# Syllabification, sonority, and perception: new evidence from a language game

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## 1. Introduction

It is common for segments to be subject to phonotactic restrictions on the phonological environments in which they can occur, especially restrictions on linear order (i.e., which segments can occur adjacent to which). Where do these restrictions come from, and how should they be expressed? This paper contrasts two theories of the nature of restrictions on linear order, which for convenience we refer to as the "sonority theory" and the "perceptibility theory".

The sonority theory says that different segment types have different inherent levels of sonority (linked, though somewhat obscurely, to acoustic energy or vocal-tract stricture), and that a segment's compatibility with a given environment depends on the permissible sonority contours within and between syllables. This is the older view, dating back at least to the 19th Century; for a review, see Clements (1990). The perceptibility theory, due originally to Steriade (1995), says that a segment's compatibility with a given environment depends on how accurately it is likely to be perceived in that environment. Although the two theories need not be mutually exclusive, the perceptibility theory has been offered as a complete replacement for the sonority theory both within the generative tradition (Wright 2004) and outside it (Ohala & Kawasaki 1997).

This paper compares the sonority and perceptibility theories as accounts of speakers' relative preference for CV versus VC productions in a language game. The use of a language game has several advantages. Since both theories were developed mostly on the basis of ordinary language data, the game allows them to be tested on facts they were not engineered to accommodate. Using a game also insures that the observed CV/VC asymmetries are productive in the synchronic grammar, rather than being descriptive artifacts of purely diachronic regularities. Language games can also reveal *covert rankings*, i.e., constraint rankings which play no role in the ordinary language, and hence cannot have been learned from it, but which emerge in games, loanword adaptation, second-language acquisition,

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etc. (Davidson, Smolensky, & Jusczyk 2004). Finally, this particular game is of practical importance in the teaching of reading and diagnosis of reading disorders.

We find that a particular pattern of errors in game outputs is due to a preference for putting more-sonorous consonants into coda position, rather than to a preference for putting consonants into contexts that maximize their perceptibility. The main conclusin we draw from this is that it is not possible to eliminate sonority from phonological theory in favor of perceptibility. The error pattern can be modelled by the interaction of a game-specific ANCHOR-LEFT constraint with the *PEAK/X and *ONSET/X hierarchies. Since these hierarchies play no role in the phonology of ordinary English, the game seems to expose a covert ranking. Our secondary conclusion is therefore that some constraint rankings are not learned from ordinary language input.

The rest of the paper is organized as follows: Section 2 describes the language game and lays out our model of it. Section 3 tells how the data corpus was collected and coded. Section 4 addresses the perceptibility theory, explaining how perceptibility was quantified and assessing it as a predictor of game outputs. Section 5 does the same for the sonority theory. Section 6 concludes the paper.

## 2. The "sounding-out" game

"Sounding out", also known as phoneme segmentation, is a technique widely used to teach "phonemic awareness" and letter-decoding skills to children so that they can learn to read English. It is described in reading-pedagogy texts as a process of pronouncing each phoneme separately in isolation (e.g., Gunning 1988:4; Baer 1999:4)[2]. Each segment of the input is required to stand at the left edge of a prosodic word in the output, as shown in (1).

| (1) | Source | Game |
|---|---|---|
| | *cheap* | [# .tʃ. # .i. # .pə. #] or [# .tʃə. # .i. # .pə. #] |
| | *beige* | [# .bə. # .eɪ. # .ʒ. #] or [# .bə. # .eɪ. # .ʒə. #] |

Naïve speakers are more consciously aware of syllables than of segments (for a recent review, see Tyler 2002, Chapter 2). "Sounding-out" is a language game which takes advantage of this fact by putting each segment into a separate syllable (indeed, into a separate prosodic word) (Feng et al. in progress). We make two assumptions to model game performance.

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2 As of July 18, 2005, audio examples are available from the U.S. Public Broadcasting Service; see the "Between the Lions" reading game "Fuzzy Lion Ears" at http://pbskids.org/lions/games.

*Assumption #1* is our phonological model of the game: Speakers add a single new constraint to their grammar, ANCHOR (SEGMENT, PRWD, L), hereinafter known as "ANCHOR-L" (McCarthy & Prince 1995), to force each segment to the left edge of an individual Prosodic Word. Other rankings are unperturbed.

*Assumption #2* is our phonological model of errors: Game outputs that violate ANCHOR-L do so because of constraint conflict. This may happen probabilistically rather than deterministically, owing to indeterminate positions of constraints within or between speakers (Anttila & Cho 1998; Boersma & Hayes 2001).

It follows from these assumptions that error patterns in the game can tell us something about what the conflicting constraints are, and, in particular, whether they refer to perceptibility in the context of adjacent segments, or to sonority in the context of syllable positions.

## 3. The game corpus

Although children's "sounding-out" errors are used to assess phonemic awareness and predict future reading difficulty (e.g., Gorrie & Parkinson 1995), standardized tests do not control for phonological structure, and very little is known about whether or how different segment types or prosodic positions lead to different response patterns (but see Treiman et al. 1995). The first step was therefore to collect a game corpus from adults (who had presumably learned the game as children). This initial study was limited to the sounding out of words containing exactly 3 segments. Our analysis focused on what happened in the game to consonants which were in the last position of a CV(:)C stimulus word.

*Materials* were 153 trisegmental English words, covering the 5 syllable types shown in (2). Only the CV:C and CVC words are analyzed in this paper.

(2) a. Tense vowels and diphthongs:
- i. $C_1C_2V$: (e.g., *three*)
- ii. **$C_1V{:}C_2$** (e.g., *phone*)
- iii. $V{:}C_1C_2$ (e.g., *east*)

b. Lax vowels:
- i. **$C_1VC_2$** (e.g., *thud*)
- ii. $VC_1C_2$ (e.g., *inch*)

The words were selected so that every C appeared at least twice as $C_1$ and twice as $C_2$ in each syllable type (if that C occurred in that position in the English lexicon at all). No consonant appeared twice in the same word, and the set contained no minimal pairs differing only in the vowel. The lexicon used was CELEX (Baayen et al. 1993). The size of the materials set was minimized by treating the set of CELEX words of a given syllable type as a bipartite graph with each word corresponding to an edge $C_1$–$C_2$, and then finding a minimal edge cover using the Bipartite Cardinality Matching Algorithm (Lawler 1976:193–196). CELEX's British pronunciations were Americanized by hand.

*Stimuli*. The words were recorded in isolation by a female American English native speaker in a soundproof studio, using a head-mount microphone and the Praat sound-analysis software (Boersma & Weenink 2004), at a sampling rate of 44.1 kHz. One token of each word was chosen, and all stimuli were equated for peak amplitude.

*Participants* were 16 native speakers of American English from the Psychology Department subject pool at Duke University in Durham, North Carolina. They received course credit for participating.

*Procedure*. "Sounding-out" was demonstrated with a few recorded examples. Thereafter, on each trial, the participant heard a stimulus word and sounded it out into a head-mount microphone. Each stimulus word was presented once, in random order.

*Coding*. The analysis was based on a broad phonetic transcription of the responses. Responses were transcribed by 3 phonetically-trained native speakers of American English. Each scribe was responsible for 1/3 of the trials, chosen randomly from the combined responses of all participants. A random 1/10 was done by all 3, for a reliability check. A pause was transcribed as a prosodic-word boundary. Audible releases were transcribed (unless followed by an approximant, in which case audible release was assumed); they were counted as voiceless vowels for this analysis. Transcribers heard the trials in random order, and saw no information about the trial except the orthography of the stimulus word.

*Excluded trials*. We dropped trials on which the participant misheard the stimulus word (2.2% of all trials), corrected him- or herself (0.4%), did not respond at all (0.2%), or produced a non-English segment (0.5%). Trials were also excluded when the transcriber felt it necessary to add a comment about syllabification, pronunciation of consonants, presence or quality of a release, or performance errors.

*Extracting "repairs"*. For each trial, the game output was examined to find the prosodic word containing $C_2$; e.g., if *phone* was produced [f # oʊ # nə], the extracted repair was [nə]. Trials where $C_2$ had been deleted, altered, or duplicated were dropped. There were 1456 trials in all where the stimulus was $C_1VC_2$. A total of 1340 (92%) yielded repairs (our general term for input-output mappings) that met the criteria for inclusion.

*Reliability.* 142 valid $C_1VC_2$ trials were transcribed by all three scribes. The $C_2$ repairs were reduced to a skeletal structure consisting of symbols indicating "consonant", "tense vowel", "lax vowel", "audible release", and boundaries between the nucleus and margins of the syllable. At least two scribes assigned identical structures to 95% of the repairs, and all three agreed on 58%.

*Results.* 7 prosodic-word types accounted for 95% of the $C_2$ repairs. These are shown in (3).

(3)

| | Correct | | | | Errors | | |
|---|---|---|---|---|---|---|---|
| PrWd | $C_2$ | $C_2$ ə | $C_2$+ | $C_2$V | ə$C_2$ | V$C_2$ | V$C_2$ə |
| Count | 374 | 254 | 219 | 95 | 26 | 284 | 21 |
| % | 28% | 19% | 16% | 7% | 2% | 21% | 2% |

Note: "+" indicates an audible release. Tense and lax vowel categories are combined.

Out of the 1340 repairs, 29% did not obey the game constraint ANCHOR-L and were classified as "errors" for the analysis. The majority of errors (83%) took the form of preceding the $C_2$ with a vowel (tense, lax, or schwa)— hereinafter "VC errors". 24% of all repairs were VC errors. What factor is responsible for the VC errors? In particular, is the game constraint in conflict with perceptibility-based constraints or with sonority-based constraints?

## 4. Hypothesis 1: Perceptibility

Perceptually-based theories of segment order are based on the observation that many segmental contrasts occur less often, or less widely, when adjacent segments render them less perceptible. For example, a retroflex consonant affects the acoustics of a preceding vowel more strongly than it does those of a following vowel, so that the preceding vowel carries more information about the retroflexion of the consonant than does the following vowel. There is a corresponding implicational pattern of neutralization in phonological typology: Some languages neutralize the retroflex/non-retroflex contrast in the environments V_ and _V, others neutralize it in _V only, still others do not neutralize it anywhere, but no language neutralizes it in V_ only (Steriade 1995). An important point is that there is no need to refer to syllabic position (e.g., onset versus coda); linear order of C and V is enough. In fact, there are many cases in which the relevant generalization *cannot* be expressed in terms of syllabic position (Steriade 1999).

The idea is implemented in phonological theory by positing perceptually-based constraints in synchronic grammar, with (for Optimality-Theoretic proposals) rankings between them set by perceptibility (Flemming 1995; Steriade 1999; Côté

2001; Blevins 2003; Wilson 2001; Fleischhacker 2001). For example, Jun (2004) proposes a constraint family PRESERVE:

(4) PRESERVE (X): Preserve perceptual cues for input features of type X, where X can be Place, Manner, etc.

Applied to the problem of explaining "sounding-out" game errors, this line of reasoning leads to the hypothesis that the odds that a source $C_2$ will emerge from the game in VC rather than CV position depends on the relative perceptibility of $C_2$ in VC and CV position: The more the perceptual advantage of CV over VC, the more CV responses are expected. Concretely, when PRESERVE is ranked above the game constraint ANCHOR-L, input consonants will surface in whichever context (_V or V_) is more favorable to the accurate perception of that consonant, regardless of whether the output is correctly left-anchored or not. Thus, PRESERVE is satisfied (by preserving cues) at the expense of ANCHOR-L..[3]

To apply the hypothesis to the data, we need a way of quantifying the relative perceptibility of a consonant in the contexts _V versus V_.. The "CV-VC perceptual advantage" was calculated using the confusion matrices of Cutler et al. (2004), who collected judgments by 16 American English speakers of both CV and VC syllables:

(5) a. CV syllables: all combinations of
C ∈ { p t k f θ s ʃ tʃ h b d g v ð z dʒ m n l r j w }
V ∈ { i ɪ eɪ ɛ ae ɑ ʌ ɔ oʊ ʊ u aɪ ɔɪ aʊ ɝ }
b. VC syllables: all combinations of
V ∈{ i ɪ eɪ ɛ ae ɑ ʌ ɔ oʊ ʊ u aɪ ɔɪ aʊ ɝ }
C ∈ { p t k f θ s ʃ tʃ b d g v ð z ʒ dʒ m n ŋ l ɹ }

The syllables were spoken by a phonetically-trained female American English speaker; final stops were released. The syllables were embedded in multi-speaker babble noise ("cafeteria noise") at 3 signal/noise ratios. A total of 30960 identification responses were collected. "No consonant" was not an option.

We defined the "perceptibility" of, e.g., /p/ in _V as the log-odds of correct perception of /p/ in Cutler et al.'s CV condition:

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3 The *purpose* of the game provides a reason to expect that when the game constraint is violated, it will be for the sake of perceptibility. The player uses the game to isolate the (cognitively hard-to-access) segments of the source word into separate prosodic words, where they are more open to conscious inspection, so that the word can be spelled correctly. The purpose of the game therefore puts a premium on getting the right segments across (to oneself), which provides a reason to rank the game constraint below some of the perceptual constraints.

(6)

$$\text{perceptibility (p/\_V)} = \ln\left(\frac{\text{No. of "pV" responses to [pV] stimuli}}{\text{No. of [pV] stimuli}}\right)$$

The CV-VC perceptual advantage for /p/ was defined as the difference between its perceptibility in the CV and VC conditions:

(7)

$$\text{CV} - \text{VC advantage (p)} = \left[\text{perceptibility (p/\_V)}\right] - \left[\text{perceptibility (p/V\_)}\right]$$

If the rate of correct perception of /p/ is the same in _V and V_, the CV-VC advantage is 0. It is positive if /p/ is more accurately perceived in _V than V_, and negative if the reverse is true.

This provided the independent variable, with a different value for each consonant. The dependent variable was the log-odds of the CV versus VC game responses for each consonant:

(8)

$$\text{log-odds (\#pV\# vs. \#Vp\#)} = \ln\left(\frac{\text{No. of "\#pV\#" game outputs for [CVp] stimui}}{\text{No. of "\#Vp\#" game outputs for [CVp] stimuli}}\right)$$

This number is zero if /p/ is produced equally often as /pV/ and /Vp/, positive if it comes out more often as /pV/, and negative if it is more often /Vp/.

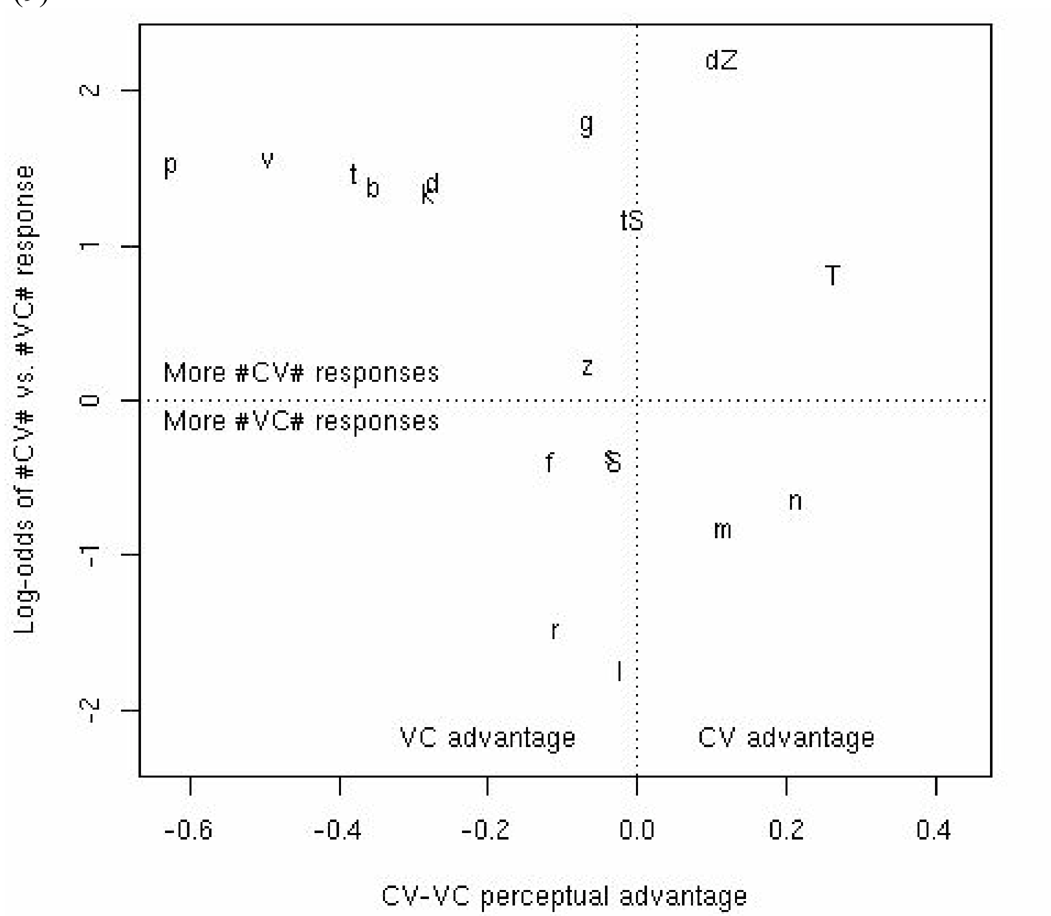
The perceptibility hypothesis predicts that the higher the CV-VC perceptual advantage is for a given C, the higher the log-odds of a CV response over a VC response. The figure in (9) shows the results. The expected relationship is not observed. The correlation is weak, if present at all, and goes the wrong way: An increase in CV-VC advantage *decreases* the log-odds of CV versus VC response.

A logistic regression model was fit to the data by maximum likelihood, with CV/VC Response as the dependent variable, CV-VC Perceptual Advantage as a fixed effect, and Speaker as a random effect, using the *glmmML* library of the R statistical package (Broström 2005). Increasing CV-VC Advantage by 1 unit changed the odds of a CV response by –2.88 logits (95% confidence interval = [–3.57, –2.19], df=887, $z$ = –8.137, different from 0 at $p < 0.0001$).

The perceptibility hypothesis is therefore not supported: Violations of the game constraint (ANCHOR-L) do not improve perceptibility; rather, they reduce it.

Hence, whatever the constraints are that cause the violations, they are not based on perceptibility in _V versus V_ contexts.

(9)




## 5. Hypothesis 2: Sonority

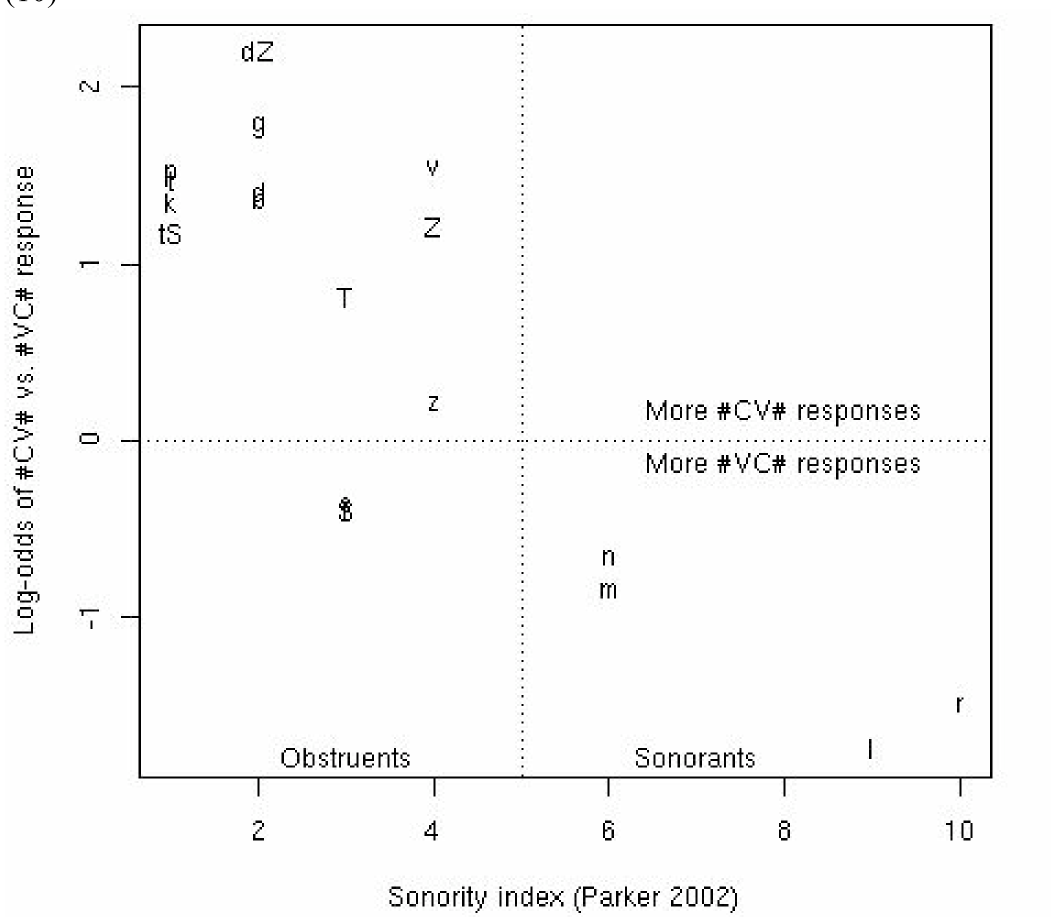
The leading alternative to perceptibility, for determining linear order, is sonority (Pike 1943; Hooper 1976; Selkirk 1984; Clements 1990; for functional motivation see Smith 2002; Wright 2004). Sonority is notoriously difficult to define in terms of a phonetic measure. We rely here on the work of Parker (2002), who proposes a phonological sonority index supported by intensity measurements in English and Spanish. The relevant subscale for English is shown in (10). The rank ordering of sonority is in agreement with that of most other versions of the sonority scale.

(10) Sonority scale (Parker 2002:239–240)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Segment class: | /ptk tʃ/ | /bdɡ dʒ/ | /fθsʃ/ | /vðzʒ/ | /mnŋ/ | /l/ | /ɹ/ |
| Sonority index: | 1 | 2 | 3 | 4 | 6 | 9 | 10 |

Consonantal sonority is potentially relevant here because it has been identified as a factor in determining acceptability as an onset or coda: Low sonority makes a good onset, while high sonority makes a good coda. If a language allows a consonant C to be an onset, it is likely to allow onsets of lesser sonority; if it allows C as a coda, it is likely to allow codas of greater sonority (Clements 1990). And indeed, when the log-odds of a CV versus VC response is plotted as a function of the sonority index of C, an inverse relationship emerges.

(10)




A logistic-regression model was again fitted to the data, with Sonority as a fixed scalar factor and Subject as a random effect. A unit increase in Sonority corresponded to a change of –0.51 logits in the odds of a CV response (95% confidence interval = [–0.60, –0.43], df=887, $z = -12.28$, different from 0 at $p < 0.0001$; AIC = 867). The figure shows, however, that responses are not perfectly predicted by the sonority index: Voiceless consonants evoke more VC responses than their voiced counterparts. Adding Voicing to the model as a factor improved the fit significantly (by a likelihood-ratio test; LR = 28, chi-square (0.005, 1) = 7.88, significant at $p < 0.005$; the final model was: coefficient of Sonority = –0.66, 95% CI = [–0.76,–0.56], df = 886, $z = -12.48$, $p < 0.0001$; coefficient of Voicing = 1.17, 95% CI = [0.73, 1.60], $z = 5.529$, $p < 0.0001$; AIC = 842).

More sonorous segments are thus more likely to evoke VC responses, which violate the game constraint ANCHOR-L. This result is consistent with the hypothesis that the game constraint conflicts with sonority-based constraints. To be specific, we propose that the effect emerges from the interaction of ANCHOR-L with two constraint hierarchies derived from the sonority scale by harmonic alignment (Prince & Smolensky 1993): the *PEAK/X hierarchy, which disfavors less-sonorous nuclei, and the *ONSET/X hierarchy, which disfavors more-sonorous onsets.

(12) *PEAK/X constraint hierarchy (Prince & Smolensky 1993)

*PK/ptk » * Pk/bdg » *PK/fθsʃ » *PK/vðzʒ » *PK/mnŋ » *PK/lr

(12) *ONSET/X constraint hierarchy (after Gouskova 2003)

*ONS/lr » *ONS/mnŋ » *ONS/vðzʒ » *ONS/fθsʃ » *ONS/bdg » *ONS/ptk

An input $C_2$ is produced as $VC_2$ (i.e., becomes a coda) when ANCHOR-L is dominated by *both* *PK/$C_2$ *and* *ONS/$C_2$. For example, voiced fricatives tend to become CV, while nasals become VC:

(13) Onset sonority causes different game outputs for /v/ and /n/

| Base | Game | *PK/vðzʒ | *PK/mnŋ | *ONS/mnŋ | ANCH-L | *ONS/vðzʒ |
|---|---|---|---|---|---|---|
| ʃeɪv | ⇒və | | | | | * |
| | v | *! | | | | |
| | əv | | | | *! | |
| foʊn | nə | | | *! | | |
| | n | | *! | | | |
| | ⇒ən | | | | * | |

The gradient distribution of responses is derived by allowing the game constraint to "float" in the hierarchy; i.e., its location varies either within or between speakers. (Anttila & Cho 1998; Boersma & Hayes 2001).

## 6. Discussion

### 6.1. Evidence for covert rankings

Violations of the game constraint do not improve perceptibility; instead, they cause more-sonorous segments to be output as syllable codas. This, we argue, means that perceptibility and string adjacency cannot entirely replace sonority and syllable positions as the basis for phonotactic constraints. Specifically, we suggest that the pattern of errors is consistent with a floating game constraint ranked within the *PEAK/X and *ONSET/X hierarchies.

These constraint hierarchies are motivated by cross-linguistic implicational universals about syllable structure, and by within-language processes in non-English languages such as Imdlawn Tashlhiyt Berber (Prince & Smolensky 1993). The crucial constrants and rankings are not evident from the phonology of ordinary English. For example, we know of no evidence *within* English that nasals are worse onsets than voiced fricatives, or that liquids are worse onsets than nasals. The effect is not even present as a statistical tendency: Among uninflected English words of the form $C_1VC_2$ in CELEX, the odds of a consonant's being $C_1$ rather than $C_2$ are ranked as shown in (14).

(14) English consonants in decreasing order of odds of being $C_1$ versus $C_2$

| | $C_1 > C_2$ | | | | | | | → | | | | | | | | | | | | $C_1 < C_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stops | | | | | | | | tʃ | p | | k | | | | | | | | | |
| | | b | | | | dʒ | g | | | | | | | | | d | | | | |
| Fricatives | h | | | f | ʃ | | | | | | | s | | | | | | θ | | |
| | | | | | | | | | | ð | | | | | v | | | | z | |
| Nasals | | | | | | | | | | | | | m | | | | n | | | ŋ |
| Liquids | | | ɹ | | | | | | | | | | | l | | | | | | |

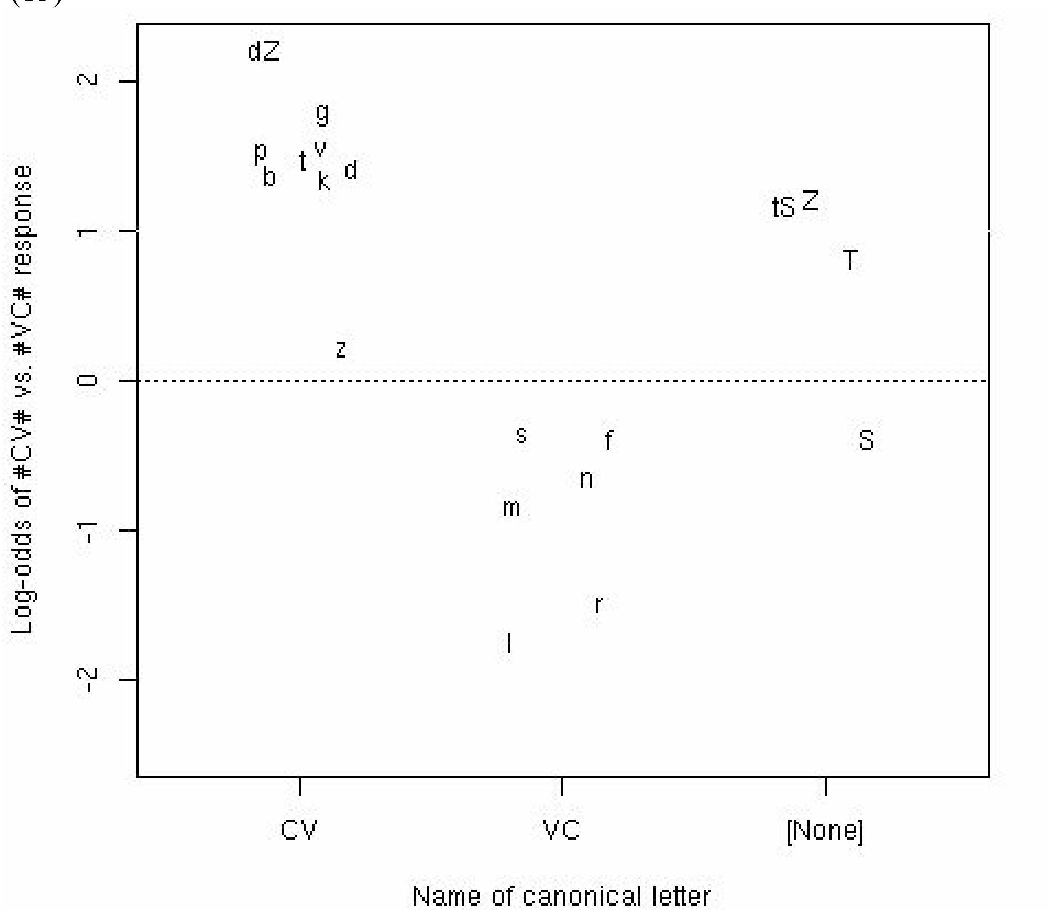
Nasals and voiced fricatives are similar, and liquids are if anything *more* likely to be onsets than nasals are. The pattern of errors in the "sounding-out" game thus reveals a covert ranking, i.e., one that is not evident in the ordinary language (Davidson et al. 2004). The results support claims that some hierarchies are universal, present in every grammar regardless of spoken-language input.[4]

[4] Which is not to say that they are innate (Hayes 1995).

## 6.2. Letter names

These conclusions depend on our assumption that game errors result from constraint conflict. But there is an another possible factor: the names of the letters. For instance, the sound [d] is canonically spelled with the letter *d*, whose name is the CV syllable [di], whereas the sound [n] is spelled with the letter *n*, whose name is the VC syllable [ɛn] or [ɪn]. The figure in (15) shows that sounds tend to be produced as CV or VC according to whether the canonical letter name is CV or VC[5]. A logistic regression with the single factor Letter Name (VC vs. not-VC) finds a significant effect (estimate = –2.49, 95% CI = [2.09,2.91], $z$ = –12.1, $p < 0.0001$).

(15)




This raises two potential alternatives to the claims made above: (A) that perceptibility and letter names might together explain what perceptibility alone

[5] Since the independent variable has only three values, random noise ("dithering") has been added so that the plotting symbols do not lie on top of each other.

cannot, or (B) "sounding-out" errors have nothing to do with phonology, and letter names alone provide a superior account. Neither is correct.

To test alternative (A), Letter Name was added to the CV-VC Perceptual Advantage regression model from Section 4. The new model indeed provided a significantly better fit than the old one (by a likelihood-ratio test; LR = 116, $p < 0.0001$)—unsurprising given how poorly Perceptual Advantage alone explains the data. The effect of Letter Name is significant (estimate = –2.27, 95% CI = [–2.72, –1.82], $z = 4.67$, $p < 0.0001$), and so is that of Perceptual Advantage (estimate = –0.84, –1.64, –0.03, $p = 0.04$). However, Perceptual Advantage again has the *opposite* effect from that predicted by the perceptibility theory: An increase in CV-VC advantage is associated with a shift from CV to VC productions.

As for alternative (B), it is clear from the figure in (14) that there are sonority-related differences in CV-VC response *within* the three letter-name categories, such as the one between liquids and nasals. Adding Sonority as a factor to the Letter Name model significantly improves the fit (LR = 50, $p < 0.0001$), whereas adding Letter Name to the Sonority-and-Voicing model yields only a marginal improvement (LR = 3.4, $p = 0.065$).

The likelihood-ratio test does not allow direct comparisons of fit between non-nested regression models. The Akaike Information Criterion, derived from the likelihood ratio by subtracting twice the number of model parameters, does permit comparisons, though it does not give a test statistic with a known distribution. Smaller AICs correspond to more effective models. The models are ranked as follows: Perceptual Advantage (1016), Letter Name (904), Perceptual Advantage plus Letter Name (902), Sonority (868), Sonority plus Voicing (843), Sonority plus Voicing plus Letter Name (841).

In short, sonority, and to a lesser extent voicing, affects "sounding out" errors by biasing more-sonorous segments towards the coda position. Letter name may play some role but is largely redundant with sonority. (It is entirely possible that sonority-based preferences for CV or VC determined the letter names, rather than the other way around.) The results run directly counter to the predicted effect of CV-VC perceptual advantage. "Sounding-out" errors are therefore a linear-order phenomenon that cannot be explained by perceptibility, but must be referred to a covert ranking of sonority-based constraints..

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