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Phonotactic probability influences speech production

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Abstract

Speakers are faster and more accurate at processing certain sound sequences within their language. Does this reflect the fact that these sequences are frequent or that they are phonetically less complex (e.g., easier to articulate)? It has been difficult to contrast these two factors given their high correlation in natural languages. In this study, participants were exposed to novel phonotactic constraints de-correlating complexity and frequency by subjecting the same phonological structure to varying degrees of probabilistic constraint. Participants' behavior was sensitive to variations in frequency, demonstrating that phonotactic probability influences speech production independent of phonetic complexity.

The possible sound sequences of a language are not all equiprobable; some are more frequent than others. For example, in English /s/ and /z/ are both found word initially (e.g., *soap* and *zone*), but the former is much more frequent¹. These differences in relative probability² can be characterized by probabilistic phonotactic constraints. A number of studies have claimed these constraints are encoded by speech production processes. However, other studies have attributed similar behavioral effects not to relative phonotactic probability but to contrasting phonetic complexity (e.g., /s/ is easier to process than /z/ because it is easier to articulate or less marked). Here we report an experimental study designed to assess if phonotactic probability influences speech production processes in adults independent of phonetic complexity.

The question of whether phonotactic probability does or does not play a role in speech production resonates with broader disputes in phonological theory. Recently proposed grammatical frameworks accord a central role to frequency (e.g., Bybee, 2001; Pierrehumbert, 2001). This stands in marked contrast to more traditional theories that completely exclude such factors (e.g., Prince & Smolensky, 1993). By examining whether sound structure frequency is a necessary property of theories of speech production, this study speaks more broadly to the question of which of these frameworks is a more appropriate model of human linguistic capacities.

¹Phonotactic probability is highly correlated with neighborhood density—the number of lexical items that are phonologically similar to a target. These effects arise at distinct, independent levels of the spoken production system (Goldrick & Rapp, 2007; Vitevitch, Armbrüster, & Chu, 2004).

²We focus on frequency-based probabilistic phonotactics, excluding those conditioned by sociolinguistic factors. As discussed by Guy (1980), these constraints differ across dialect groups, suggesting they are not a simple reflection of phonetic complexity.

Phonotactic probability and phonetic complexity in speech production

Phonotactic probability correlates with a variety of production measures. Vitevitch, Armbrüster, and Chu (2004) found faster picture naming latencies when picture names were composed of high vs. low probability sound sequences. Laganaro and Alario (2006) found similar results when picture names were composed of high vs. low frequency syllables (see also Cholin, Levelt, & Schiller, 2006; Levelt & Wheeldon, 1994). Studies of speech errors that were experimentally induced (Kupin, 1982) or arose subsequent to acquired production deficits (Goldrick & Rapp, 2007) have reported that errors are more likely to occur on low vs. high frequency segments. Finally, some studies have shown that speech errors are more likely to result in high vs. low frequency segments³ (Levitt & Healy, 1985; Motley & Baars, 1975).

However, other studies have documented correlations between speech production measures and phonetic complexity. Building on notions such as cross-linguistic markedness (Jakobson, 1941), we use this term to refer to the intrinsic perceptual, articulatory, and/or cognitive well-formedness of different phonological structures. Studies of acquired deficits to speech production (e.g., Béland & Paradis; 1997, Romani & Calabrese, 1998) have shown that phonetic complexity (as indexed by cross-linguistic markedness) influences both accuracy and the probability of error outcomes.

Resolving these conflicting perspectives is difficult as phonetically complex sound structures also tend to have low probability within a particular language (Berg, 1998; Frisch,

³Note some studies have not found asymmetries in the probability of high vs. low frequency outcomes (e.g., Shattuck-Hufnagel & Klatt, 1979). Furthermore, in a series of studies, Stemmerger has shown that the general preference for higher frequency error outcomes is coupled with a preference for lower frequency structures over (very high frequency) default forms (see Stemmerger, 2004, for a review). Following Stemmerger we attribute this “anti-frequency” effect to properties of lexical representations. As our stimuli are primarily composed of nonce forms, we expect this effect to be minimized.

2000; Greenberg, 1966; Zipf, 1935). Studies examining the small number of structures where these are de-correlated have reported mixed results. Some results favor complexity (Goldrick & Rapp, 2007) while others favor frequency (Motley & Baars, 1975). It is therefore unclear which of these factors gives rise to apparent effects of phonotactic probability in speech production.

The current study

To determine if the spoken production system can encode probabilistic phonotactic constraints or if processing simply reflects phonetic complexity, participants were trained on novel phonotactic constraints. To varying degrees, these constrained the same phonological structure to one syllable position (e.g., /f/ was confined to onset in 80% vs. 40% of sequences). If the apparent effects of probabilistic phonotactics are due solely to phonetic complexity, participant performance should not vary across conditions—identical phonological structures (e.g., /f/-onset) occur in each condition. In contrast, if participants can acquire probabilistic phonotactic constraints, error distributions should reflect the relative frequency of phonological structures within each condition⁴.

The constraints were acquired in an implicit learning paradigm (Dell, Reed, Adams & Meyer, 2000) that builds on two well-attested features of speech errors (Vousden, Brown, & Harley, 2000). First, speech errors tend to preserve syllable position. Given a target sequence like “bad cat,” an error like “bad bat” (onset -> onset) is more likely than “bad cab” (onset -> coda). Second, this tendency is massively strengthened when segments are subject to language-

⁴ A similar strategy has been used in research examining a different topic in speech production—the order in which segmental contrasts are acquired. In this work, complexity is held constant by examining acquisition of the same segments cross-linguistically. The influence of frequency can then be examined based on the contrasting properties of the two languages (e.g., in one language, /s/ may be relative frequent compared to /ʃ/, whereas the opposite pattern holds in another language). This work suggests both complexity and frequency influence the order of acquisition of segmental contrasts (see Edwards & Beckman, in press, for a recent review).

specific phonotactic constraints. For example, /h/ is categorically confined to onset position in English. Given a target sequence like “hag cat,” an error like “hag hat” (onset -> onset) is much, much more likely than an error like “hag cah” (onset -> coda; the latter type of error is observed extremely infrequently).

Dell et al. (2000) used these two features of errors to examine the influence of novel phonotactic constraints. Participants were asked to read aloud tongue twisters composed of CVC syllables. Some consonants freely occurred in both onset and coda (e.g., /m/ appeared in each syllable position with equal frequency). Others reflected experiment-specific constraints (e.g., /f/ occurred only in onset). When participants read these tongue twisters aloud quickly, their errors tended to respect syllable position. Interestingly, similar to naturally occurring phonotactic constraints, this effect was massively strengthened by constraints specific to the experimental syllables. For example, when /f/ was restricted to onset, only 3% of the erroneously produced /f/ segments occurred in coda—suggesting participants acquired the experiment-specific phonotactic constraint (for replications and extensions, see Goldrick, 2004; Taylor & Houghton, 2005; Warker & Dell, 2006).

We adapted this paradigm to expose participants to novel probabilistic phonotactic constraints. A single critical consonant (/f/ or /s/, following previous studies with this paradigm) was associated with onset and coda position. Across conditions, the relative frequency of the segment in these two positions was varied from categorically onset biased (100% onset/0% coda), to unbiased (50%/50%), to categorically coda biased (0%/100%; see Table 1). For example, in the unbiased /f/ condition, 50% of the tongue twister sequences contained syllables like /fɛm/ while the other 50% contained syllables like /mɛf/. If participants can encode probabilistic phonotactic constraints, the distribution of speech errors should vary across

conditions. Specifically, the tendency of errors to preserve syllable position should increase with the relative frequency (or phonotactic probability) of the segment in that position. For example, /f/-coda errors (e.g., *hef mep*->*hef mef*) should be more likely to preserve syllable position when 80% vs. 20% of /f/ targets appear in coda. In contrast, if participants cannot acquire such constraints, their speech error distributions should be relatively constant, reflecting only the relative phonetic complexity of segments in particular prosodic positions.

Experimental Study

Method

Participants. 62 individuals from the Northwestern University community participated, receiving either partial course credit or money as compensation. Six were excluded due to equipment failure or inability to perform the task. The remaining 56 individuals (37 women; 48 right-handed, 2 ambidextrous; 11 bilingual) were all native English speakers who reported no history of speech or hearing problems.

Materials. Two critical segments (/s/ and /f/) occurred in one of seven frequency distributions (see Table 1), yielding a total of 14 conditions. Participants were randomly assigned to a single condition (yielding 4 per condition).

Table 1. Relative frequency distribution of critical segments.

Distribution type	Percentage of targets with segment in:		Total number of trials per participant
	Onset	Coda	
Categorical—Onset	100	0	196
	80	20	200
	60	40	160
Probabilistic	50	50	196
	40	60	160
	20	80	200
Categorical—Coda	0	100	196

Tongue twisters consisting of four C/ε/C syllables (e.g., *hes nev pem gek*) were constructed to reflect the phonotactic constraints of each condition. Syllables were composed of the critical segment plus six filler consonants: /m/, /n/, /p/, /g/, and /k/ plus /v/ (/s/ conditions) or /z/ (/f/ conditions). These differed from the target segment by at least two features. Each was evenly distributed in onset and coda position and occurred equally frequently with the other fillers. Each segment occurred once per tongue twister.

Two additional filler consonants /h/ and /ŋ/ were used to balance out the distribution of the critical segment in the twisters. For example, if /s/ occurred in onset position 100% of the time, /h/ never occurred in a string, and /ŋ/ always occurred. However, if /s/ occurred 60% of the time in onset, then /h/ occurred the other 40% of the time in onset to fill out onset position, and /ŋ/ occurred 60% of the time to fill out coda position.

A random set of tongue twisters respecting the constraints of each condition was constructed. In some cases, this required more twisters than could be administered to a participant in a single experimental session (e.g., 400 in the 80%/20% condition). Therefore, each participant received only half of the full set of tongue twisters (see Table 1 for total number of trials). These were split into two blocks. The distribution of filler segments was controlled within each block, and block order was counterbalanced across participants. Each block was further divided in two; within each of these quarters, the distribution of the critical segment reflected the phonotactic constraint of the experimental condition.

Procedure. Targets were presented on a computer screen in a sound-attenuated room. Participants read each tongue twister once slowly (1 syllable/second) and three times quickly (3.5 syllables/second) in time to a metronome. Trial onset was self-paced. Productions were recorded for analysis. The entire session lasted approximately 50 minutes.

Results

Data analysis. Each participant's data was randomly assigned to one of four transcribers for broad phonetic transcription. The overall agreement rate on 40 trials from 2 randomly selected participants was high, 91.3% (n = 687 errors across the transcribers). Agreement rate on critical consonants (in this case /s/) was also good, 92% (n = 25 errors across all transcribers). In 5 conditions (see Table 2), some participants failed to generate errors involving critical segments; these data points were excluded from the analysis.

Following previous studies with this paradigm (e.g., Dell et al., 2000), the dependent variable is the proportion of error outcomes preserving target syllable position⁵. As discussed

⁵ As noted in the introduction, studies with other paradigms have also used accuracy as a dependent measure. However, analysis of the tongue twister productions in this study revealed no significant correlation between phonotactic probability within each condition and accuracy.

above, categorical phonotactic constraints massively strengthen the tendency of errors to preserve target syllable position. For probabilistic constraints, we therefore expect that as the probability of a segment appearing in a syllable position increases, the tendency of errors to preserve syllable position should also increase (reaching nearly 100% for the categorical conditions).

The mean percentage (across participants) of errors preserving syllable position at each level of phonotactic probability⁶ is shown in Figure 1. Table 2 reports the total number of errors produced at each probability level. For the /f/-conditions, as well as /s/ in coda, the tendency of errors to preserve syllable position clearly increases with phonotactic probability—suggesting participants have acquired probabilistic constraints. In contrast, /s/-onset targets virtually always preserve syllable position, obscuring any influence of probabilistic phonotactics in this condition.

These patterns were quantitatively assessed using a linear mixed logistic regression model. The results are summarized in Table 3⁷. Consistent with the encoding of probabilistic phonotactic constraints, the likelihood of errors preserving syllable position was positively correlated with phonotactic probability⁸ ($z = 8.35$, $p < .0001$). (No other main effects were significant; $|z|s < 1$.) The significant interaction of consonant and target position ($z = 3.32$, $p < .001$) reflects the tendency of /s/-onset errors to virtually always preserve syllable position.

⁶Note that since the specified segment never appears in that syllable position there is no data for the 0% probability condition.

⁷Qualitatively similar findings were observed when the analysis was limited to nonword outcomes or when results were collapsed across participants. The effect of probabilistic phonotactic constraints was not significantly different across the first and second blocks of trials.

⁸Similar results were found for separate analyses focusing solely on errors preserving vs. violating syllable position. As the phonotactic probability of /f/ or /s/ increased, the likelihood of an error resulting in /f/ or /s/ that preserved syllable position increased and the likelihood of an error violating syllable position decreased.

Figure 1. Mean percentage of errors (across participants) preserving syllable position at varying levels of phonotactic probability (separated by consonant and syllable position).

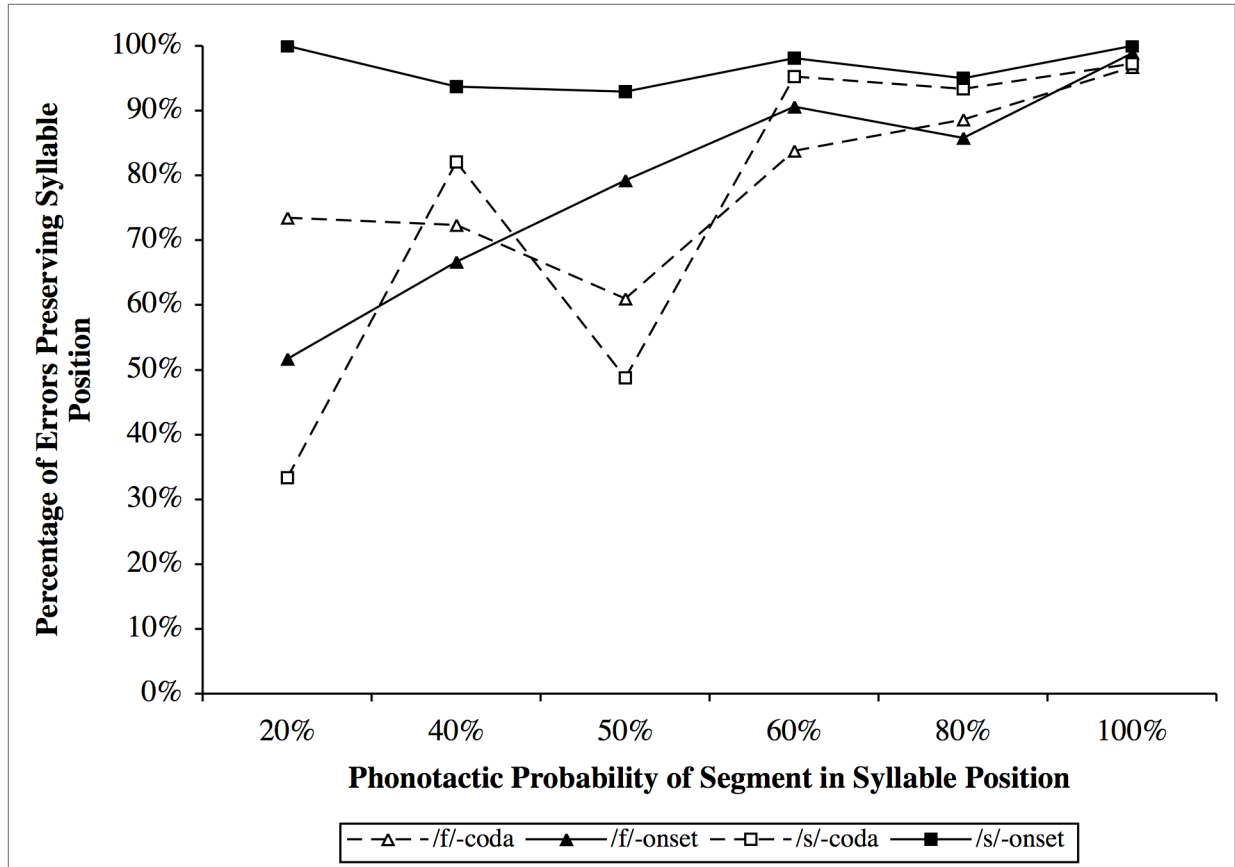


Table 2. Total number of errors violating vs. preserving syllable position. *S* denotes the number of participants that produced errors in the condition.

Consonant	Syllable Position	Errors violating vs. preserving syllable position	Phonotactic probability of consonant in syllable position					
			20%	40%	50%	60%	80%	100%
/f/	Coda	Violating	7	6	19	16	5	5
		Preserving	14	18	34	55	67	169
			<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4
	Onset	Violating	7	9	8	3	6	2
		Preserving	7	16	23	20	48	85
			<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4
/s/	Coda	Violating	2	7	8	1	1	1
		Preserving	2	10	7	10	17	27
			<i>S</i> = 2	<i>S</i> = 3	<i>S</i> = 4	<i>S</i> = 3	<i>S</i> = 3	<i>S</i> = 4
	Onset	Violating	0	3	5	1	2	0
		Preserving	1	19	30	56	32	84
			<i>S</i> = 1	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4	<i>S</i> = 4

Table 3. Summary of by-participant mixed logistic regression analysis of likelihood that errors will preserve syllable position. (Standard deviation of random intercept term: 0.48). Note: ‘**’ = $p < .005$; ‘***’ = $p < .0005$.

Predictor	B	SE B	Odds Ratio (e^B)
Consonant (/f/ vs. /s/)	-0.34	0.36	0.71
Target position of consonant (coda vs. onset)	-0.03	0.25	0.97
Phonotactic probability of consonant in target position (20-100%)	4.30***	0.52	73.70
Interaction: Consonant * target position	1.69**	0.51	5.42

General Discussion

Participants in an implicit learning paradigm were exposed to novel probabilistic phonotactic constraints. Unlike natural constraints, these de-confounded phonetic complexity and frequency by subjecting the same sound structure to varying levels of probabilistic constraint. The results show that the spoken production system can acquire probabilistic constraints. This is consistent with a number of results in speech perception and language acquisition (Auer & Luce, 2003). The pervasive effects of probabilistic phonotactics on phonological processing suggest that frequency must play a critical role in theories of sound structure (Bybee, 2001; Pierrehumbert, 2001).

The finding that participants can encode probabilistic phonotactics does not imply that phonetic complexity does not also exert an influence on processing. Results from artificial phonological grammar learning (Wilson, 2006) and child language acquisition (Edwards & Beckman, in press) suggests that both of these factors influence acquisition. Instead of simply being opposing perspectives, probabilistic phonotactics and phonetic complexity may constitute two interacting components of the cognitive system encoding sound structure.

The results of the current study may provide some support for this perspective. Errors involving /s/-onset targets were much less sensitive to variation in probability. This is intriguing, as some results suggest that /s/-onset is phonetically preferred (see Goldrick & Larson, in press, for discussion) even though it is not favored by the statistics of English⁹. By examining how the

⁹ For example, across all word forms in the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995), /f/, not /s/, is more strongly biased to onset. While only 67% of /s/s appear in onset (N = 59856), 83% of /f/s appear in this position (N = 21717). For additional frequency calculations demonstrating that /f/, not /s/, is more strongly biased to onset position, see <http://ling.northwestern.edu/~goldrick/sandf.pdf>

phonetic properties of phonological structures interact with phonotactic probability, future studies can help elucidate how these two sources of information are integrated during speech production.

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