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Phonological Features and Phonotactic Constraints in Speech Production

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Abstract

Languages are subject to phonotactic constraints — restrictions on sound sequences. An implicit learning paradigm examined whether participants could acquire constraints at two levels of representation through exposure to a set of nonwords. Participants were exposed to categorical segment-level constraints (e.g., /f/ only in onset, /s/ only in coda) as well as gradient featural-level constraints (e.g., labiodental fricatives /v/ and /f/ occurred in onset position 75% of the time, coda 25%). Speech errors revealed that participants encoded constraints at both levels of representation. By biasing errors towards a single syllable position, segmental constraints strengthened the tendency of errors to preserve target syllable position (e.g., virtually no /s/ errors occurred in onset). In contrast, since the featural constraint allowed errors to occur in both syllable positions, encoding it weakened the tendency to preserve target syllable position (e.g., /f/ errors, influenced by featural as well as segmental constraints, surfaced in coda more often than /s/ errors surfaced in onset). Finally, participants in a second study failed to learn featural constraints for dorsal stop consonants. The implications of these results for the representation and processing of features are discussed.

Keywords: speech production; speech errors; features; phonotactic constraints
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It is well known that languages do not make use of all possible sequences of sounds. Within a particular language, sound sequences are constrained in well-defined ways. In English, for example, no lexical item begins with the segment /ŋ/, even though it can occur at the end of words (as it does in “king”). These phonotactic constraints — restrictions on the environments in which sounds appear — are part of what defines the phonology of English; other languages are not similarly constrained (e.g., Wolof contains words such as /ŋɔ:m/ ‘jaw’).

Although it is clear that sound sequences are subject to phonotactic constraints, and that these constraints are encoded by the language processing system (see below), it is not precisely clear how these constraints are encoded. One area of debate is the types of representations the processing system uses to encode constraints. For example, how is the English constraint on /ŋ/ represented by the speech processing system? One possibility is that it is represented in terms of a particular segment in a specific word position (e.g., the processing system disfavors structures where the segment /ŋ/ occurs at the beginning of words). However, these are not the only representational structures that could be used to encode phonotactic constraints. Most phonotactic theories assume complex phonological structures (for a review, see Goldsmith, 1990). For example, instead of using the segmental level, the processing system could encode a constraint on the occurrence of phonological features. Features are the most basic level of phonological structure, characterizing the component articulations of segments. For example, /ŋ/ is produced when the tongue forms an obstruction near the soft palate (referred to as the feature [dorsal]) and the soft palate is lowered (referred to as the feature [nasal]). This phonotactic constraint may therefore be equivalently encoded through processes that disfavor the...
combination of features [dorsal, nasal] at the beginning of words. In both cases, the processing system represents a restriction on sounds — the contrast is in the types of representations that are used to encode this restriction.

Similarly, instead of word position, the processing system could represent the position of /ŋ/ within suprasegmental phonological representations. For example, many theories claim that segments are grouped into syllables (e.g., Kahn, 1976). If all segments are part of a syllable, the beginning of the word is also the beginning of a syllable; the constraint can therefore be encoded as a ban on syllable-initial /ŋ/.

This representational ambiguity has helped fuel theoretical disagreements regarding what levels of representation are used by the language processing system to encode phonotactic constraints. For example, at the suprasegmental level, some theories in generative linguistics claim that the syllable is not used (e.g., Chomsky & Halle, 1968; Steriade, 1999), while others have claimed it is crucial (e.g., Kahn, 1976). Some theories (e.g., Archangeli & Pulleyblank, 1994) have claimed that segmental representations are superfluous, while others (e.g., Chomsky & Halle, 1968) have assumed that they are basic representational units.

Disagreements about phonotactic constraints occur not only within generative linguistics, but also across disciplines. Most generative linguistic theories assume features are used to encode phonotactic constraints (e.g., Archangeli & Pulleyblank, 1994; Chomsky & Halle, 1968; Goldsmith, 1990). In contrast, some processing-oriented theories have eschewed this representational level. Luce, Goldinger, Auer, and Vitevitch (1999) present a theory of speech perception in which phonotactic constraints are encoded in terms of segmental and suprasegmental representations alone. Specifically, Luce et al.’s theory claims that the speech perception system encodes constraints on the occurrence of segments in particular positions.
within the word, as well as constraints on the co-occurrence of segments across these positions. Coleman and Pierrehumbert (1997; see also Frisch, Large, & Pisoni, 2000) formulate a stochastic phonological grammar that also omits featural representations. Phonotactic constraints are encoded in terms of segments (grouped into syllable constituents) in particular word positions. Finally, Hartley & Houghton (1996) claim that the speech production system encodes constraints on the occurrence of segments (not features) in different syllable positions.

More generally, speech production theories have tended to assume that features have a fairly limited functional role relative to segments. For example, Dell (1986) assumes that selection processes operate at the level of segments but not at the level of features (although the presence of feedback allows features to influence segment selection). Levelt, Roelofs, and Meyer (1999; see also Roelofs, 1997) assume that features are only activated as part of retrieving whole-syllable articulatory representations (i.e., gestural scores in the syllabary). The feature, so central to generative linguistic theories of phonotactic constraints, is generally de-emphasized in speech production theories.

This study examines whether the diminished functional role of features precludes them from being used to encode phonotactic constraints within the speech production system. Following a review of research on phonotactic constraints and features within the production system, the results of an implicit learning study are presented. These results show that phonotactic constraints can be encoded at the level of features, contradicting the predictions of theories which omit this level of representation.

**Phonotactic constraints in speech production**

Previous research has demonstrated that phonotactic constraints are encoded by speech production processes. Spontaneous speech errors rarely result in the production of sequences
that violate phonotactic constraints (e.g., Arabic: Abd-El-Jawad & Abu-Salim, 1987; English: Vousden, Brown, & Harley, 2000; German: MacKay, 1972; Mandarin: Wan & Jaeger, 1998). Similar results have been found in studies of individuals with selective deficits to phonological processes in speech production (e.g., Romani & Calabrese, 1998). Although some studies of experimentally-induced speech errors have noted the production of significant numbers of forms violating phonotactic constraints (Butterworth & Whittaker, 1980; Laver, 1980), most studies have reported that these errors are vastly outnumbered by ones that conform to such constraints (but see Goldstein, Pouplier, Chen, Saltzman, & Byrd, 2004; Mowrey & MacKay, 1990).

In addition to encoding phonotactic constraints of the speaker’s native language, the speech production system can acquire new phonotactic constraints in adulthood. Dell, Reed, Adams, and Meyer (2000) examined the influence of novel phonotactic constraints which restricted English consonants to particular syllable positions. Many studies have observed that segments tend to preserve their target syllable position in errors. For example, “tap man” is more likely to be erroneously produced as “tan map” (two codas exchanging) than “nap mat” (where an onset and coda exchange; see Vousden et al., 2000, for a recent review). This effect is massively strengthened when phonotactic constraints of one’s native language restrict segments to particular position. Although the /n/ in “man” tends to appear in coda in errors (e.g., “tap man” → “tan map”), virtually all /ŋ/ errors are restricted to coda position (Vousden et al., 2000).

Drawing on these results, Dell et al. asked English-speaking participants to read aloud sequences of four CVC syllables. These syllables reflected not only the phonotactic constraints of English (e.g., /ŋ/ occurred only in coda as in “meng”) but also constraints specific to the experiment. For example, in one condition, the consonant /f/ occurred only in onset position — syllables like “fem” were presented, but others like “mef” were not.
Speech errors were then induced by having the participants read the sequences quickly. Dell et al. found that the errors not only respected the constraints of English (e.g., no erroneously produced /ɪ/ segments occurred in onset) but also the constraints specific to the experimental syllables. For example, when /f/ was restricted to onset, approximately 3% of the erroneously produced /f/ segments occurred in coda. In contrast, for those segments that were not associated with a phonotactic constraint in the experiment, nearly 30% of the errors were produced in a non-target syllable position. Like a naturally-occurring phonotactic constraint, the constraint specific to the experiment massively strengthened the tendency of errors to preserve target syllable position.

This finding generalized to other consonants and syllable positions. Across conditions, participants in Dell et al.’s experiments were able to encode constraints restricting any one of four consonants /f, s, k/ to either onset or coda. Furthermore, in a final experiment, Dell et al. showed that the speech production system could also encode constraints on consonant-vowel combinations (e.g., /f/ preceded /æ/ but not /i/, whereas it could follow either).

Note that Dell et al. (2000) informed some participants that consonants were constrained to particular syllable positions; other participants were not informed of this experimental manipulation. Performance was unaffected by this manipulation, suggesting that these constraints were implicitly encoded by the processing system. Furthermore, before producing the sequences quickly (and producing errors), participants repeated the sequences slowly—without producing errors. This suggests that the errors occurred within speech production processes, not within memory or perceptual processes.
Dell et al.’s (2000) study also revealed that phonotactic constraints can be acquired extremely quickly. Participants repeated the same task on 4 separate days (with at most 1 day intervening between sessions). Experiment-specific constraints influenced errors starting from the very first experimental session; for example, in Dell et al.’s Experiment 1, only 4 out of the 184 errors in the first session violated the experiment-specific constraint. There appeared to be a slight improvement with time, but the differences were insignificant. (The only significant effects of learning were observed with constraints on consonant-vowel combinations; see Dell & Warker (in press) for further discussion.) Furthermore, within each session, Dell et al. found no pattern to the violations; experiment-specific constraints were violated throughout the entire session. This suggests that the speech production system can rapidly acquire constraints on sound sequences within a single experimental session.

Features and phonotactic constraints

Although it is clear that phonotactic constraints can be rapidly encoded by speech production processes, it is not clear whether featural representations are used to encode these constraints. Studies attempting to examine this question have failed to control for the possibility that instead of featural constraints, correlated constraints at higher levels of representation are encoded. For example, Romani and Calabrese (1998) examined the performance of DB, an Italian speaker with a selective deficit to phonological processes in speech production. They showed that his errors tended to create syllables that satisfied featural constraints. Specifically, DB’s errors respected sonority constraints (a featural property of segments referring to vocal tract resonance; Clements, 1990). For example, when DB produced errors in onset position, high-sonority segments were eliminated and replaced with low sonority segments (mirroring phonotactic constraints found across a variety of languages). However, it is unclear whether a
featural level is required to account for these results. For example, high sonority segments may simply be less frequent in onset relative to low sonority segments (see Frisch, 2002, for evidence that frequency is correlated with sonority). By failing to contrast alternative characterizations of phonotactic constraints, studies such as these fail to support a specific role for features.

In contrast to features, there is clear evidence that constraints at the supra-segmental and segmental levels can be encoded. As noted above, Dell et al.’s (2000) final experiment showed that suprasegmental constraints on consonant-vowel combinations can be encoded. Other results suggest that participants are able to encode constraints that are specific to single consonants, ignoring high levels of featural similarity. In Dell et al.’s experiment 2, the segments /k/ and /g/ — which share all features save voicing — were restricted to separate syllable positions (e.g., in one condition, /k/ appeared only in onset while /g/ appeared only in coda). Performance in this experiment was comparable to the first. In the condition described above, virtually all /k/ errors were confined to onset, and all /g/ errors to coda. Furthermore, in all of Dell et al.’s experiments (as well as in studies of spontaneous speech errors), participants clearly encoded a constraint specific to /ŋ/ without influencing performance on featurally similar consonants such as /m/ and /n/ (i.e., /ŋ/ errors were restricted to coda, while /m/ and /n/ errors occurred in both syllable positions).

Features in speech production

The encoding of segment-specific phonotactic constraints accords with results from other studies suggesting that segments, not features, are the focus of phonological processing in speech production. Virtually all speech errors appear to involve the deletion, substitution, or exchange of an entire segment (Fromkin, 1971). This result does not appear to arise from a lack of
opportunities for feature errors. Shattuck-Hufnagel and Klatt (1979) analyzed 90 spontaneous
speech errors that involved two consonants differing in more than one feature. In 70 of these
errors, a single feature could have moved between the two consonants (given the structure of
English). Out of these 70 opportunities, Shattuck-Hufnagel and Klatt found only 3 unambiguous
single feature errors. Stemberger (1991) found similar results in a study of experimentally-
induced errors. With so few errors in the presence of so many opportunities, it would appear that
features are inextricably bound to the segment. This tight relationship between segments and
features may make it impossible to encode phonotactic constraints at the featural level.

Stemberger (1990) provides additional evidence that some speech errors are insensitive to
featural structure. Many studies show that repetition of a phoneme increases the likelihood of
errors on adjacent phonemes (e.g., Dutch: Nooteboom, 1969; English: Dell, 1984; German:
MacKay, 1970). For example, a sequence like “side line,” where the vowel /a1/ is repeated, is
more likely to have errors than a sequence like “hot pad”, where two different vowels (/a/ and
/æ/) are used. Stemberger analyzed his own corpus of English spontaneous speech errors to
determine the representational level at which the repeated phoneme effect arose. He found that
repetition of an identical segment increased error rates above chance, while repetition of
segments sharing many features did not. Roelofs (1999) found similar results in a picture
naming task. He found that if all the names of pictures in a block of a trials shared the same
initial segment (e.g., book, bear), participants named the pictures more quickly relative to blocks
where the picture names had highly dissimilar initial segments (e.g., file, kite). This form-
overlap advantage was not found when the pictures in a block shared featurally similar segments
(e.g., book, pear). Both results suggest that priming was limited to a segmental level where
features are not specified.
However, it should be noted that other results suggest that features do play an important role in speech production processes. First, experimental results suggest that it is possible for errors to target individual features. Guest (2001) reports that participants in a tongue twister experiment produced a significant number of unambiguous single feature errors (see also Stemberger & Treiman, 1986). Also within a tongue twister task, Goldstein et al. (2004) observed single feature errors in articulatory data. Furthermore, Pouplier & Goldstein (in press) show that featural errors are often imperceptible; it is therefore not surprising that these errors are missed by studies of spontaneous speech errors. Second, speech errors appear to be influenced by featural similarity; the more similar two segments are, the more likely it is that they will interact. This result has been replicated by studies of spontaneous speech errors in a number of different languages (e.g., Arabic: Abd-El-Jawad & Abu-Salim, 1987; Dutch: Van den Broecke & Goldstein, 1980; English: Frisch, 1997; German: Berg, 1991; Spanish: García-Albea, del Viso, & Igoa, 1989; Swedish: Söderpalm, 1979) as well as experimentally-induced speech errors in English (e.g., Stemberger, 1991). The presence of these featural effects leaves open the possibility that phonotactic constraints could be encoded using this level of representation.

**Motivation for the current study**

Using the paradigm developed by Dell et al. (2000), the current study attempted to create a situation in which featural constraints would be acquired. As in Dell et al., the stimuli reflected two constraints at the segmental level. Two consonants were restricted to particular syllable positions. For example, in one condition, /f/ was restricted to onset while /s/ was restricted to coda. If participants successfully encoded these segmental constraints, errors on these segments should be more likely to respect syllable position than unconstrained control consonants (e.g., /m, k, g/, which occurred with equal frequency in onset and coda positions).
Unlike Dell et al., the stimuli also reflected a featural constraint. In this same condition, the distribution of labiodental fricatives (/f/ and /v/) was biased towards onset position. The consonant /v/ was added to the stimulus set, occurring with equal frequency in onset and coda position. Because the overall frequency of /f/ and /v/ was matched, this meant that 75% of labiodental fricatives occurred in onset position, while 25% occurred in coda. Encoding this constraint should have the opposite effect as that of the segmental constraints. While the segmental constraints strengthen the tendency of errors to preserve syllable position, this constraint should encourage errors to violate target syllable position. For example, although all /f/ targets occur in onset position, the constraint on labiodental fricatives allows these segments to occur in either syllable position. Encoding this constraint should therefore increase the number of errors occurring in coda—violating /f/’s target syllable position. Similarly, although /v/ targets occur with equal frequency in onset and coda position, the labiodental fricative constraint biases these segments towards onset (75% of tokens occur in this position). This should encourage errors violating target syllable position; when /v/ is in coda, the constraint will attract errors towards onset position.

Figure 1 illustrates a hypothetical set of results on these consonants, assuming that both featural and segmental constraints are encoded. Because of speech errors’ general tendency to respect target syllable position, /k, g, m/ should violate target syllable position at levels less than chance. This tendency to respect target syllable position is depicted by an arrow with a single solid line. For consonants subject to segmental phonotactic constraints (e.g., /s/ and /f/), this effect should be massively strengthened (as shown by the solid double lines). The featural constraint should have the opposite effect; it should encourage errors to violate target syllable position (shown by the dotted double lines). The featural constraint should work against the
general tendency to respect syllable position (as shown for /v/) as well as against any segmental phonotactic constraints (as shown for /f/).

The design of these stimuli should encourage the encoding of constraints at the featural level more so than the design of Dell et al.’s (2000) experiments. In their study, consonants with similar features never occurred in the same syllable position. Since participants encoded constraints specific to different syllable positions (e.g., /f/ should only occur in onset), there was no pressure to encode constraints at the featural level. In contrast, in this study, features overlapped within a syllable position; this may lead participants to encode constraints at both the featural and segmental levels. Experiment 1 examined performance under these conditions for 4 consonant pairs differing in the feature [voice].

**Experiment 1**

**Method**

**Participants**

Forty undergraduate and graduate students at Johns Hopkins University participated in the experiment (16 males, 15 right-handed; 24 females, 19 right-handed). They were compensated or received extra-credit in introductory courses. All participants reported that they were native speakers\(^3\) of English and reported no history of speech/language impairment.

**Materials**

**Featural constraints.** Participants were exposed to featural constraints for four pairs of consonants contrasting in voicing. Each pair generated two conditions. In one, the voiceless member of the pair was confined to a single syllable position, while the voiced appeared in both syllable positions with equal frequency. In the second condition, the situation was reversed.
To examine whether the results generalized across different manners of articulation, two pairs of fricatives (/z/-/s/; /v/-/f/) and two pairs of stops (/d/-/t/; /g/-/k/) were selected. The fricative conditions examined the influence of two variables. First, the place of articulation of the consonants (coronal vs. labiodental); second, the syllable position of the constraints. These two variables were manipulated simultaneously. In the labiodental conditions (as illustrated above), the fricatives were biased towards onset. In the coronal conditions, fricatives were biased towards coda position (e.g., 75% of /s, z/ tokens appeared in coda, while 25% appeared in onset). The stop conditions examined the influence of place of articulation alone (coronal vs. dorsal).

The combination of these variables (voicing, place/syllable position, and manner) yielded a total of 8 conditions. Five participants were assigned randomly to each condition.

Segmental constraints. As noted above, within each condition one member of the voiced-voiceless pair was confined to a single syllable position, reflecting one segmental constraint. To provide a baseline measure of the influence of segmental constraints alone, another segment was confined to the opposite syllable position (e.g., when /f/ was restricted to onset, /s/ was restricted to coda). For this baseline consonant, the corresponding voiced/voiceless segment was absent (e.g., when /v/ was present, /z/ was absent).

For the fricative conditions, a consonant with the place of articulation from the other fricative condition was selected. For the labiodental pair, /s/ was confined to coda position. For the coronal pair, /f/ was confined to onset position. /f/ and /s/ were also used for the stop conditions. /f/, restricted to coda, was used for the coronal stops; use of /s/ may have induced
interactions along the dimension of place. /s/, restricted to coda, was therefore used for the dorsal condition.

**Control consonants.** To provide a baseline measure of the influence of segmental and featural constraints, each condition included a set of control consonants subject to neither segmental nor featural regularities. The default set consisted of a consonant pair differing in voicing (/k, g/) as well a nasal segment (/m/). This set could obviously not be used for the dorsal stop condition (as /k/ or /g/ was restricted to a particular syllable position); for this condition, the voiced-voiceless pair /f, v/ was substituted for /k, g/.

An additional control was the inclusion of /h/ and /η/, restricted to onset and coda respectively (following the constraints of English). This provided a baseline to demonstrate that participants had encoded the constraints of English.

**List composition.** These consonants were presented to participants in sequences of four CVC syllables (the vowel was always /e/). All possible combinations of consonants appeared (subject to the constraints of the experimental condition). The majority of the syllables produced by these combinations were nonwords⁴; analyses below will consider whether the effect of phonotactic constraints derives exclusively from the presence of word stimuli. Each consonant appeared once per sequence. For each condition, a total of 3456 sequences satisfied these constraints. For each participant, a list of 192 sequences was drawn from this set in a random order.

**Presentation format.** Each sequence of four syllables was spelled (for visual presentation to participants) in the following way. The vowel /e/ was always spelled “e”. /g/ was spelled “gh” in initial position (e.g., “ghem”); all other initial consonants were spelled with single letters.
Consonants were doubled in final position except when this would violate English orthographic constraints (specifically, /d, v, k, m/ were spelled with single consonants).

Procedure

The experimental session took place in a sound attenuated chamber. Stimuli were presented on a laptop computer placed on a small table in front of the participant. Each participant’s productions were recorded onto audio tape by a head-mounted microphone.

Experimental trials proceeded as follows:

1. **Familiarization**: Participants were shown a single sequence of four syllables (e.g., /heŋ fek meg ness/, spelled “heng fek meg ness”) centered on a computer monitor in black 18 point Charcoal type (white background). They were instructed to read the sequence aloud in time to metronome-like clicks from the computer.

2. **Practice**: After the participant pressed a key, a set of four clicks was played at a rate of 1/second. The participant read aloud the sequence in time to these slow-playing clicks. This was done to ensure that the participants correctly encoded the target sequence before repeating it quickly.

3. **Test**: After the participant pressed a key again, a set of twelve clicks was played at a rate of 2.5/second. This allowed for three fast repetitions of the sequence. These repetitions were intended to elicit speech errors.

The sequence remained visible through the entire trial, minimizing the memory demands of the task.

A set of three practice trials preceded the experimental trials. Practice trials were identical to experimental trials except that none of the consonants within these sequences were used in the experimental trials. Following the practice trials, participants were pre-trained on the
pronunciation of syllables that occurred in experimental sequences. Participant were asked to read each syllable aloud and corrected if their pronunciation did not match the desired one. At no time were participants instructed regarding the distribution of segments within the experiment, nor the similarity between different segments in the experiment. The experimental session itself consisted of four blocks of 48 sequences apiece. The entire procedure took approximately 45 minutes to complete.

Results

Recordings were examined, and consonantal substitution errors produced during fast repetitions were transcribed using broad transcription. Vowel errors were rare and not transcribed. Cutoff errors, where both the error segment and the target were produced (e.g., /kɛŋ/ → /m…kɛŋ/) were included. Each error is referred to by the segment that was inserted. For example, suppose /hɛŋ fek meŋ nes/ was produced as /hɛŋ sek meŋ nes/ (the error segment is underlined). This is referred to as a /s/ error in onset; /s/ replaced the segment /f/, and the error was produced in onset.

Voicing errors were excluded from the analysis. In a voicing error, the target consonant differed from the inserted consonant only with respect to voicing (e.g., /k/→/g/, /g/→/k/). As noted in the Introduction, featural similarity affects segmental speech errors. Within each condition, consonants subject to featural constraints (e.g., /f, v/) had the opportunity to interact with highly similar segments. Similar opportunities were also available for one pair of the control consonants (e.g., /k, g/). In contrast, the consonant subject to segmental constraints alone (e.g., /s/) had no such opportunity. All voicing errors were therefore excluded.
Each participant was randomly assigned to one of two transcribers. Inter-transcriber reliability was good. Both transcribers analyzed two 10 minute recordings (randomly selected from two participants). Out of 2880 consonants, both transcribers agreed on 2878 consonants (99.9% agreement). For errors alone (n = 9), the agreement rate was 77.8%. Overall consonantal error rate across all conditions was 4.8% (n = 184320). After voicing errors were excluded, a total of 6762 errors were analyzed.

The participants’ errors were clearly influenced by the phonotactic constraints of English. Replicating many other studies, none of the errors violated these constraints. All 867 /h/ errors occurred in onset (e.g., /fɛŋ/ → /hɛŋ/: target /f/ in onset was replaced by an /h/); all 771 /ŋ/ errors occurred in coda.

**Analysis method.** To statistically assess the encoding of segmental and featural constraints within the experiment, we can compare the rate at which different classes of consonants preserve target syllable position. As noted above, segments tend to preserve their target syllable position in errors. Encoding segmental constraints—which associate a segment with a single syllable position—should strengthen this tendency. For example, when all /s/ targets appear in coda position, participants should encode a constraint restricting it to that syllable position. Virtually all /s/ errors should therefore appear in their target position—coda. In contrast, encoding featural constraints—which associate segments to multiple syllable positions—should weaken the tendency to preserve syllable position. For example, although all /f/ targets appear in onset position, participants may encode a constraint on labiodental fricatives allowing them to surface in coda position. Relative to /s/, /f/ errors should therefore be more likely to appear in a non-target syllable position.
Analysis of Fricative Conditions

Since the fricative conditions manipulated both consonantal place and syllable position simultaneously, and different places of articulation were contrasted within each manner condition, separate analyses were performed for each manner. An Analysis of Variance (ANOVA; SAS GLM procedure) was performed on the percentage of each participant’s errors that violated target syllable position. Between-participants factors were the voicing of the consonant subject to segmental and featural constraints (voiced vs. unvoiced) and place of articulation (coronal vs. labiodental). Two within-participants factors defined the four categories of consonants; first, whether the consonant category was subject to featural constraints or not; second, whether the consonant category was subject to segmental constraints. Following our running example: /s/, restricted to coda, without /z/ present, was subject to segmental but not featural constraints; /f/, restricted to onset, with /v/ present, was subject to both types of constraints; /v/ was subject to featural constraints alone; and /q, k, m/ were subject to neither type of constraint.

Effects of featural and segmental constraints. The results for each condition are shown in Table 1. Figure 2 shows the results collapsing over all between-participants factors. The main effect of segmental constraints was significant; consonants subject to segmental constraints were less likely to violate target syllable position (mean: 6.7%) than those not subject to segmental constraints (mean: 31.2%; $F(1,16) = 66.0, p < .0001$). This results replicates Dell et al.’s (2000) finding that the tendency to preserve target syllable position could be strengthened by experiment-specific segmental constraints. Furthermore, as predicted by the encoding of featural constraints, consonants subject to these constraints were more likely to violate target syllable position (mean: 23.0%) than those not subject to featural constraints (mean: 14.9%; $F$
The interaction of these two factors was not significant (F (1,16)= 1.1, p > .30). These effects suggest that participants were able to independently encode featural as well as segmental phonotactic constraints within the experiment.

Before discussing whether these results generalize across voiced and unvoiced segments, as well as different places of articulation, we first consider several possible confounds. First, it is well known that there are lexical influences on speech errors. For example, errors are subject to a lexical bias—all else being equal, errors are more likely to result in words compared to nonwords (e.g., Dell & Reich, 1981). Although most of the stimuli were nonwords, the distribution of words was not explicitly controlled; it is therefore possible that the phonotactic constraint effects are entirely due to lexical influences. To control for this potential confound, the analysis was repeated with all word outcomes removed. Effects of both types of phonotactic constraints were still observed. Consonants subject to segmental constraints were less likely to violate target syllable position than those not subject to these constraints (15.4% vs. 21.3%; F(1,16) = 58.2, p < .0001). Consonants subject to featural constraints were more likely to violate target syllable position than those not subject to these constraints (30.0% vs. 14.8%; F(1,16) = 5.2, p < .04).

Second, it is possible that intrinsic differences among consonants could influence these results. Within any condition, we are necessarily comparing different consonants to measure the influence of phonotactic constraints (e.g., /f/ to /s/). This is of particular concern because the consonants subject to segmental constraints are similar to other consonants in the stimulus set. For example, /f/ and /s/ are similar not only to /v/ and /z/ but also /h/; interactions with this consonant—restricted to onset by English phonotactics—may be influencing the results (for example, increasing the number of /s/ errors that violate target syllable position).
To control for these factors, we can directly compare the results in two conditions: the labiodental condition where /f/ was restricted to onset versus the coronal condition where /s/ was restricted to coda. After excluding all /v/ targets and errors from the first condition, and all /z/ targets and errors from the second condition, the error opportunities are precisely matched. In both conditions, /f/ was restricted to onset and /s/ to coda; /k,ɡ,ɱ/ appeared with equal frequency in onset and coda. The only distinction is whether /v/ or /z/ was present in the stimulus set, and we have excluded all interactions involving these consonants. The results for /f/ and /s/ across these conditions are shown in Table 2. When all error opportunities are controlled, the influence of featural constraints can still be observed. When subject to both featural and segmental constraints, a consonant was significantly less likely to preserve its target syllable position compared to situations when it was subject to segmental constraints alone (t(18) = 2.6, p < .02). Changes in the percentage of consonants violating target syllable position were therefore not attributable to intrinsic differences between consonants or to differences in their error opportunities; they were due to the encoding of a phonotactic constraint at the level of features.

The last potential confound we consider concerns the consonant subject only to featural constraints. If featural constraint were encoded, errors on this consonant should have violated target syllable position because they were attracted towards one particular syllable position. The analysis above did not examine this specific effect; the results may simply reflect a general increase in the number of errors violating target syllable position. Further analysis reveals that this is not the case. For a baseline measure, we calculated the rate at which the control consonant of the same voicing appeared in the same syllable position as its voiced/voiceless counterpart. Following the running example, when /f/ was restricted to onset position, we compared the rate
at which /v/ appeared in /f/’s syllable position to the rate at which /g/ appeared in /k/’s syllable position. Across participants, errors on the consonant subject to featural constraints alone appeared in the syllable position predicted by the featural constraint at a mean rate of 42.1% (standard error 3.6%). In contrast, errors on the control consonant appeared in the same syllable position as its voiced/voiceless counterpart at a rate of 36.8% (standard error 3.1%). This difference is comparable to the effect size observed in the overall analysis (mean difference here: 5.3%; overall analysis: 5.5%; note, however, that this particular comparison is not significant [paired t(19) = 1.1, p < .27]). The comparable effect size in this analysis suggests that the effects in the overall analysis are not due to a general increase in the rate of errors violating target syllable position.

Interaction of featural and segmental constraints with other factors. The results were also examined to see if the effect of featural and segmental constraints generalized across different types of segments. One potential difference was found across conditions; the strength of the featural constraint appeared to vary depending on the voicing of the consonant subject to featural and segmental constraints. The interaction between voicing and the featural constraint was marginally significant ($F(1,16) = 4.0, p < .065$). The significance level was the same when word outcomes were excluded from the analysis. As shown in Table 3, the effect of featural constraints was stronger when the voiceless consonant was subject to both featural and segmental constraints (mean difference for voiceless conditions: 13.9%; voiced conditions: 2.3%). To make this concrete using our running example—for conditions where labiodentals were biased towards onset position, errors were more likely to violate target syllable position when /f/ was restricted to onset than when /v/ was restricted to onset.
A three-way interaction was found between the effect of segmental constraints, featural constraints, and the place of articulation/syllable position of the featural constraint (F(1,16) = 6.2, p < .03). This effect appears to be driven by differences in the relative strength of segmental and featural constraints across place of articulation/syllable position. However, since this interaction failed to reach significance when lexical items were excluded from the analysis (F(1,16) = 1.6, p > .20), we will not discuss it further.

No other main effects (Voicing F(1,16) = 2.3, p > .15; Place F(1,16) = .12, p > .70) nor interactions (Fs range from .01 to 1.4) were significant in the overall ANOVA.

Time course of learning. The results show that phonotactic constraints could be acquired within a single experimental session, replicating Dell et al. (2000). These results also provide some suggestive evidence of learning occurring within the session. As shown in Table 4, both the featural and segmental constraints appear to be stronger in the second half of the experiment compared to the first. Errors on the consonants subject to segmental constraints were numerically less likely to violate target position in the second half of the experiment; in particular, the rate on the consonant subject to both segmental and featural constraints had a mean decrease of 4.9%. The strengthening of the tendency to maintain target syllable position is consistent with a strengthened segmental constraint. In contrast, violations of target syllable position numerically increased for errors on the consonant subject to featural constraints alone. This weakening of the tendency to preserve target syllable position is consistent with the strengthening of a featural constraint biasing errors towards a single syllable position.

Although the numerical differences are consistent with strengthened constraints, they failed to be statistically reliable. The ANOVA was repeated, adding in time (first half vs. second
half of the experiment) as a within-participants variable. The time variable failed to interact with either segmental ($F(1,16) = 2.5$, $p > .14$) or featural ($F(1,16) = 0.5$, $p > .48$) constraints.

**Analysis of Stop Conditions**

Similar ANOVAs were performed for participants in the stop conditions. Table 5 shows the results for each condition. Figure 3 shows the results collapsing across all between-participants effects. The main effect of segmental constraints was significant; consonants subject to segmental constraints were less likely to violate target syllable position (mean: 10.7%) than those not subject to segmental constraints (mean: 28.6%; $F(1,16) = 18.0$, $p < .001$). The main effect of featural constraints was also significant; consonants subject to these constraints were more likely to violate target syllable position (mean: 23.2%) than those not subject to featural constraints (mean: 16.0%; $F(1,16) = 5.7$, $p < .04$). The interaction of these two factors was not significant ($F(1,16) = 0.01$, $p > .9$). These effects suggest that, just as in the fricative conditions, participants are independently encoding featural as well as segmental phonotactic constraints.

As in the analysis above, the effect of featural and segmental constraints could not be reduced to lexical bias effects. After removal of all word outcomes, consonants subject to segmental constraints were still less likely to violate target syllable position than those not subject to these constraints (29.3% vs. 8.5%; $F(1,16) = 26.7$, $p < .001$). Similarly, consonants subject to featural constraints were numerically more likely to violate target syllable position than those not subject to these constraints (21.1% vs. 16.8%) although the difference failed to reach significance ($F(1,16) = 1.3$, $p < .25$).

Furthermore, effects on the consonant subject only to featural constraints could not be attributed to a general increase in the rate of errors violating target syllable position. Across participants, errors on the consonant subject to featural constraints alone appeared in the syllable
position predicted by the featural constraint at a mean rate of 36.9% (standard error 5.3%). In contrast, errors on the control consonant appeared in the same syllable position as its voiced/voiceless counterpart at a rate of 31.6% (standard error 3.2%). This difference is comparable to the effect size observed in the overall analysis (mean difference here: 5.3%; overall analysis: 7.8%) although the particular comparison is not significant (t(19) = 1.0, p < .35). This suggests that the effects in the overall analysis are not due to a general increase in the rate of errors violating target syllable position.

Interaction of featural and segmental constraints with other factors. Following the fricative analysis, the effect of featural constraints was significantly greater when the voiceless consonant was subject to both featural and segmental constraints (Table 6; F(1,16) = 5.4, p < .04). (Note, however, that the interaction was not significant when word outcomes were excluded from the analysis [F<1].)

No other main effects (Fs < 1) nor interactions (Fs range from .03 to 2.4) were significant in the overall ANOVA. However, we do note that in the dorsal conditions errors on the consonants subject to segmental constraints did not provide strong evidence of the effect of featural constraints. As shown in Table 5, the mean results for the voiceless dorsal condition show only a slight weakening of the tendency to respect syllable position on the consonant subject to segmental and featural constraints (6.1% compared to 1.7% on the consonant subject to segmental constraints alone). In the voiced dorsal condition, the mean results show no such effect; in fact, the consonant subject to segmental constraints alone had a greater mean rate of target syllable position violation (20.0% vs. 10% on the consonant subject to featural and segmental constraints). The highly variable performance in these conditions is still cause for concern; we return to this point below.
Time course of learning. As shown in Table 7, the results suggested that the segmental and featural constraints strengthened over the course of the experiment. Errors on consonants subject to segmental constraints were less likely to violate target syllable position in the second half of the experiment; in contrast, errors on the consonant subject to featural constraints alone were slightly more likely to violate syllable position. Once again, these differences failed to be reliable. In the ANOVA including time, this variable failed to interact with either segmental (F(1,16) = 1.4, p > .20) or featural (F(1,16) = 0.03, p > .80) constraints.

Discussion

Replicating Dell et al. (2000), participants were able to extract segmental phonotactic constraints present in the stimulus set. In addition, the results show that participants can encode featural constraints; encoding these constraints significantly weakened the errors’ tendency to preserve syllable position. These results are not simply a reflection of lexical biases, nor do they derive from intrinsic differences between segments or error opportunities in the different conditions. The results appear to be robust; similar patterns are found across differ manners, places of articulation, and syllable positions.

In addition to these primary findings, it should be noted that other variables appeared to influence performance in this task. First, although the effect of phonotactic constraints was not merely a lexical bias effect, the exclusion of word outcomes often altered the magnitude of segmental and featural constraint effects. Future research should do more to determine how lexical information and phonotactic properties interact in speech production processes (for a recent examination of these issues, see Vitevitch, Armbrüster, & Chu, 2004). Second, several analyses suggested that featural constraints have a stronger effect on errors when the voiceless member of the pair was restricted to a single syllable position. However, it should be noted that
the effect was marginally significant in several of these analyses, and was not found in others. Finally, the results here also provide some indication that error distributions did in fact change over the course of the experiment, reflecting the learning of phonotactic constraints. However, these differences failed to reach significance.

One concern about the results is performance in the dorsal stop conditions. As noted above, performance on the consonants subject to segmental constraints is highly variable. The mean results did not provide strong evidence of the influence of featural constraints. One possible reason for these results could be the presence of another highly similar segment in the stimulus set: /ŋ/. This segment shares all of the features of the voiced dorsal consonant /ɡ/ save manner. Since /ŋ/ is restricted to coda in the stimulus set (as well as in English), while /ɡ/ or /k/ is restricted to onset, this may have inhibited the encoding of constraints at the featural level. Recall that in Dell et al. (2000)’s experiment 2, participants did not encode constraints at the level of features when similar consonants did not overlap in syllable position. Experiment 2 examined whether featural constraints on dorsal consonants would be more robustly encoded when /ŋ/ was removed.

**Experiment 2**

**Method**

**Participants**

15 participants were drawn from the same pool as above and compensated in a similar fashion. 1 participant was excluded due to equipment failure. The remaining 14 participants consisted of 10 males (8 right handed) and 4 females (4 right handed). All participants reported that they were native speakers$^5$ of English and had no history of speech/language impairment.
Materials

Materials were similar to the dorsal stop conditions above. Instead of including /h/ and /η/, restricted to onset and coda, /d/ and /n/ were added as unrestricted consonants. As above, the majority of syllables were nonwords\(^6\). A total of 11,520 sequences respected the constraints outlined above. For each participant, a list of 192 sequences was drawn from this set in a random order. Each participant was randomly assigned to one of the 2 conditions (yielding 7 participants per condition).

Procedure

Procedure was identical to the previous experiment.

Results

Scoring and transcription methods were identical to the previous experiment. As above, voicing errors were excluded, and cutoff errors included in the analysis. Table 8 shows the result for each condition.

As shown in Figure 4, consonants subject to segmental constraints were significantly less likely to violate target syllable position (mean: 2.6\%) than those not subject to segmental constraints (mean: 31.1\%; F(1,12) = 58.0, p < .0001). However, the main effect of featural constraints was not significant. Although consonants subject to these constraints were slightly more likely to violate target syllable position (mean: 17.4\%), the difference was not significant (F (1,16) = 0.2, p > .60). The interaction of these two factors was also not significant (F (1,16)= 0.2, p > .60). Exclusion of word outcomes did not alter these results. Participants did not appear to extract featural constraints in these conditions.
Interaction of featural and segmental constraints with other factors. Although neither main effect was significant, there was a significant cross-over interaction between the featural constraint and voicing. When the voiceless consonant /k/ was subject to both featural and segmental constraints, featural constraints had the predicted effect (14.1% errors violated target syllable position for segments subject to featural constraints vs. 20.6% for segments not subject to constraints). However, when /g/ was subject to featural and segmental constraints, the direction of the effect was reversed (18.5% vs. 14.2%). This interaction was significant in the overall analysis (F(1,12) = 4.8, p < .05) but not when word outcomes were excluded (F (1,12) = 1.3, p >.25). There was also a significant three-way interaction between segmental constraints, featural constraints, and voicing (F (1,12) = 8.6, p < .02; with word outcomes excluded, F (1,12) = 6.5, p < .03). (No other main effects (F < 1) nor interactions (Fs range from .01 to .23) were significant.)

Post-hoc analyses suggest that these odd interactions are due to a confound in the stimuli. Note that one large difference between the voiced and voiceless conditions is performance on the control consonants (those not subject to featural constraints). In the voiceless condition, 14.2% violate target syllable position; in the voiced, 20.6%. Inspection of the data revealed that this was largely due to changes in the distribution of /n/ errors. In the voiced condition, a mean of 51.3% of each participants’ /n/ errors violated target syllable position; in the voiceless condition, only 23.5%. This increase in errors violating target syllable position is because /n/ was more likely to interact with /g/ than with /k/. In both conditions, /n/ errors were 3 times more likely to occur on /g/ targets than /k/ targets. (This is consistent with Stemberger’s (1991) finding that nasals are more likely to interact with voiced obstruents compared to their voiceless
counterparts.) When /g/ is confined to a single syllable position in the voiced condition, /n/ errors were attracted to the onset—leading to greater violations of target syllable position.

Because of this asymmetry in interactions between these consonants, the analysis was repeated with all errors involving /k, g/ and /n/ removed. The interaction between featural constraints and voicing was only marginally significant (F(1,12) = 3.9, p < .10); and clearly insignificant after word outcomes were excluded (F (1,12) = 1.3, p < .30).

**Time course of learning.** An ANOVA including time as a within-participants revealed an interaction between time and the strength of the featural constraint (F (1,12) = 5.9, p < .04) as well as the segmental constraint (F(1,12) = 5.6, p < .04). (The other interactions were not significant; Fs ranged from 0.4 to 2.8). However, after elimination of all errors involving /k, g/ and /n/, these interactions were no longer significant (featural: F(1,12) = 0.1, p > .75; segment: F(1,12) = 2.9, p > .10).

**Discussion**

It appears that the presence of /ŋ/ in the stimulus set did not cause the variable results observed for dorsal consonants in Experiment 1. As in the previous experiment, participants were able to rapidly learn new segmental constraints. However, participants were unable to acquire featural constraints. Together with the highly variable performance of participants in Experiment 1, these results suggest that encoding featural constraints on dorsal stops is difficult for English speakers. Other results suggest that it may difficult to encode constraints on dorsal consonants; for example, Dell et al. (2000) found that the greatest number of violations of the experiment-specific segmental constraints occurred with /k/.
Although /ŋ/’s presence specifically within the stimulus set cannot account for these results, it is possible that the null results are due to a more general transfer effect. In the course of learning English, participants have had to learn a constraint that is specific to /ŋ/—it does not generalize to other nasals, nor to other dorsal consonants. This experience may make it difficult to learn new constraints that make use of /ŋ/’s features. Another possibility is that unlike the other obstruent pairs, /k/ and /g/ do not participate in any alternations in English. Coronal fricatives alternate in the regular plural morpheme (e.g., cats/s/-dogs/z/). Similarly, coronal stops alternate in the regular past tense morpheme (e.g. walked/t/-jogged/d/). Finally, labiodental fricatives exhibit a much more restricted alternation in some plural forms (e.g., wife/f/-wives/v/). Since /k/ and /g/ lack such support, participants may have difficulty learning constraints on dorsal stops. Investigation of other non-alternating pairs that are not similar to /ŋ/ (e.g., bilabial stops /p/-/b/) may help distinguish these hypotheses.

**General Discussion**

The results suggest that participants can encode phonotactic constraints not only at the segmental level, but also at the featural level. By biasing errors towards a single syllable position, segmental constraints strengthened the tendency of errors to preserve target syllable position. In contrast, the featural constraints weakened the syllable position effect. For consonants subject to segmental constraints, the featural constraint allowed errors to occur in both syllable positions—weakening the effect of the segmental constraint. For consonants not subject to segmental constraints, the featural constraint’s bias towards one syllable position increased the likelihood that errors would violate target syllable position. It appears that
encoding featural constraints is more difficult for dorsal stops than for other obstruents; however, the reason for this difficulty is unclear.

Relationship to other domains of language processing

The results of this study accord with findings in other areas of language processing suggesting a crucial role for featural representations. Moreton (2002) showed that phonotactic constraints on features, not individual segments, influence perception of ambiguous speech sounds. Jusczyk, Hohne, and Bauman (1999) showed that 10 1/2 month old infants used constraints on the featural specification of segments (i.e., constraints on allophonic variation) to segment words in continuous speech. Saffran and Thiessen (2003) also examined infant word segmentation; they utilized a modified version of Dell et al.’s (2000) paradigm to test the ability of infants to use phonotactic constraints specific to the stimulus set. They found 9 month old infants could acquire new constraints at the level of features but not at the level of individual segments. These studies all show that featural constraints are encoded by perceptual processes—processes required to discriminate ambiguous speech sounds or identify lexical items in running speech. By examining errors produced in fast speech, this study demonstrates that featural phonotactic constraints are encoded specifically within speech production processes.

Additional implications for how constraints are encoded

Theories of how phonotactic constraints are encoded disagree not only in terms of what levels of representation are needed. Another area of contention is whether only categorical phonotactic constraints are encoded, or whether gradient constraints are also encoded. Categorical constraints are absolute, distinguishing only well-formed and ill-formed structures. For example, in English, a form with /ŋ/ in onset is absolutely ill-formed relative to a form without /ŋ/ in onset. If such a constraint is encoded, one structure is absolutely dispreferred; for
example, all /ŋ/ errors should be blocked from onset. Most theories of generative linguistics (e.g., Chomsky & Halle, 1968; Prince & Smolensky, 1993) have focused exclusively on such constraints, making the implicit assumption that only categorical constraints are encoded.

However, these are not the only types of constraints that could be encoded; languages also exhibit non-categorical phonotactic constraints. Gradient constraints specify degrees of well-formedness (e.g., Coleman & Pierrehumbert, 1997; Frisch, Broe, & Pierrehumbert, 2004). For example, in Arabic, there is a categorical phonotactic constraint banning adjacent identical consonants in initial position (e.g., roots like “samam” are found, but roots like “sasam” are not). In addition to this categorical constraint, there is a gradient constraint on consonants; the more perceptually similar the two initial consonants are, the lower the frequency (e.g., roots with highly perceptually similar consonants like /t/ and /s/ are less frequent than roots with consonants like /t/ and /n/; Frisch et al., 2004). Encoding gradient constraints should result in relative preferences. For example, errors should be more likely to lead to /t/-/n/ combinations than /t/-/s/ combinations (see Rose & King, 2003, for evidence of OCP effects on experimentally-induced speech errors).

The results here suggest that in addition to categorical constraints, gradient restrictions on featural representations can be encoded by the speech production system. The phonotactic constraint on features was gradient; although features were biased to appear in one syllable position, they occurred in both. This constraint was successfully encoded, leading to biases in errors. Errors tended to surface in one syllable position, but could occur in either. This accords with findings from other studies based on well-formedness judgments (e.g., Frisch & Zawaydeh, 2001), showing that the same effects can be observed specifically within speech production.
processes. The results are also consistent with other speech production studies suggesting that gradient segmental constraints are encoded (Vitevitch et al., 2004). These results provide support for the encoding of gradient constraints specifically at the level of features.

Although the results provide strong support for the encoding of gradient constraints, it should be noted that the effect of these constraints was much weaker than that of the categorical segmental constraints. For the fricative conditions in Experiment 1, consonants subject to segmental constraints violated target syllable position at a mean rate of 6.7%, 24.5% less than that of consonants not subject to these constraints (31.2%). The effect of featural constraints was much weaker; consonants subject to featural constraints violated target syllable position only 8.1% more often than those not subject to featural constraints (23.0% vs. 14.9%). Similar results were found for the stop conditions (mean effect of segmental constraints: 17.9% reduction in violation of target syllable position; mean effect of featural constraints: 7.3% increase).

It is unclear what mechanism is responsible for this difference in constraint strength. Are featural constraints simply inherently weaker than segmental constraints? Many speech production theories assume that features are activated only after more abstract segmental representations have been retrieved from the lexicon (e.g., Dell, 1986; Garrett, 1980; Levelt et al., 1999). If this view is correct, we might expect segmental representations to dominate processing, accounting for the stronger influence of segmental constraints. Alternatively, the featural constraint may be weaker because it is gradient; unlike the categorical segmental constraint, it allows violations. Furthermore, if constraint violation is assessed in a non-linear fashion (e.g., Frisch, Broe, & Pierrehumbert, 1997), we might expect a constraint that is only respected 75% of the time (e.g., the featural constraint) to be a great deal weaker than one
respected 100% of the time (e.g., the segmental constraint). Future work should do more to contrast these and other alternative accounts.

**Implications for speech production theories**

The results clearly favor speech production theories that use features to encode phonotactic constraints. This position has been adopted by many proposals that focus specifically on how phonotactic constraints are encoded by speech production processes (e.g., Dell, Juliano, & Govindjee, 1993; Harris, 2002; Stemberger, 1985; Vousden et al., 2000; Wheeler & Touretzky, 1997). However, not all theories have shared this assumption. Hartley and Houghton (1996) assume that phonotactic constraints are encoded by processes that link segmental nodes to syllable positions. In such an architecture, phonotactic constraints have no access to features; it is therefore unable to account for these results. It is unclear whether the theory proposed by Levelt and colleagues can account for these results. As noted in the introduction, they propose features are accessed only in the course of retrieving whole-syllable articulatory representations. Although not explicitly discussed in Levelt et al. (1999), Levelt (1989) discusses how processes at this level are not sensitive to syllable-level phonotactic constraints. In particular, he cites vowel reduction processes in fast speech that create phonotactically illegal sequences (e.g., “remember” produced as “r’member”). In contrast, processes at the level of segments are sensitive to these restrictions. Clearly, this theory must be extended so that both levels may participate in the encoding of phonotactic constraints.

A second implication concerns the relationship between featural and syllabic representations. Some theories have assumed that featural representations are indexed for syllable position. For example, Dell (1986) assumes that segment as well as feature nodes are indexed for syllable position (e.g., there are distinct /v/ nodes for onset and coda, as well as
distinct [fricative] and [voiced] nodes). In Levelt et al. (1999), features are bound to syllable positions within articulatory representations; they are never represented independently. The problem with such approaches (as noted by Dell, 1986) is that they have difficulty registering the similarity of features (or segments) across syllable positions. Clearly, such information is required to account for these results; the speech production system has encoded the distribution of a set of features (e.g., labiodental fricatives) across both onset and coda. A system such as that proposed by Dell (1986) could not encode this distribution; since his theory assumes that features are indexed for syllable position, there is no sense in which the “same” features could occur in two different syllable positions. For example, [fricative]-onset and [fricative]-coda are simply two distinct nodes; there is no sense in which they are more similar than [nasal]-onset and [voiced]-coda.

Note, however, that simply eliminating syllable position distinctions will not suffice. Dell et al. (2000, Experiment 2) showed that highly similar segments did not interfere with one another if they did not occur in the same syllable position. When /k/ was confined to onset and /q/ to coda, participants were able to ignore featural similarity and encode segment-specific constraints. If there was no distinction between features in different syllable positions, we could not account for these results. The speech production system must therefore use multidimensional representations that allow it recognize the similarity of features across syllable positions (e.g., registering that [fricative]-onset and [fricative]-coda share structure) without losing the ability to distinguish between them (e.g., that the feature occurs in onset in one representation and coda in the other).

Finally, some theories have claimed that features are highly abstract, categorical units of contrast (e.g., distinctive features; Chomsky & Halle, 1968), while others have supposed that
features gradiently specify degree and duration of constriction along some articulatory dimension (e.g., gestures; Browman & Goldstein, 1989). Both of these perspectives assume that the most basic unit of phonological representation is more abstract than the motoric representations which actually drive the articulators. This degree of abstraction allows both representational frameworks to account for the results; both distinctive features and gestures are capable of representing the similarity (and difference) of features across syllable positions. The results do not, therefore, speak to the question of whether features are highly abstract or more directly related to motoric representations.

**Conclusions**

These results emphasize the importance of representations in understanding the organization of phonological processing in speech production. This suggests that theories of cognitive processes have much to learn from the insights of generative linguistic theories. In turn, linguistic theories must acknowledge the need to accommodate gradient phenomena — a strength of theories of language processing. Future work combining these multiple perspectives should provide a more complete picture of the processing and representation of phonotactic constraints.
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Footnotes

1 Dell et al. (2000) do not report results specific to /f/ in onset; these figures are taken from collapsed results for /f/ and /s/.

2 Damian & Bowers (2003) demonstrated that the form-overlap advantage can be disrupted by pure orthographic differences between items (e.g., camel, kidney showed no form-overlap advantage despite having the same initial phoneme). These results may therefore reflect disruption from conflicting orthographic representations, not the absence of features.

3 Note that several of the participants were native bilinguals and/or had extensive training in foreign languages. Languages spoken by the bilinguals in this group included: Estonian; Japanese; Korean (2 participants); Mandarin Chinese; Spanish; Vietnamese. Exclusion of data from bilingual participants did not alter the overall results.

4 Percentage of stimulus syllables that are words, fricative conditions (listed by segment subject to segmental and featural constraints): /f/: 15.6%; /v/: 15.6%; /s/: 15.6%; /z/: 18.8%. Stop conditions: /t/: 28.1%; /d/: 25.0%; /k/: 12.5%; /g/: 12.5%

5 It should be noted that several participants were native bilinguals and/or had extensive training in foreign languages. Languages spoken by the bilinguals in this group included: Farsi, Japanese, and Spanish.

6 Percentage of stimulus syllables that are words (listed by segment subject to segmental and featural constraints): /k/: 20.9%; /g/: 18.6%

7 It should be noted that these results may by attributable to problems encoding featural constraints on dorsal consonants (see Experiment 2).
Table 1

Mean percentage of participant errors violating target syllable position, Experiment 1 (fricative conditions). Standard error shown in parentheses. \( \tilde{n} \) denotes mean number of participant errors.

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<thead>
<tr>
<th>Properties of fricative subject to segmental and featural constraints</th>
<th>No Segmental Constraint</th>
<th>Segmental Constraint</th>
<th>No Segmental Constraint</th>
<th>Segmental Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voiced</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronal</td>
<td>29.3% (2.9%)</td>
<td>1.1% (1.1%)</td>
<td>31.3% (11.5%)</td>
<td>5.4% (2.4%)</td>
</tr>
<tr>
<td>( \tilde{n} = 75.2 )</td>
<td>( \tilde{n} = 16.0 )</td>
<td>( \tilde{n} = 10.0 )</td>
<td>( \tilde{n} = 11.8 )</td>
<td></td>
</tr>
<tr>
<td>Voiceless</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronal</td>
<td>22.9% (1.6%)</td>
<td>2.2% (1.6%)</td>
<td>50.2% (7.4%)</td>
<td>13.2% (6.3%)</td>
</tr>
<tr>
<td>( \tilde{n} = 101.2 )</td>
<td>( \tilde{n} = 31.0 )</td>
<td>( \tilde{n} = 20.6 )</td>
<td>( \tilde{n} = 14.2 )</td>
<td></td>
</tr>
<tr>
<td>Voiced</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labiodental</td>
<td>29.9% (6.7%)</td>
<td>2.3% (1.5%)</td>
<td>23.1% (8.5%)</td>
<td>11.9% (3.5%)</td>
</tr>
<tr>
<td>( \tilde{n} = 51.6 )</td>
<td>( \tilde{n} = 14.4 )</td>
<td>( \tilde{n} = 19.8 )</td>
<td>( \tilde{n} = 13.0 )</td>
<td></td>
</tr>
<tr>
<td>Voiceless</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labiodental</td>
<td>31.7% (3.6%)</td>
<td>0%</td>
<td>31.1% (5%)</td>
<td>17.7% (9.5%)</td>
</tr>
<tr>
<td>( \tilde{n} = 84.0 )</td>
<td>( \tilde{n} = 12.0 )</td>
<td>( \tilde{n} = 36.4 )</td>
<td>( \tilde{n} = 15.0 )</td>
<td></td>
</tr>
</tbody>
</table>
Table 2

Mean percentage of participant errors violating target syllable position, Experiment 1 (fricative conditions). Errors involving consonants not shared across conditions are excluded.

<table>
<thead>
<tr>
<th>Consonant</th>
<th>Segmental Constraint</th>
<th>Segmental + Featural Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>/s/</td>
<td>0%</td>
<td>13.2% (6.3%)</td>
</tr>
<tr>
<td>/f/</td>
<td>2.4% (1.9%)</td>
<td>17.7% (9.5%)</td>
</tr>
</tbody>
</table>
Table 3

Mean percentage of each participant’s errors in Experiment 1 that violated target syllable position (fricative conditions).

<table>
<thead>
<tr>
<th>Consonant subject to segmental constraints</th>
<th>Voiceless</th>
<th>Voiced</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Featural Constraint</td>
<td>14.2% (4.6%)</td>
<td>15.6% (5.2%)</td>
</tr>
<tr>
<td>Featural Constraint</td>
<td>28.0% (6.6%)</td>
<td>17.9% (5.8%)</td>
</tr>
<tr>
<td>Mean effect of Featural Constraint</td>
<td>13.9%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
Table 4

Mean percentage of each participant’s errors in Experiment 1 that violated target syllable position (fricative conditions).

<table>
<thead>
<tr>
<th></th>
<th>No Featural Constraint</th>
<th>Featural Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Segmental Constraint</td>
<td>Segmental Constraint</td>
</tr>
<tr>
<td>Blocks 1 + 2</td>
<td>29.8% (2.8%)</td>
<td>1.4% (0.7%)</td>
</tr>
<tr>
<td>Blocks 3 + 4</td>
<td>27.4% (2.4%)</td>
<td>0.8% (0.6%)</td>
</tr>
<tr>
<td>Mean change</td>
<td>–2.5%</td>
<td>–0.6%</td>
</tr>
</tbody>
</table>
Table 5

Mean percentage of participant errors violating target syllable position, Experiment 1 (stop conditions).

<table>
<thead>
<tr>
<th>Properties of stop subject to segmental and featural constraints</th>
<th>No Featural Constraint</th>
<th>Featural Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Segmental Constraint</td>
<td>Segmental Constraint</td>
</tr>
<tr>
<td>Voiced Voiceless Dorsal</td>
<td>25.2% (5.9%)</td>
<td>20.0% (20.0%)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{n} = 27.4$</td>
<td>$\tilde{n} = 4.6$</td>
</tr>
<tr>
<td>Voiced Voiceless Coronal</td>
<td>22.2% (3.6%)</td>
<td>2.9% (1.8%)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{n} = 131.0$</td>
<td>$\tilde{n} = 35.8$</td>
</tr>
<tr>
<td>Voiceless Voiced Dorsal</td>
<td>25.0% (4.1%)</td>
<td>4.4% (3.2%)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{n} = 51.6$</td>
<td>$\tilde{n} = 13.6$</td>
</tr>
<tr>
<td>Voiceless Voiced Dorsal</td>
<td>26.4% (7.4%)</td>
<td>1.7% (1.7%)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{n} = 57.2$</td>
<td>$\tilde{n} = 10.8$</td>
</tr>
</tbody>
</table>
Table 6
Mean percentage of each participant’s errors in Experiment 1 that violated target syllable position (stop conditions).

<table>
<thead>
<tr>
<th></th>
<th>Voiceless</th>
<th>Voiced</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Featural Constraint</td>
<td>14.4% (4.7%)</td>
<td>17.6% (7.4%)</td>
</tr>
<tr>
<td>Featural Constraint</td>
<td>28.8% (8.0%)</td>
<td>17.8% (5.7%)</td>
</tr>
<tr>
<td>Mean effect of Featural Constraint</td>
<td>14.4%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
Table 7

Mean percentage of each participant’s errors in Experiment 1 that violated target syllable position (stop conditions).

<table>
<thead>
<tr>
<th></th>
<th>No Featural Constraint</th>
<th>Featural Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Segmental Constraint</td>
<td>Segmental Constraint</td>
</tr>
<tr>
<td>Blocks 1 + 2</td>
<td>21.9% (2.6%)</td>
<td>6.6% (5.0%)</td>
</tr>
<tr>
<td></td>
<td>29.0% (4.2%)</td>
<td>19.6% (4.8%)</td>
</tr>
<tr>
<td>Blocks 3 + 4</td>
<td>24.7% (3.5%)</td>
<td>3.5% (2.5%)</td>
</tr>
<tr>
<td></td>
<td>31.5% (5.0%)</td>
<td>14.3% (6.1%)</td>
</tr>
<tr>
<td>Mean change</td>
<td>2.7%</td>
<td>-3.1%</td>
</tr>
<tr>
<td></td>
<td>2.5%</td>
<td>-5.3%</td>
</tr>
</tbody>
</table>
Table 8

Mean percentage of each participant’s errors in Experiment 2 that violated target syllable position.

<table>
<thead>
<tr>
<th>Properties of stop subject to segmental and featural constraints</th>
<th>No Featural Constraint</th>
<th>Featural Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Segmental Constraint</td>
<td>Segmental Constraint</td>
</tr>
<tr>
<td>Voiced</td>
<td>37.1% (3.8%)</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>( \bar{n} = 117.3 )</td>
<td>( \bar{n} = 9.0 )</td>
</tr>
<tr>
<td>Voiceless</td>
<td>25.3% (2.8%)</td>
<td>2.9% (2.1%)</td>
</tr>
<tr>
<td></td>
<td>( \bar{n} = 100.4 )</td>
<td>( \bar{n} = 10.0 )</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. Hypothetical results on consonant categories if featural as well as segmental constraints are encoded (with no interaction of constraints).

Figure 2. Mean percentage of participant errors that violated target syllable position (Experiment 1, fricative conditions). Errors bars represent standard error.

Figure 3. Mean percentage of participant errors that violated target syllable position (Experiment 1, stop conditions). Errors bars represent standard error.

Figure 4. Mean percentage of participant errors that violated target syllable position (Experiment 2). Errors bars represent standard error.
Figure 1
Figure 2
Figure 3
Figure 4