *clup-celup*)—the initial consonant and the epenthetic vowel. The other half of the non-identical pair members differed by only one phoneme (*consistent*; e.g., *blup-belup*). Given this manipulation, onsets with a large rise (e.g., *clup*), small rise (e.g., *cnup*), and plateau (e.g., *ctup*) were included, but not sonorant-initial onsets with falling sonority. The control items were arranged into two counterbalanced lists. Each list included an equal number of identical and non-identical trials matched for sonority distance, consistency, and presentation-order. Within a list, a single item was presented in the identical or non-identical trials, but not both. Participants responded to a single control list—distributed in counterbalanced order

between the two experimental lists. Each control list comprised 48 trials: 2 identity (identical, non-identical) X 2 presentation-order (the monosyllable occurred in either the first or second position) X 2 consistency (consistent, inconsistent) X 3 sonority distance (large rise, small rise, plateau) X 2 items. Appendix C lists all monosyllabic printed control items.

Procedure. Participants were seated in front of a computer. Each trial began with message indicating the trial number and an instruction to press space bar. The participant initiated the trial by pressing space bar, triggering the successive presentation of a fixation point (e.g., “**”) for 100 ms, the stimulus (printed in lowercase, e.g., *fnik*) for 500 ms, a pattern mask (e.g., XXXXXXXX) for 2500 ms, and the target (printed in uppercase, e.g., *FNK*). The target remained on screen until a response was entered using the numeric keypad (1 = identical, 2 = non-identical) or 2500 ms. One-half of the trials included an identical pair and the other half included a non-identical pair. Participants were instructed to respond quickly and that it was important for their response to be accurate.

The increased SOA (3000 ms), the pattern mask (XXXXXXX) and the presentation of the target in uppercase were intended to encourage phonological processing and prevent the preservation of the printed stimuli in iconic memory (following Berent & Lennertz, 2010). Because letter case differed between the stimulus and the target, both identical and non-identical trials were comprised of different types.

Prior to the experiment, participants completed a short practice with real English words (e.g., *drive-derive*). As in Berent and Lennertz (2010), feedback on response accuracy was provided during the practice, experimental, and phonology control trials—this was intended to motivate participants to perform well throughout the experiment. Feedback on response time was also provided for all trials. To motivate participants to respond quickly, responses longer than 1200

ms, irrespective of their accuracy, triggered a computerized warning message (“TOO SLOW”). Participants received a short break at the midpoint of the experiment. Trial order was randomized for each participant. The entire procedure took about 40 minutes.

Results

Identical trials elicited fast ($M = 665$ ms) and accurate ($M = 89.40\%$) responses. Our interest concerns responses to non-identical trials. Correct non-identical responses falling 2.5 SD above the mean or faster than 200 ms (about 2.39 % of the total observations) were excluded from the analysis of response time. We examined non-identical responses for the experimental and phonology control conditions separately.

Block effects

Before examining our main question of interest—readers’ sensitivity to the sonority profiles of stop and fricative onsets—we must first ascertain that these findings are not contaminated by learning and fatigue resulting from exposure to the two blocks of trials in the experiment.

To address this possibility, we first submitted the results to a 2 block X 2 presentation-order (the monosyllable either occurred first or second) X 2 obstruent-type X 3 sonority distance ANOVA on response time and accuracy. Of interest is whether block modulates the effects of sonority distance or obstruent type. The analyses on response accuracy indeed yielded a significant block by sonority distance interaction ($F_1(2, 70) = 3.21$, $MSE = 0.034$, $p < 0.05$; F_2

(2, 14) = 4.53, MSE = 0.005, $p < 0.04$; in response time: both $F < 1$).¹¹ This finding suggests that participants changed their response strategy along the experimental session due to either fatigue or learning. A separate 2 presentation-order X 2 obstruent-type X 3 sonority distance ANOVA on response accuracy for the second block indeed yielded no significant interactions (all $F < 1.14$, $p = 0.33$). We thus limited all subsequent analysis to the initial block of trials.

Sonority effects in the first block

A 2 presentation-order X 2 obstruent-type X 3 sonority distance ANOVA on response accuracy for the first block yielded a significant obstruent-type by sonority distance interaction ($F_1(2, 70) = 3.68$, MSE = 0.036, $p < 0.04$; $F_2(2, 14) = 4.72$, MSE = 0.006, $p < 0.03$) and a significant presentation-order by obstruent-type interaction ($F_1(1, 35) = 4.62$, MSE = 0.0138, $p < 0.04$; $F_2(1, 7) = 10.76$, MSE = 0.0013, $p < 0.02$). These same interactions were not significant in the analysis of response time (all $F < 1.21$, $p = 0.28$, see Table 7 for respective response times). Response accuracy to fricatives and stops in the first block were next examined separately by means of 2 presentation-order X 3 sonority distance ANOVAs.

The analysis of fricative-onsets (see Figure 6) resulted in no significant effects (all $F < 1.45$, $p = 0.24$). In contrast, stop-onsets (see Figure 7) yielded significant main effects of both presentation-order ($F_1(1, 35) = 6.74$, MSE = 0.0227, $p < 0.02$; $F_2(1, 7) = 9.10$, MSE = 0.004, $p < 0.02$) and sonority distance ($F_1(2, 70) = 3.46$, MSE = 0.0439, $p < 0.04$; $F_2(2, 14) = 7.37$, MSE = 0.005, $p < 0.007$). Although the interaction was not significant (both $F < 1.08$, $p = 0.35$),

¹¹ The interaction in response accuracy was largely confirmed using a mixed logit model: a 2 block X 3 sonority distance model yielded a marginally significant interaction ($\beta = 0.065$, $SE = 0.036$, $\zeta = 1.81$, $p < 0.07$). The 2 block X 2 sonority distance (small rises and plateaus only) model yielded a significant interaction ($\beta = 0.135$, $SE = 0.062$, $\zeta = 2.19$, $p < 0.03$).

we did predict a priori that any phonological effects associated with sonority distance should be stronger when the onset is held in memory, a prediction supported by the significance of the presentation order x obstruent-type interaction in the omnibus ANOVA of the first block. We thus proceeded to examine the simple main effect of sonority distance separately for trials when the cluster was presented first (e.g., *ptik-petik*) or second (e.g., *petik-ptik*).

Table 7. Mean correct response time (ms) to non-identical trials in the first block of Experiment 4 as a function of obstruent-type, presentation-order, and sonority distance. Standard deviations are indicated in parentheses (N = 35).

		Small Rise	Plateau	Fall
Fricative	CeC-CC	745 (145)	763 (124)	761 (102)
	CC-CeC	744 (123)	740 (127)	744 (127)
Stop	CeC-CC	694 (122)	725 (118)	714 (115)
	CC-CeC	742 (130)	721 (140)	712 (105)

Figure 6. Mean response accuracy to non-identical trials with a fricative-onset as a function of sonority distance and presentation-order (N = 36). Error bars reflect confidence intervals constructed for the difference between the means.

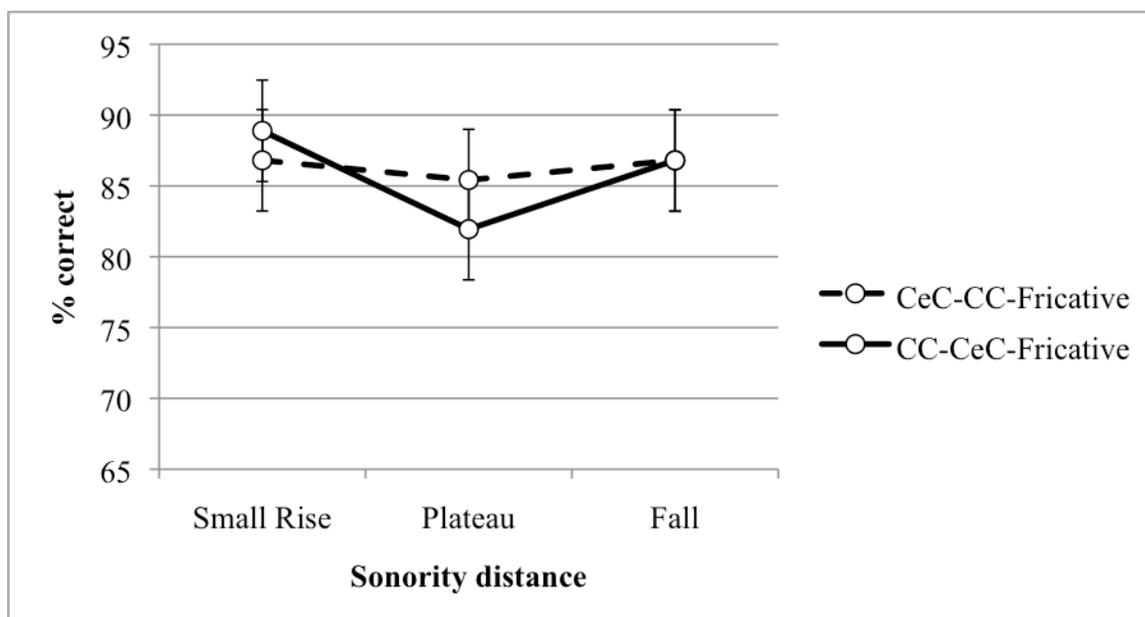
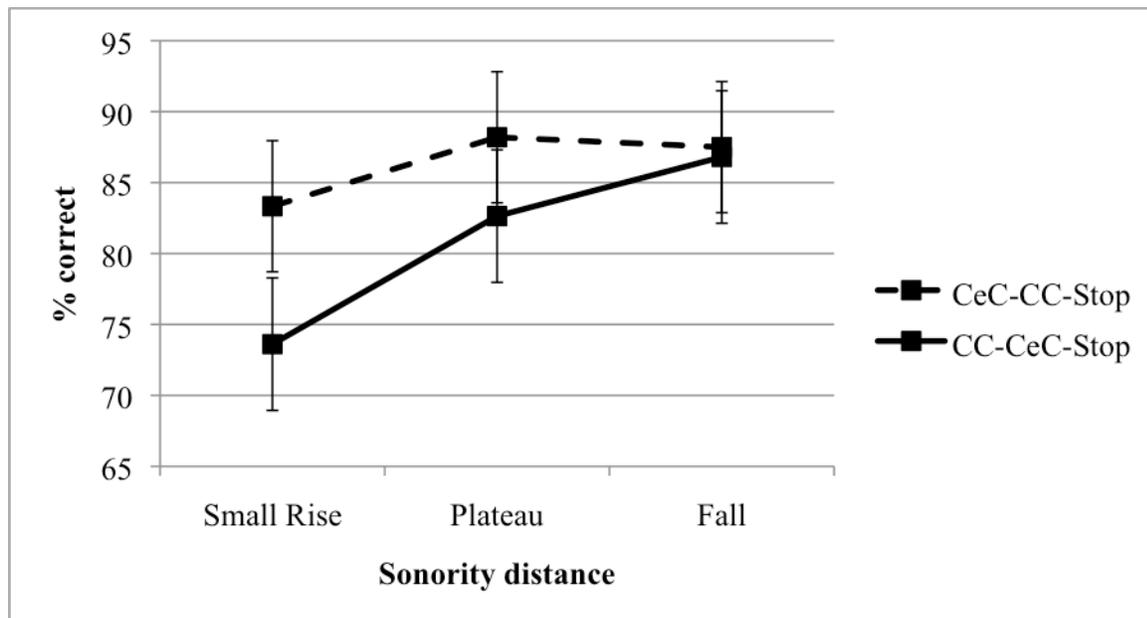


Figure 7. Mean response accuracy to non-identical trials with a stop-onset as a function of sonority distance and presentation-order (N = 36). Error bars reflect confidence intervals constructed for the difference between the means.



As expected, an analysis of trials in which the cluster was presented second (e.g., *petik-petik*) did not yield a simple main effect of sonority distance (both $F < 1.28$, $p = 0.31$). In contrast, the effect of sonority distance was significant when the cluster was retained in memory (e.g., *petik-petik*; $F_1(2, 70) = 4.16$, $MSE = 0.039$, $p < 0.02$; $F_2(2, 14) = 4.62$, $MSE = 0.0079$, $p < 0.03$). Planned comparisons demonstrated that onsets with a small sonority rise elicited *less* accurate responses compared to onsets with either sonority plateaus ($t_1(70) = 1.93$, $p < 0.058$; $t_2(14) = 2.03$, $p < 0.062$) or falls ($t_1(70) = 2.82$, $p < 0.007$; $t_2(14) = 2.97$, $p < 0.011$). Thus, sonority-distance modulated responses to stop-, but not fricative-initial onsets, and this effect was obtained only when the onset had to be held in memory. Unlike Experiment 3, however, stop-initial onsets with a small rise elicited less accurate responses than sonority plateaus.

The sensitivity of sonority effects to working-memory demands suggests that these effects reflect phonological rather than orthographic processing. To further examine people's sensitivity

to the phonological structure of the materials, we also examined the effect of presentation order (i.e., the monosyllable either occurred first or second) for each of the sonority distances. The simple effect of presentation-order was found with onsets of rising sonority, ($F_1(1, 35) = 3.77$, $MSE = 0.045$, $p < 0.06$; $F_2(1, 7) = 7.30$, $MSE = 0.005$, $p < 0.04$) but not for sonority plateaus (both $F < 3.08$, $p = 0.09$) or falls (both $F < 1$). These findings suggest that people engaged in the assembly of phonology from print only for the better-formed onsets of rising sonority, but not for the ill-formed onsets with sonority falls. Since phonology assembly is more difficult for onsets with falling sonority, people likely switched to a visual strategy—a consequence of ill-formedness.

Responses to phonology control trials

To further gauge the assembly of phonology, we next turned to examine the effect of phonological similarity (e.g., inconsistent: *clup-celup* vs. consistent: *blup-belup*) and presentation-order (e.g., *blup-belup* vs. *belup-blup*) on our phonological control items. The 2 presentation-order X 2 consistency X 3 sonority distance ANOVA did not yield any significant effects (in accuracy, all $F < 1.45$, $p = 0.31$; in response time, all $F < 3.42$, $p = 0.10$).

Discussion

Experiment 4 examined whether people remain sensitive to the sonority levels of fricatives and stops in the absence of phonetic cues. In accord with the findings with auditory materials, fricative- and stop-initial onsets yielded different patterns of results. Fricative-initial onsets yielded attenuated effects of sonority distance, which in the present experiment did not reach significance. In contrast, sonority distance reliably modulated responses to stop-initial onsets.

The findings across the two modalities nonetheless diverged in two important respects. First, the effect of sonority-distance with printed stop-initial onsets was modulated by presentation order: people were only sensitive to sonority distance when the onset cluster had to be maintained in phonological working memory—when the item with the onset cluster was presented first. Second, responses to stop onsets of rising sonority elicited *fewer* accurate responses compared to onsets of level and falling sonority.

The first discrepancy is straightforwardly explained by the increase in SOA in the current experiment relative to Experiment 3—a fact that exacerbated working memory demands. The SOA in Experiment 4—3000 ms—is twice as long as the SOA in Experiment 3¹². An account of the second discrepancy could be explained by noting that, unlike auditory items, visual stimuli offer two routes to perform the identity judgment task—people could either rely on phonological decoding or visual spelling verification. Their likelihood of relying on these two routes depends on the availability of the two codes. Because the maintenance of verbal materials requires maintenance in phonological working memory, items presented first are more likely to undergo phonological decoding, hence, the stronger effect of their sonority distance. At the same time, however, phonological decoding also depends on well-formedness: Better-formed onsets of rising sonority are more likely to undergo phonological encoding than ill-formed onsets of falling sonority, and consequently, the effect of presentation order (associated with phonological coding) was absent with sonority falls. But because the phonological decoding of unattested onsets is

¹² In Experiment 3, non-identical trials were also presented with the monosyllable either occurring first or second. A 2 presentation-order X 2 obstruent-type X 3 sonority-distance ANOVA yielded a significant main effect of presentation-order in response accuracy ($F_1(1, 35) = 38.92$, $MSE = 0.054$, $p < 0.00001$; $F_2(1, 7) = 41.68$, $MSE = 0.011$, $p < 0.0004$)—trials in which the monosyllable was presented first elicited less accurate responses. Correct responses to such trials also tended to take more time ($F_1(1, 24) = 6.61$, $MSE = 16732$, $p < 0.02$; $F_2 < 3.38$). Presentation-order, however, did not interact with sonority-distance or obstruent-type (all $F < 2.96$).

imperfect and more error-prone than a visual detection strategy, the phonological decoding of well-formed onsets would put them at a disadvantage compared to sonority falls.

While the effect of presentation order suggests that people did engage in the encoding of phonology from print, phonology effects were not detected by our phonology-control manipulation (e.g., *clup-celup* vs. *blup-belup*). This null effect is probably due to the insensitivity of our manipulation, which relied on fine-grained differences associated with the change in a single phoneme (e.g., /k/ to /s/). Nonetheless, when people had to commit the first item to phonological working memory in the experimental trials, their performance was sensitive to both the general phonological structure of the input, the distinction between monosyllables and disyllables—as well as the fine-grained phonological structure of the monosyllable, specifically, the structure of its onset cluster. The finding that responses were sensitive not only to coarse sonority distance, in general, and the sonority levels of fricatives vs. stops, specifically, suggest that the different patterns associated with stop- and fricative-initial auditory onsets is not solely due to their phonetic robustness. Rather, this distinction reflects abstract phonological knowledge that is irreducible to the phonetic properties of auditory stimuli.

General Discussion

The present research investigated whether speakers have knowledge of universal restrictions on the sound structure of language. Our specific case examined restrictions on the sonority levels of fricatives and stops. Across languages, fricatives are more sonorous than stops, however, productive phonological alternations in English do not make this distinction (Giegerich, 1992). We examined whether English speakers are nonetheless sensitive to this distinction.

If English speakers consider fricatives more sonorous than stops, then the sonority distance between small rises and plateaus should be attenuated for fricative-initial onsets (e.g., *fn*,

fʒ) compared to stop-initial ones (e.g., *pn*, *pt*). Consequently, the rise in a stop-nasal onset (e.g., *pn*) should be larger than the rise in a fricative-nasal one (e.g., *fʒ*). Given that ill-formed onsets with small sonority distances are more likely to be repaired as disyllabic (Berent et al., 2007; 2008; 2009), we predicted that identification accuracy should vary depending on the status of the initial obstruent as a stop or fricative. Specifically, the rate of repair for onsets with rising and level sonority should be more similar for fricative-initial monosyllables (e.g., *fʒ*, *fʒ*) compared to stop-initial ones (e.g., *pn*, *pt*).

Our results are consistent with this prediction. In each of our experiments, performance was constrained by the status of the obstruent—a fricative vs. a stop. In Experiments 1 and 2, both using syllable count tasks, the rate of misidentification differed between stop-initial and fricative-initial monosyllables. In line with previous research, stop-initial monosyllables with a small rise (e.g., *pna*) elicited more accurate responses than stop-initial monosyllables with a plateau (e.g., *pta*). In contrast, the identification of fricative-initial monosyllables with a small rise (e.g., *fna*) and plateau (e.g., *fsa*) did not differ reliably. Experiment 3, an identity judgment task, provided further evidence for the distinction between fricatives and stops: Sonority rises produced faster responses than plateaus for items comprising stop-, but not fricative-initial onsets. Moreover, Experiment 4 demonstrated that the sensitivity to the status of the initial consonant as a fricative or stop obtains even with printed items that carry no phonetic information. Once again, responses to stop-initial items were modulated by sonority distance, whereas responses to fricative-initial items were not. But unlike previous experiments with auditory materials, printed words yielded a reverse effect of sonority distance (i.e., more accurate response to ill-formed onsets), an effect we attributed to the propensity of ill-formed onsets to trigger an additional spelling-verification strategy, which protected them from the effects of phonological repair. Taken together, our results demonstrate that English speakers consistently failed to differentiate

between the sonority distance of fricative-initial monosyllables with onsets of rising and level sonority (e.g., *fna* - *fsa*)¹³. In contrast, the perception of stop-initial monosyllables with onsets of rising and level sonority was reliably modulated by sonority distance (e.g., *pna* > *pta*). In what follows, we examine several explanations for our findings.

Do the different rates of misidentification for fricative- and stop-initial onsets reflect non-grammatical sources?

Why do fricative-initial onsets of rising and level sonority elicit a similar rate of repair whereas the corresponding stop-initial onsets differ? According to Optimality Theory (Prince & Smolensky, 1994/2006), onsets with small sonority distance are ill-formed relative to onsets with larger sonority distance (e.g., *pn* > *pt* > *lp*). If fricatives are more sonorous than stops, then the sonority distance of fricative-nasal onsets is attenuated—rendering fricative-nasal onsets of rising sonority (e.g., *fn*) more similar to plateaus compared to stop-nasal combinations (e.g., *pn*). For this reason, fricative-initial onsets of rising and level sonority elicit more similar rates of repair, whereas stop-sonorant combinations are less likely to undergo repair compared to their corresponding stop-stop combinations. On this account, the difference in the rate of misidentification of stop- and fricative-initial onsets reflects their grammatical status.

¹³ Strictly speaking, a sonority-based account only predicts an attenuation of the sonority cline for fricative-initial onsets—it does not necessarily predict that the sonority distance between small rises and plateaus is *equal*. Although the omnibus analyses failed to detect significant differences between *fn*- and *fs*-type onsets, a closer inspection offers several indications that small rises are better-formed relative to plateaus. In Experiment 1, fricative-initial monosyllables with rising sonority elicited more accurate responses, albeit not significantly, than monosyllables with level sonority (M = 88.5; 83.9). In Experiment 3, non-identical trials comprising items with rising sonority elicited more accurate responses than such trials with items of level sonority (t1 (70) = 6.70, p < .00001; t2 (14) = 3.40, p < .005). Moreover, when this contrast is examined in response time, correct responses to non-identical trials with rising sonority tended to be faster than correct responses to non-identical trials with level sonority (t1 (70) = 2.25, p < .03; t2, p > .12).

Alternatively, the differential rate of misidentification between fricative- and stop-initial onsets may occur for non-grammatical reasons. We consider two such explanations. On one non-grammatical account, misidentification reflects differences in the perception of the phonetic properties of fricatives and stops (e.g., intensity, duration)—not their sonority levels. In particular, stop-initial onsets with level sonority (e.g., *pt*) may be less perceptible and hence more likely to be misidentified compared to small-rises than their fricative-initial counterparts (e.g., *fs*). The results with printed materials (in Experiment 4) challenge this account. English speakers remained sensitive to the distinction between fricatives and stops even when presented with visual monosyllables that do not differ in their phonetic perceptibility.

Another non-grammatical account attributes our results to the statistical properties of the English language. Specifically, stop-initial monosyllables with ill-formed onsets may be misidentified because their statistical properties are unfamiliar compared to stop-initial monosyllables with better-formed onsets (e.g., *pna* > *pta*), whereas fricative-initial onsets of rising and level sonority elicit a similar rate of misidentification because their statistical properties are equally unfamiliar (e.g., *fna* - *fsa*). To assess whether this explanation can capture our results, we first examined the lexical familiarity of our monosyllabic items using several statistical properties. In particular, auditory lexical familiarity was defined by an item's number of neighbors (i.e., words created by adding, substituting or deleting a single phoneme), neighbors' frequency (i.e., summed frequency of neighbors), the position-specific phoneme probability (i.e., the probability that a phoneme occurs in a given position, mean across the four positions) and bi-phone probability (i.e., the probability that a pair of adjacent phonemes occurs in a given position,

mean across the three positions)¹⁴. Lexical familiarity for printed items was assessed using bigram count (i.e., number of words sharing a pair of adjacent letters in a given position, from Solso & Juell, 1980), bigram frequency (i.e., summed frequency of words sharing a bigram, from Kučera & Francis, 1967), number of neighbors and neighbors' frequency. As shown in Table 8, these statistical patterns do not match our results. First, *pn*-type items with a small rise are not invariably more frequent than *pt*-type ones—on the contrary, *pn*-type items actually tend to be more frequent than *pt*-type members. Second, the difference between monosyllables with rising and level sonority is not consistently larger for stop-initial items compared to fricative-initial ones.

Table 8. Statistical properties of our fricative- and stop-initial monosyllables. The averaged values across 8 items per onset-type are shown.

	Fricatives		Stops	
	Small rise	Plateau	Small rise	Plateau
Auditory items				
Number of neighbors	0.75	0.625	1.125	1.75
Neighbors' frequency (summed)	18.38	13.88	9.50	30.38
Position-specific phoneme probability	0.0351	0.0273	0.0392	0.0354
Bi-phone probability	0.0006	0.0005	0.0006	0.0007
Visual items				
Number of neighbors	0.63	0.63	0.63	0.50
Neighbors' frequency (summed)	597.38	67.88	53.88	53.75
Bigram count	54.13	43.50	19.00	19.75
Bigram frequency	1464.88	1132.88	828.88	995.75

¹⁴ Phoneme and bi-phone probabilities were obtained from the Phonotactic Probability Calculator prepared by Vitevitch & Luce (2004). Neighborhood properties were obtained from the Speech and Hearing Lab database at <http://128.252.27.56/Neighborhood/Home.asp>. When accessed (November 2009) this database failed to distinguish between the letter case of the phonological input (e.g., “S” corresponding to /ʃ/ and “s” corresponding to /s/). Two researchers manually inspected the output for its accuracy.

To further test the statistical account, we submitted the data from each experiment (i.e., Experiments 1, 2, 4: response accuracy; Experiment 3: response time) to a stepwise linear regression, controlling for the statistical properties of the monosyllable in the first step and examining the unique effect of sonority distance in the second step or vice versa. Since we are specifically interested in accounting for the $pn > pt$ and $fn - fs$ pattern, only the statistical properties of monosyllabic items with a small rise or plateau were entered in the regression. The results are shown in Table 9. After controlling for the statistical properties, sonority distance does not reliably account for a unique portion of variance for fricative-initial monosyllables. This is expected given that responses to fricative-initial items were not reliably modulated by sonority distance in Experiments 1-4. But, importantly, the regression results demonstrate that our pattern of response is also not captured by the statistical properties of the fricative-initial monosyllables. For stop-initial monosyllables, after controlling for sonority distance, the statistical properties do not capture the results in any of our experiments. In contrast, the effect of sonority distance is always significant for each experiment, for both auditory stimuli and printed ones.

Table 9. The results of a series of step-wise linear regressions from Experiments 1-4.

		Fricatives				Stops			
Experiment	Last Predictor	R² change	df	F	p- value	R² change	df	F	p- value
1	sonority distance	.096	1, 10	2.10	NS	.364	1, 10	7.57	.020
	statistical properties	.490	4, 10	2.67	NS	.129	4, 10	< 1	NS
2	sonority distance	.005	1, 10	< 1	NS	.186	1, 10	4.62	.057
	statistical properties	.300	4, 10	1.19	NS	.296	4, 10	1.83	NS
3	sonority distance	.275	1, 10	5.57	.04	.535	1, 10	12.77	.005
	statistical properties	.346	4, 10	1.76	NS	.169	4, 10	1.01	NS
4	sonority distance	.112	1, 10	1.56	NS	.230	1, 10	4.67	.056
	statistical properties	.177	4, 10	< 1	NS	.290	4, 10	1.47	NS

How is the distinction between stops and fricatives represented in the grammar?

The findings presented so far suggest that our results cannot be explained by non-grammatical factors, such as difficulties to extract the phonetic forms of stop-initial onsets or unfamiliarity with their statistical properties. Having rejected these non-grammatical explanations, we next consider the possibility that misidentification is triggered by grammatical knowledge. In this account, *pt*-type onsets are misidentified because they are ill-formed relative to *pn*-type onsets, whereas the grammatical well-formedness of *fn*- and *fs*- type onsets is more similar. This proposal, however, leaves open two questions. First, what are the grammatical determinants of ill-formedness—does the dislike of *pt*-type items reflect their sonority profile or some other factors unrelated to sonority? A second question concerns the source of the relevant knowledge—whether it is acquired from experience, or whether it is experience-independent. We consider each of these questions below.

Grammatical knowledge unrelated to sonority

Consider first the possibility that the relevant grammatical knowledge is unrelated to sonority and obtains from experience with the co-occurrence of stop- and fricative features in the English lexicon. For example, Hayes and Wilson (2008) present a learning model—while not specific to the sonority levels of obstruents—that can induce phonotactic patterns given the co-occurrence of features in the lexicon. It is possible that our results also obtain with such experience. Indeed, English fricatives co-occur with both sonorants (e.g., *fl*, *sn*) and obstruents (e.g., *sk*), whereas stops only occur with sonorants (e.g., *pl*). If speakers registered the co-occurrence of fricatives with other obstruents and sonorants, then such information could lead them to accept both combinations for fricatives, but allow only obstruent-sonorant combinations for stops. Note, however, that in this view, the grammar only encodes feature co-occurrence, rather than a distinction between the sonority levels of fricatives and stops per se.

This account, however, faces several challenges. First, previous research shows that sonority-related preferences do not necessarily mirror the lexical co-occurrence of features. Specifically, past research has shown that the preference for obstruent-sonorant over obstruent-obstruent onsets obtains in Korean despite lacking onsets of either type (Berent et al., 2008). An additional challenge is presented by English speakers' perception of onset clusters comprising a nasal consonant. In English, sonorants (a group that includes nasal consonants) occur in the second onset position (e.g., *snail*) more frequently than stops (e.g., *street*; there are 21 clusters in English where C₂ is a sonorant and 9 clusters where C₂ is a stop), but monosyllables with nasal-sonorant combinations (e.g., *mnif*) elicit less accurate responses than nasal-stop onsets (e.g., *mdif*; see Berent et al., 2009). These two observations challenge the assumption that well-formedness transparently reflects feature co-occurrence.

Feature-co-occurrence likewise fails to capture our present findings. Although at first glance the number of attested fricative- and stop-initial onset clusters in English, shown in Table 10, appears to mirror our results (i.e., fricatives co-occur with both sonorants and obstruents, whereas stops only occur with sonorants), a closer inspection of these statistical patterns shows that they match our results rather coarsely.

One challenge is presented by the precise manner of articulation of obstruent-obstruent clusters in English. Nearly all fricative-obstruent onsets in English comprise a fricative-stop combination (e.g., *sk, st*)—only one fricative-fricative onset is attested (e.g., /*sf*/ in *sphere*). In our materials, however, fricative-obstruent onsets always included two fricatives (e.g., *fs*), and such onsets are *less* frequent than fricative-sonorant ones (e.g., *fn*). If the contrast in the statistical frequency of the manner feature in the first onset position is sufficient to promote the observed contrast between stop- and fricative- initial clusters, then it remains a puzzle why a similar contrast in the onset’s second position would be ignored.

Table 10. The number of attested fricative- and stop-initial onset clusters by manner of articulation (e.g., sonorant or obstruent).

Type of cluster	Fricative-initial	Stop-initial
Obstruent-sonorant (e.g., <i>fl, pl</i>)	9	14
Obstruent-obstruent (e.g., <i>sp</i>)	10	0

A second challenge to a feature co-occurrence account is presented by the place of articulation of attested onsets. In English, fricative-obstruent onsets are limited to coronal fricatives (e.g., *sp, sk*). If speakers’ knowledge faithfully tracks feature co-occurrence, then the overall *fn - fs* pattern should only obtain for onsets beginning with a coronal-fricative. In contrast, labial-initial fricatives occur only with sonorants (e.g., *fl*), not obstruents, a pattern

similar to stop-initial items. Thus, labial-initial onsets show similar patterns of co-occurrence for stop- and fricative-initial onsets, whereas for coronal-initial onsets, stop- and fricative-initial onsets diverge. For this reason, this account predicts that the contrast between sonority rises and plateaus should be attenuated for coronal- compared to labial-initial items. But a comparison of the labial-fricative (e.g., /f/) and a coronal-fricative (e.g., /ʃ/) items used in our experiments does not support this prediction. First, a 2 place of articulation (labial vs. coronal) by 2 sonority-distance (small rise vs. plateau) ANOVA on the relevant responses from each experiment yielded no support for the predicted pattern of attenuation—the perception of sonority distance was never modulated by whether the onset comprised a labial- or a coronal-fricative (all $F < 5.93$, $p = 0.09$). Second, contrary to the prediction of this account, labial-initial monosyllables often elicit similar responses—in fact, they tend to elicit even more similar responses than coronal-initial monosyllables (see Table 11).

In sum, the performance of participants in our experiments does not faithfully mirror the co-occurrence of features in the English lexicon. People are insensitive to the co-occurrence of place features (e.g., labial vs. coronal)—features that are irrelevant to sonority, but are sensitive to the co-occurrence of manner (e.g., stop vs. fricative)—features that are relevant to sonority. Therefore, the misidentification of *pta* relative to *pna*, and the similar misidentification of *fna* relative to *fsa* appears to reflect grammatical knowledge that is specifically related to sonority.

Table 11. Response accuracy (Experiments 1, 2, 4) and correct response time (Experiment 3) by sonority distance for onsets with a coronal- or labial-fricative.

	Coronal-fricatives		Labial-fricatives	
	Small rise	Plateau	Small rise	Plateau
Experiment 1	96.88	87.5	80.21	80.21
Experiment 2	95.31	93.75	87.5	95.31 ¹⁵
Experiment 3	1030	1075	1086	1105
Experiment 4	96.67	81.25	84.03	86.11

Grammatical distinctions between the sonority of fricatives and stops: Their nature and origins

Our conclusions so far suggest that people rely on grammatical knowledge, and that this knowledge is inexplicable by feature co-occurrence unrelated to sonority. In the absence of a sonority-free explanation for the findings, we thus conclude that the relevant grammatical knowledge is specifically related to sonority—it is informed by sonority-relevant features, such as the distinctions between obstruents and sonorants, in general, and the manner-distinction between stop- and fricative-obstruents, but ignores distinctions on place-features—features unrelated to sonority. This conclusion, however, opens up the question of how sonority-related knowledge leads to the inference that fricatives are more sonorous than stops. In particular, assuming that people have grammatical knowledge that fricatives and stops *differ* on their sonority levels, is there any experience that would allow English speakers to infer their ranking (i.e., that fricatives are *more* sonorous than stops). We consider two explanations: a) that the distinction

¹⁵ This particular pattern is the opposite of our prediction (i.e., that monosyllables with small rises should be perceived with similar or higher accuracy than monosyllables with plateaus). Recall in Experiment 2, monosyllables were in the context of prothetic counterparts (e.g., *ɛfsik*). In this context, it may have been easier for participants to distinguish *fs*-type onsets from their disyllabic counterparts compared to *fn*-type ones, yielding this pattern of results.

between fricatives and stops is inferred from the structure of the English lexicon, and b) that this distinction is inferred from the phonetic properties of obstruents.

Consider first the possibility that this distinction is inferred in a manner that is informed by the lexicon. We further assume that English speakers represent sonorants as more sonorous than obstruents, know that obstruents comprise both fricatives and stops with different sonority levels, and prefer onsets with a large rise in sonority. The preferences for rising sonority and the obstruent-sonorant contrast can be either learned or experience-independent—we do not consider these questions here. Rather, our interest is in how speakers might specifically rank the sonority levels of fricatives and stops given their linguistic experience and the sonority-preferences that are already available to them. On this account, speakers might set the relative sonority level of fricatives and stops based on the occurrence of stops and fricatives in the lexicon. How, precisely, does lexical experience inform the inference of sonority levels is not clear a priori. Here, we will assume that speakers set the sonority levels in a manner that would optimize the rise in sonority of attested onsets. Specifically, the sonority level is set such that clusters that occur more frequently should have a maximal rise in sonority. As shown in Table 12, fricative-initial onset clusters tend to be more frequent in English than stop-initial onset clusters (type: $\chi^2(1) = .76$, ns; token: $t(31) = 2.10$, $p < .05$). Under the assumption that English speakers consider onsets that are more frequent to manifest a larger rise in sonority distance than less frequent ones, and given that fricative-initial onsets are more frequent than stop-initial ones—this could lead an English speaker to infer that fricative-initial onsets are better-formed, manifesting a larger rise, than stop-initial ones. Using this evidence, an English speaker could further infer that to manifest a larger rise—fricatives must be at a lower sonority level than stops. Therefore, one could incorrectly arrive at the conclusion that fricatives are less sonorous than stops. On this

account, the lexicon does not provide evidence that would lead an English speaker to correctly infer fricatives are more sonorous than stops.

An alternative account, however, could allow one to correctly infer the sonority levels of fricatives and stops from the English lexicon. Consider the status of /s/-initial onsets: /s/-initial onsets violate the minimum sonority distance requirements in English. Indeed, /s/-initial onsets are an exception to the requirements on syllable structure in many languages (Blevins, 1995; Selkirk, 1982), and their special status is further supported by experimental evidence (e.g., Gierut, 1999; Barlow, 2001b; Treiman, Gross, & Cwikel-Glavin, 1992). The grand majority of fricative-initial onsets in English are /s/-initial. Assuming people have knowledge about the exceptional status of /s/-initial onsets, such onsets would be considered distinct from all other obstruent-initial ones. When /s/-initial onsets are therefore excluded from the English lexicon, stop-initial onsets tend to be more frequent than fricative-initial ones (see Table 12; type frequency: $\chi^2(1) = 4.27, p < 0.04$; token frequency: $t(17) = 1.30, ns$). The higher frequency of stop-initial onsets relative to fricative-initial ones provides evidence that stop-initial onsets are better-formed—manifesting a larger sonority distance than fricative-initial ones. Using this evidence, an English speaker could correctly infer that for stop-initial onsets to manifest a larger rise—stops must be less sonorous than fricatives. Therefore—unlike all previous accounts—this one does provide a plausible explanation as to how the ranking of the sonority levels of stops and fricatives can be acquired. This account, however, assumes the learner has substantial knowledge related to sonority, including knowledge of sonority distinctions between sonorants and obstruents, knowledge that obstruents comprise both fricatives and stops, a preference for onsets with large rising sonority distance, and lastly, knowledge of the exceptional status of /s/-initial onsets.

Table 12. Type (e.g., the number of unique clusters) and token (e.g., the frequency of clusters in particular words) frequency for attested fricative- and stop-initial onset clusters in English. Token frequencies were obtained from Vitevitch and Luce (2004).

	Fricatives – All onsets	Fricatives – Excluding /s/-initial onsets	Stops
Type	19	5	14
Token	0.058	0.003	0.007

A final possibility is that knowledge concerning the sonority levels of fricatives and stops is inferred directly from phonetic experience (cf. Hayes & Steriade, 2004; Wright, 2004). While such knowledge is represented in the grammar, it can be obtained from experience perceiving the phonetic properties of fricatives and stops. Fricatives tend to be longer in duration and more intense than stops (Kent & Read, 1992). Using such experience, an English speaker could correctly infer that fricatives are more sonorous than stops. Nonetheless, it remains an open question as to how knowledge of the sonority levels of fricatives and stops relates precisely to experience with their phonetic properties.

Conclusion

In sum, our results are consistent with the prediction that English speakers consider fricatives more sonorous than stops. In each experiment, the pattern of misidentification was modulated by whether the initial obstruent comprised a fricative or a stop. Fricative-initial onsets (e.g., *fn*, *fs*) consistently yielded a similar rate of repair—a consequence of their attenuated sonority distance. In contrast, stop-initial onsets of rising (e.g., *pn*) and level sonority (e.g., *pt*) elicited a different rate of repair—a consequence of their larger sonority distance. Overall, these results suggest that small rises are of more similar ill-formedness for fricative-initial onsets compared to stop-initial ones.

Our results cannot be captured by learning mechanisms that assume no grammatical knowledge related to sonority—they are not due to an inability to correctly perceive the phonetic form of the onsets, nor are they due to the statistical properties of the onsets. Rather, the pattern of results implies grammatical knowledge that is specifically related to sonority. Such grammatical knowledge, however, could in part be inferred from English experience. English speakers could use both the structure of the lexicon and their experience perceiving the phonetic differences between obstruents to infer that fricatives are more sonorous than stops. But, to adequately capture our results, these learning mechanisms must be equipped with considerable knowledge. Specifically, to infer our results from the structure of the English lexicon, a learner must have knowledge of grammatical restrictions on sonority, including knowledge that sonorants are more sonorous than obstruents, know that obstruents comprise both fricatives and stops as well as the exceptional status of /s/-initial onsets, and have a preference for onsets with a large rise in sonority. Similarly, to infer that fricatives are more sonorous than stops from phonetic experience, an English speaker must have a learning mechanism that relates the phonetic differences between obstruents, such as intensity and duration to the phonological distinction between the sonority of fricatives and stops. The need for such extensive sonority-related knowledge suggests that these learning mechanisms might be specific to language.

Given that the ranking of the sonority of stops and fricatives could be learned from the structure of the English lexicon, our results do not allow us to determine whether fricatives are universally as *more* sonorous than stops. Unlike the ranking of the sonority levels of fricatives and stops, however, the knowledge that fricatives and stops comprise of *different* sonority levels cannot be inferred from lexical experience. The documentation of such knowledge in English, in the absence of relevant experience, is consistent with the hypothesis that this distinction is universal.

Whether this distinction is innately specified or inferred from some putatively universal phonetic input remains to be seen.

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Appendices

Appendix A

The experimental and filler monosyllabic items from Experiments 1-3. The items are written in phonetic notation.

	Filler	Small Rise	Plateau	Fall
Fricatives				
	fɛp	fnik	fsik	msik
	fruk	fnuk	fsuk	msuk
	fɛt	fnɛt	fsɛt	msɛt
	frop	fnot	fsot	msot
	ʃrip	ʃmik	ʃfik	lfik
	ʃruk	ʃmuk	ʃfuk	lfuk
	ʃrɛp	ʃmɛk	ʃfɛk	rfɛk
	ʃrok	ʃmok	ʃfok	rfok
Stops				
	plik	pnik	ptik	mtik
	prum	pnuk	ptuk	mtuk
	plɛʃ	pnɛʃ	ptɛʃ	mtɛʃ
	proʃ	pnoʃ	ptoʃ	mtoʃ
	trom	tmik	tpik	lpik
	trum	tmuk	tpuk	lpuk
	trɛf	tmɛk	tpɛk	rpɛk
	trok	tmok	tpok	rpok

Appendix B

The printed experimental and filler monosyllabic items from Experiment 4.

	Filler	Small Rise	Plateau	Fall
Fricatives				
	flep	fnik	fsik	msik
	fruk	fnuk	fsuk	msuk
	flet	fnet	fset	mset
	frop	fnot	fsot	msot
	shrip	shmik	shfik	lfick
	shrak	shmak	shfak	lfack
	shrep	shmek	shfek	rfeck
	shrok	shmok	shfok	rfock
Stops				
	plik	pnik	ptik	mtik
	prum	pnuk	ptuk	mtuk
	plesh	pnesh	ptesh	mtesh
	prosh	pnosh	ptosh	mtosh
	trom	tmik	tpik	lpik
	trem	tmak	tpak	lpak
	tref	tmek	tpek	rpek
	trok	tmok	tpok	rpok

Appendix C

The printed phonology control monosyllabic items from Experiment 4.

	Large rise	Small Rise	Plateau
Consistent			
	blup	bnup	bdup
	drof	dmof	dbof
	truf	tmuf	tpuf
	prug	pnug	ptug
Inconsistent			
	clup	cnup	ctup
	crof	cmof	cpof
	cruf	cnuf	ctuf
	crug	cmug	cpog