# Temporally organized lexical representations as phonological units

STEFAN FRISCH*

[To appear in: M. Broe & J. B. Pierrehumbert (eds.), *Language acquisition and the lexicon: Papers in laboratory phonology V*. Cambridge: Cambridge University Press.]

## X.1 Introduction

In traditional generative phonology, there is no role for the mechanism of lexical access as a part of linguistic competence. Lexical access is assumed to be relevant only to aspects of linguistic performance such as speech production and perception. In fact, much of what is known about lexical access comes from the study of errors in production and perception. Errors are traditionally considered part of linguistic performance, as competence is assumed to be error free.

This paper has two distinct, but related goals. The first goal is to demonstrate that lexical processing does influence linguistic competence, by showing that the beginning-to-end temporal order in which the segments in a word are processed is a functional influence on the phonology. More generally, I claim that cognitive factors influence phonology, and may be the source of language particular constraints or universal linguistic tendencies. In general, cognitive influences should not be ignored or factored out of linguistic theories, rather they should be recognized as sources of explanation for linguistic patterns. The second goal is to investigate a model of gradient constraint combination in the phonotactics of the verbal roots of Arabic, based on the stochastic constraint model (Frisch, Broe, & Pierrehumbert, 1997).

It will be shown that the Arabic verbal roots obey a gradient consonant cooccurrence constraint, OCP-Place, which is a dissimilarity constraint that applies to homorganic consonants (McCarthy, 1994; Pierrehumbert, 1993). This

* My thanks to Michael Broe, Janet Pierrehumbert, Dan Silverman, and an anonymous reviewer for comments on this work. This research was supported by NSF grant BNS 9022484 to Northwestern University and a Northwestern University Dissertation Year Grant. Thanks also to David Pisoni for support while writing this paper.

constraint is more strictly enforced at the beginning of a root, between the first consonant pair, than at the end of the root, between the second consonant pair. There is an analogous pattern in speech production in English. Errors between similar consonants at the beginning of a word are more frequent than errors between similar consonants later in the word.

Both the phonotactic constraint and the speech error pattern share an underlying dependence on the *similarity* of the consonants involved, and an interaction between segment similarity and the position of the consonants in the word. I propose that word initial consonants have special status because the similarity of consonants is evaluated on a sequentially accessed representation of the word. In other words, access of the segmental content of the lexical item takes place in its natural temporal sequence, rather than all-at-once, in *both phonological processing and phonotactic constraint evaluation.* The interaction between segment similarity and position in the word can be explained as a functional constraint grounded in an activation/competition model of lexical access and encoding (e.g. Sevald & Dell, 1994). Word onsets are special because no previous segments have been accessed before the word initial one.

Functional constraints, whether cognitive or phonetic, call into question the traditional competence/performance distinction. Since lexical access is considered an aspect of performance, and access has an effect on phonotactics, there is a direct influence of performance on competence. This influence can impact both the synchronic grammar, through the productivity of morphemes and the assimilation of borrowed words, and the diachronic grammar, as the cumulative effects of the influence of performance become grammaticized (Bybee, this volume).

Since both the phonotactic constraint in Arabic and phonological speech errors in English depend on the similarity of segments, a metric of segmental similarity is needed. The metric developed in Frisch (1996) and Frisch, Broe, & Pierrehumbert (1997), where similarity is based on shared natural classes, is presented in the next section.

## X.2 Natural classes similarity metric

The similarity of segments is usually computed by counting shared and non-shared distinctive features (e.g. van den Broecke & Goldstein, 1980). However, a similarity metric based directly on features is undesirable for a number of reasons. Feature-based metrics are overly sensitive to the type and number of features used to describe the segments (Frisch, Broe, & Pierrehumbert, 1997). In addition, similarity is influenced by the contrastiveness of features (Medin, Goldstone, & Gentner, 1993). This can only be captured in a feature-based metric by eliminating non-contrastive features (e.g. Pierrehumbert, 1993), which is a theoretically and empirically undesirable move (Broe, 1993; Frisch, 1996).

Finally, subjective similarity judgments are not linearly related to the number of shared and non-shared features (Hayes-Roth & Hayes-Roth, 1977).

These problems are avoided if the similarity metric is based on natural classes rather than features. Inspired by the lattice representation of the segment inventory in Broe (1993), Frisch (1996) implemented a similarity metric based on natural classes, shown in (1). The natural classes similarity metric is less sensitive to differences in the type and number of features used, is influenced by the contrastiveness of features without eliminating them from the representation, and is able to provide an appropriate non-linear relationship between similarity and the number of shared and non-shared features between two segments (Frisch, Broe, & Pierrehumbert, 1997).

(1) $$\text{Similarity} = \frac{\text{shared natural classes}}{\text{shared natural classes} + \text{nonshared natural classes}}$$

In the natural classes similarity metric, identical consonants have similarity 1, and similarity is always in the range [0,1]. In the interests of space, full feature matrices and tables of similarity values between all consonant pairs in English and Arabic are not presented here (see Frisch, 1996). Table X.1 shows similarity ranges and sample consonant pairs for English. The consonant pairs given are those used in the speech error experiment in Section X.5. Overall, similarity between non-identical English consonants using the natural classes metric ranges between 0.03 and 0.58. The natural classes similarity metric is a good predictor of speech error rates between consonants in English (Frisch, 1996). In the following section, the natural classes similarity metric is used in combination with a mathematical model of a gradient phonotactic constraint to predict consonant cooccurrence in the Arabic verbal roots.

Table X.1. Similarity ranges and example consonant pairs in English. The pairs are those used in the speech error experiment (see X.5).

| Natural classes similarity | Consonant pairs |
|---|---|
| 0 - 0.1 | {k,m}, {s,p} |
| 0.1 - 0.2 | {k,s}, {r,b}, {r,d}, {s,d}, {s,f}, {s,l} |
| 0.2 - 0.3 | {b,d}, {f,p} |
| 0.3 - 0.4 | {b,p}, {r,n} |
| 0.4 - 0.5 | {p,k} |
| 0.5 - 0.6 | {l,r} |

## X.3 Stochastic constraint model

Arabic verbal root morphemes consist of a set of two to four consonants, with the canonical root containing three. Part of the Arabic morphological system is non-concatenative: Vowels are inserted between the consonants to make word forms. For example, the verb *ktb* has among its word forms *katab* “to write” and *kutib* “to be written”. The Arabic consonant inventory is shown in (2). The segments /T/, /D/, /S/, /Z/ are coronal obstruents with a secondary pharyngeal constriction.

| (2) | Labial | Coronal | | | | Dorso-guttural | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | t | T | | k | q | | ʔ |
| | b | | d | D | | g | | | |
| | f | θ | s | S | ʃ | | χ | ħ | h |
| | | ð | z | Z | | | ʁ | ʕ | |
| | | | l r | | | | | | |
| | m | | n | | | | | | |

A long line of research has shown that the triliteral verbal roots of Arabic reflect a dissimilarity constraint between homorganic consonants, known as OCP-Place (Greenberg, 1950; McCarthy, 1994; Pierrehumbert, 1993). This constraint has been found in many other languages (Koskinen, 1964; Bender & Fulass, 1978; Mester, 1986; Hayward & Hayward, 1989; Yip, 1989; Buckley, 1993; Berkley, 1994; Broe, 1995; Padgett, 1995). In Arabic, these cooccurrence restrictions apply to both the adjacent consonant pairs in the root (C1C2 and C2C3) as well as to the non-adjacent consonant pair (C1C3). The constraint in Arabic is gradient; patterns of cooccurrence are a function of the similarity of homorganic consonant pairs.

Gradient, quantitative patterns of cooccurrence can be examined by extending the traditional phonotactic distinction between occurring and non-occurring combinations to a quantitative measure of cooccurrence that includes intermediate levels of occurrence. Following Greenberg (1950), the observed number of combinations of two consonants (O) is compared to the number expected if consonants were to cooccur at random (E). The ratio of observed to expected occurrences (O/E) provides a measure of the relative frequency of a combination (Pierrehumbert, 1993). If a combination is found far less often than expected (O/E near 0), it is unacceptable. If a combination is found quite frequently (O/E $\geq$ 1), then it is acceptable. Intermediate levels of cooccurrence ($0 < O/E < 1$) indicate gradient constraints with intermediate degrees of acceptability. Robust and systematic intermediate levels of cooccurrence are found in the phonotactic patterns of the verbal roots of Arabic.

Since the OCP-Place constraint depends crucially on the homorganicity of consonants, similarity between Arabic consonants was computed counting only those natural classes that involved place features (Frisch, 1996). Table X.2 shows similarity ranges and sample consonant pairs for Arabic when similarity is computed in this way. Non-homorganic consonants shared no natural classes containing place features, and so have similarity 0. Table X.2 also shows aggregate observed, expected, and O/E measures for all adjacent consonant pairs (C1C2 or C2C3) in each similarity group. Observed counts are taken from Wehr's 1979 dictionary (Cowan, 1979). The relationship between similarity and cooccurrence in Table X.2 is clear.

Table X.2. Similarity ranges and example consonant pairs in Arabic, with observed, expected, and O/E for adjacent consonant pairs in each group.

| Similarity | Consonant pairs | Observed | Expected | O/E |
|---|---|---|---|---|
| 0 | {b,d}, {s,h} | 2978 | 2349.3 | 1.27 |
| 0-0.1 | {h,g}, {l,t} | 481 | 365.2 | 1.23 |
| 0.1-0.2 | {d,s}, {T,g} | 492 | 550.6 | 1.18 |
| 0.2-0.3 | {d,n}, {t,D} | 151 | 260.2 | 0.58 |
| 0.3-0.4 | {b,f}, {s,t} | 29 | 131.2 | 0.22 |
| 0.4-0.5 | {t,T}, {l,n} | 14 | 180.2 | 0.08 |
| 0.5-0.6 | {h,ʔ}, {l,r} | 3 | 40.8 | 0.07 |
| 0.6-0.7 | {k,q}, {T,S} | 0 | 90.2 | 0 |
| 1 | {b,b}, {l,l} | 1 | 199.6 | 0.01 |

The relative frequency of cooccurrence (O/E) reflects the level of acceptability of the consonant pair under the OCP-Place constraint. To explicitly predict relative frequency from similarity, Frisch, Broe, & Pierrehumbert (1997) propose the *stochastic constraint model*; a logistic function, shown in (3), which links relative frequency to similarity. Figure X.1 shows the O/E levels for adjacent consonant pairs in Arabic, with the best fitting stochastic constraint model. The stochastic constraint model has three parameters, *A*, *K*, and *S*. The *A* parameter scales the logistic function, which normally has range (0,1), to the observed range of O/E values. The *K* parameter controls the location of the *constraint boundary* of the function; the halfway point between the upper and lower asymptotes where there is a change in acceptability from relatively acceptable to relatively unacceptable. The *S* parameter controls the *sharpness* of the constraint. If *S* is large, the constraint is more categorical. If *S* is small, the constraint is more gradient.

(3) $$\mathrm{O/E} = A \cdot \frac{1}{1 + e^{K + S \cdot \mathrm{Similarity}}}$$

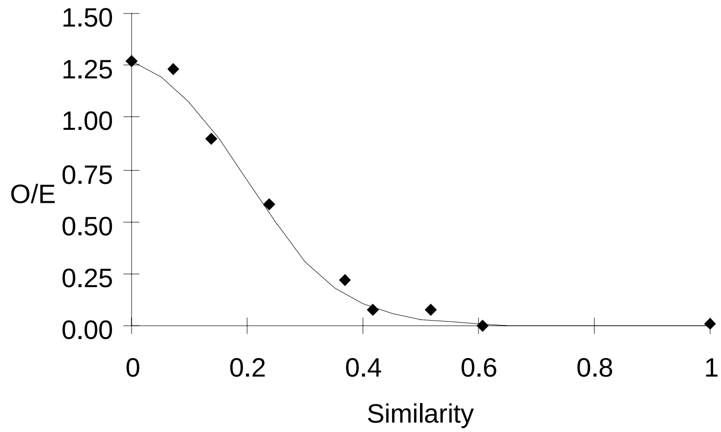


Figure X.1. Relative frequency (O/E) and stochastic constraint model of adjacent consonant pairs in the Arabic verbal roots. The model parameters are $A$ = 1.4, $K$ = -2.6, $S$ = 12.7.

The stochastic constraint model provides a good fit to the patterns of consonant cooccurrence in the Arabic roots. However, a model of cooccurrence patterns of adjacent and non-adjacent consonant pairs does not account for how these pairs combine together to form an entire root. A complete model of the Arabic cooccurrence constraints simultaneously considers the acceptability of a root given the similarity of all consonant pairs (C1C2, C2C3, and C1C3). In the next section, a model of gradient constraint combination is implemented which provides a very good fit to the Arabic root lexicon. In addition, this model reveals that the dissimilarity constraint is sharper for the root initial consonant pair than for the final consonant pair, a new finding.

### X.4 Constraint combination and word onsets in Arabic

Combinations of consonants in Arabic are allowed for each consonant pair as a function of their similarity. The simplest model of constraint combination applies the constraints on each consonant pair independently to the entire root. For the stochastic constraint model, independent combination is achieved by multiplication of the logistic functions of the individual constraints. In this section, a multiplicative model of gradient constraint combination is implemented for the Arabic verbal roots. Such a model appears to be appropriate, as roots containing OCP-Place violations on more than one consonant pair are extremely rare.

Table X.3 shows the observed number of roots containing combinations of adjacent consonants pairs as a function of the similarity of C1C2 and C2C3 independently. Table X.4 shows O/E for combinations as a function of similarity, assuming that consonants combine at random. There is an apparent cumulative interaction of the similarity of the first and second consonant with the similarity of the second and third consonant. There are fewer roots with similar homorganic C1C2 *and* C2C3 (two OCP-Place violations) than roots where one pair is non-homorganic and the other has higher similarity (one OCP-Place violation). Upon closer examination, it also appears that the distribution of violations is asymmetric. It appears there are fewer violations of OCP-Place for C1C2 than for C2C3.

Table X.3. Distribution of roots in Arabic by similarity of C1C2 and C2C3. Gray shading indicates cells used in $\chi^2$-test for symmetry.

| Sim | C2C3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C1C2 | 0 | 0-0.1 | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 1 | Total |
| 0 | 1694 | 146 | 196 | 45 | 9 | 4 | 0 | 0 | 0 | 2094 |
| 0-0.1 | 170 | 19 | 23 | 7 | 0 | 1 | 1 | 0 | 0 | 220 |
| 0.1-0.2 | 177 | 27 | 31 | 12 | 1 | 2 | 1 | 0 | 0 | 251 |
| 0.2-0.3 | 55 | 12 | 12 | 3 | 1 | 0 | 1 | 0 | 0 | 84 |
| 0.3-0.4 | 12 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 18 |
| 0.4-0.5 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| 0.5-0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.6-0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Total | 2113 | 208 | 264 | 67 | 11 | 7 | 3 | 0 | 0 | 2676 |

Table X.4. O/E for roots in Arabic by similarity of C1C2 and C2C3.

| Sim | C2C3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| C1C2 | 0 | 0-0.1 | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 1 |
| 0 | 1.37 | 1.87 | 1.51 | 0.75 | 0.31 | 0.07 | 0 | 0 | 0 |
| 0-0.1 | 1.74 | 0.90 | 1.04 | 0.92 | 0 | 0.16 | 0.59 | 0 | 0 |
| 0.1-0.2 | 1.06 | 1.10 | 0.54 | 0.61 | 0.09 | 0.29 | 0.29 | 0 | 0 |
| 0.2-0.3 | 0.68 | 1.18 | 0.51 | 0.21 | 0.18 | 0 | 0.66 | 0 | 0 |
| 0.3-0.4 | 0.29 | 0.58 | 0.17 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.4-0.5 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5-0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.6-0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

An account of consonant cooccurrence in Arabic which uses a single constraint for all adjacent consonant pairs predicts that violations of OCP-Place for C1C2 are the same as violations for C2C3. In other words, the relative frequency (O/E) of violations should be symmetric across the two pairs. For example, the O/E for roots with sim(C1C2) = 0.2-0.3 and sim(C2C3) = 0.1-0.2 (O/E = 0.51) should be the same as the O/E for roots with sim(C2C3) = 0.2-0.3

and sim(C1C2) = 0.1-0.2 (O/E = 0.61). To test for symmetry statistically, the observed occurrences were compared to the expected number of occurrences if the distribution were symmetric using a $\chi^2$-test. The expected symmetric distribution was created by dividing the total number of occurrences for the two cells with a particular pair of similarities (e.g. 0.2-0.3 and 0.1-0.2) between the cells according to their expected probability. In other words, a single aggregate O/E was applied to the matched cells to predict the symmetric distribution. For example, for roots with one pair with similarity 0.2-0.3 and one pair with similarity 0.1-0.2, there are 12 + 12 = 24 occurrences (see Table X.3). The expected number of occurrences is 23.7 + 19.8 = 43.5. So the aggregate O/E is 24/43.5 = 0.55. The expected symmetric occurrences are $0.55 \times 23.7 = 13.1$ and $0.55 \times 19.8 = 10.9$, respectively. The shaded cells in Table X.3 indicate cells with sufficient expected symmetric occurrences to be included in the test. The observed occurrences are marginally significantly deviant from the expected symmetric distribution ($\chi^2 = 16.2$, $p = 0.04$, df = 8).

The hypothesis that the OCP-Place constraint is stronger for C1C2 than for C2C3 (i.e. that OCP-Place violations for C1C2 are less frequent than violations for C2C3) can be tested by comparing whether the O/E values for violations on C1C2 are less than O/E values for violations on C2C3 using a t-test. Since O/E values are ratios, they are compared using log(O/E) to better satisfy the normality condition of the t-test. Comparisons are made between cells which are matched for the similarity of their consonant pairs as above. The mean log(O/E) for cells with stronger violations of OCP-Place for C1C2 (i.e. sim(C1C2) > sim(C2C3)) is compared to the mean log(O/E) for cells with stronger violations of OCP-Place for C2C3 (i.e. sim(C2C3) > sim(C1C2)). A paired t-test was performed including all pairs of cells where at least one cell in the pair had O/E > 0. For cells with O/E = 0, where log(O/E) would be undefined, a small positive O/E equal to 0.001 was used. The trend was for log(O/E) for C1C2 violations to be less than log(O/E) for C2C3 violations, but the difference did not reach significance ($t = 1.6$, $p = 0.06$, df = 16).

In order to predict the occurrence of verbal roots in Arabic, it is clearly necessary to model the combination of consonant pairs into a complete root, taking into account the possibility of OCP-Place violations between any of the consonant pairs. In addition, constraint violations should interact cumulatively; forms with no violations should be found more frequently than forms with one violation, which in turn should be found more frequently than forms with multiple violations.

Figure X.2 shows the product of two stochastic constraints, based on the parameterizations of the constraint models of adjacent consonant pairs in Arabic presented below. This figure models the data presented in Tables X.3 and X.4. The product of stochastic constraints captures cumulative gradient constraint interaction. Since the range of the logistic function in the stochastic constraint is

(0,1), the product of two logistics will always be less than either logistic alone. The product also produces a well-defined result: a combined range of (0,1).

The multiplicative model of stochastic constraint combination is given in (4). Each term in the denominator is a stochastic constraint; one for each pair of consonants in the triliteral root.

(4) $$O / E = A \cdot \frac{1}{1 + e^{K1 + S1 \cdot \mathrm{Sim12}}} \cdot \frac{1}{1 + e^{K2 + S2 \cdot \mathrm{Sim23}}} \cdot \frac{1}{1 + e^{K3 + S3 \cdot \mathrm{Sim13}}}$$

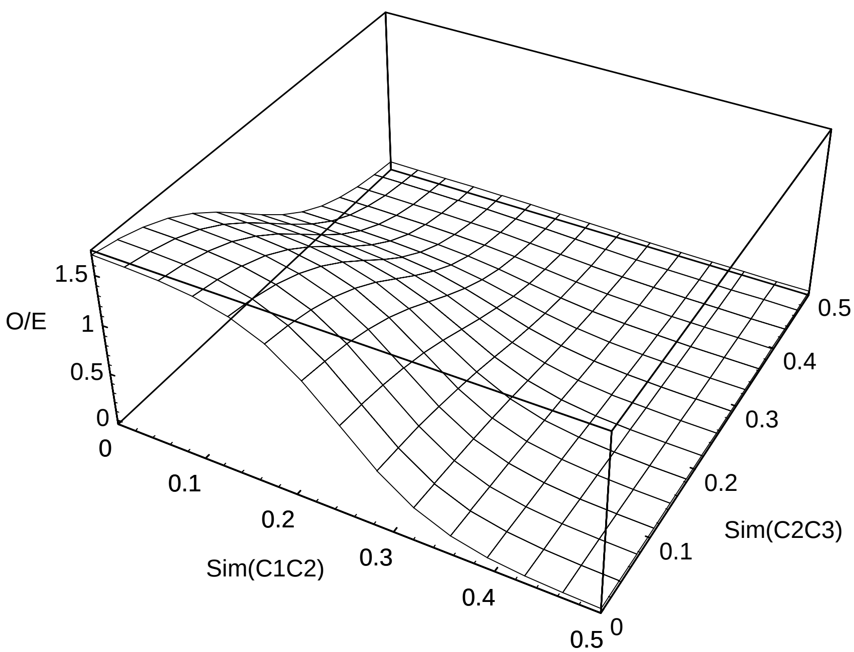


Figure X.2. Product of two stochastic constraints as a model of gradient constraint combination which provides cumulative interaction of constraints.

The model in (4) contains a *K* and *S* parameter for each consonant pair in the root (i.e. for each stochastic constraint). In addition, there is a scaling parameter *A* as before. Allowing the parameters for the stochastic constraints governing the C1C2 and C2C3 pairs to be different allows the model to reflect the asymmetry described above. This model, referred to as the “Asymmetric” model was fit to the distribution of roots in Arabic and compared against the fits of five other models.

The five other models which were fit to the Arabic data were chosen to test the necessity of various characteristics of the Asymmetric model. The "Frequency" model assumes that consonants combine independently. This model has no phonotactic constraint and is given to demonstrate how much the distribution of roots in the lexicon can be accounted for by the frequency of the consonants themselves. The "Categorical" model is an implementation of the traditional autosegmental account of these cooccurrence patterns. In this model, roots containing homorganic consonants are disallowed by the OCP applied to tier-separated place features, and other roots occur in proportion to their expected frequency. The "Soft" model uses a constant gradient cooccurrence constraint for homorganic pairs and a categorical constraint against identical pairs (McCarthy, 1994). This model reflects the improvement achieved when a gradient constraint is used, without incorporating the similarity of consonant pairs into the model. The "Stochastic" model is an extension of the model of Frisch, Broe, & Pierrehumbert (1997) to the entire root. This model has two stochastic constraints, one for all adjacent consonant pairs and one for non-adjacent consonant pairs. The only difference between this model and the Asymmetric model is that the Asymmetric model allows differences between the strength of the OCP-Place constraint for C1C2 and C2C3. All models were fit to the similarity aggregated distribution of roots in the Arabic lexicon using non-linear regression.

Table X.5 compares the model fits. The second column shows overall $R^2$ for each model. Note that the Frequency model predicts a significant amount of the variability in the distribution of roots, highlighting the importance of combinatorial probability in phonotactics (cf. Pierrehumbert, 1994). A better comparison of the remaining models should take into account this common source of variance. Frequency is taken into account using a measure of the proportion of reduction in the residual sum of squares of each model over the Frequency model. This is the "Freq. $R^2$" in the third column of Table X.5.

The Categorical model, which incorporates the simplest version of the OCP-Place constraint, provides considerable improvement in fit over the Frequency model. However, the models involving gradient constraints (the Soft model, the Stochastic model, and the Asymmetric model), improve the fit significantly more, confirming the hypothesis that the OCP-Place constraint in Arabic is best described as a gradient constraint.

Table X.5. Model parameters and fits to the Arabic triconsonantal roots.

| Model | $R^2$ | Freq. $R^2$ | Hom. $R^2$ | Model Parameters |
|---|---|---|---|---|
| Frequency | 0.85 | - | - | O = E |
| Categorical | 0.97 | 0.79 | - | O/E = 0 homorganic<br>O/E = 1.55 otherwise |
| Soft | 0.99 | 0.91 | 0.45 | O/E = 0 for identical<br>O/E = 0.89 homorganic<br>O/E = 1.58 otherwise |
| Stochastic | 0.995 | 0.97 | 0.80 | A = 1.63<br>Adj.: S = 19.0, K = -4.6<br>N-Adj.: S = 7.6, K = -3.6 |
| Asymmetric | 0.997 | 0.98 | 0.87 | A = 1.80<br>C1C2: S1 = 21.9, K1 = -5.5<br>C2C3: S2 = 13.0, K2 = -2.9<br>C1C3: S3 = 5.2, K3 = -2.5 |

All the gradient OCP-Place models performed equally well in fitting roots containing all non-homorganic consonants. The need for a gradient *similarity-based* account of cooccurrence in Arabic can be seen when the crucial roots containing homorganic consonant pairs are examined more closely. The proportion of variability beyond that given by the Frequency model for roots containing at least one homorganic consonant pair (adjacent or non-adjacent) is given as the "Hom. $R^2$" in the fourth column of Table X.5. While the distinction between identical and non-identical homorganic pairs in the Soft model can account for about half of the variability in cooccurrence among roots with homorganic pairs, the Stochastic model and Asymmetric model do much better. In these models, cooccurrence depends on the similarity and distance between consonant pairs. In these models, the constraint is weaker for non-adjacent consonants and those with low similarity.

Comparing the Asymmetric model to the Stochastic model we see a modest improvement in fit in the Asymmetric model for roots containing homorganic pairs, reflecting the difference between C1C2 and C2C3 violations of OCP-Place discussed above. Further evidence that the Asymmetric model is a genuine improvement over the Stochastic model can be found in the differences in parameterizations for these two models. The Stochastic model has a single *S* parameter for all adjacent consonant pairs ($S$ = 19.0). In the Asymmetric model there is a clear difference in the sharpness of the stochastic constraints for C1C2 and C2C3. The stochastic constraint for the first and second consonants is sharper ($S1$ = 21.9, 95% confidence interval is $18.3 < S1 < 25.4$) than the constraint for the second and third consonants ($S2$ = 13.0, 95% confidence interval is $11.3 < S2 < 14.6$). In the Asymmetric model of the Arabic verbal roots, the dissimilarity constraint is stronger word initially than later in the word. This asymmetry is not unique to Arabic. Frisch (1996) showed that differences between OCP-Place effects in word onsets and other consonants are found in English as well.

To summarize, consonant cooccurrence constraints in the Arabic verbal roots reveal two important patterns. First, multiple violations of the OCP-Place constraint interact cumulatively. This pattern cannot be captured by current phonological theories, which either have no violable constraints, or have non-cumulative interaction between violable constraints. The distribution of roots containing multiple OCP-Place constraint violations can only be accurately described by a stochastic phonology which includes interacting gradient phonotactic constraints. Second, there are differences in the strengths of OCP-Place constraints between different consonant pairs in the root. The root initial consonant pairs (C1C2) are more strongly constrained than the non-initial, adjacent consonant pairs (C2C3) and the non-adjacent consonant pairs (C1C3). I propose that this difference is not specific to the OCP in Arabic, but is a general cognitive phenomenon affecting the perceived similarity of initial consonants that is caused by the process of lexical access and phonological encoding. In the next section, evidence that the interaction between segment similarity and position in the word is not restricted to phonotactic constraints is presented. In particular, stronger word initial similarity effects are also found in phonological speech errors in English.

### X.5 Word onsets in speech errors

In general, errors between word onset consonants are prevalent in published error analyses. For example, in the MIT-Arizona corpus, Shattuck-Hufnagel (1987) reports that 82% of naturally occurring sub-lexical interaction errors are between word onsets. Based on a 1,000 word sample of running speech, she estimated that only 33% of the consonants in the sample were word onsets. The prevalence of word onsets in speech errors has prompted some researchers to give the word onset a special structural position in lexical processing, where the word onset is separated from the rest of the word (e.g. Shattuck-Hufnagel, 1987). I propose that the word onset need not be given a special structural position. The fact that it is the first consonant in the word is sufficient. In this section, this claim is supported using the tongue twister paradigm of Shattuck-Hufnagel (1992) to elicit speech errors. This experiment shows that word initial speech errors are more influenced by the similarity between consonants than speech errors involving the onset of the second syllable.

A set of tongue twisters using all bisyllabic words was used, in order to compare error rates between word onsets and second syllable onsets. The stimuli were created in groups of four, using one similar and one dissimilar consonant pair per group. Sample stimuli are shown in (5). The similar pair of consonants (b/p) appear in both first and second syllable onset positions, in stressed and unstressed syllables. The dissimilar pair (k/s) appears in the complementary position in each stimulus. The groups of stimuli were designed for a three-way ANOVA, with word position, stress, and consonant similarity as factors.

(5) a. beacon possum piercing bookie (b/p are stressed word onsets)
b. became pursue percent bouquet (b/p are unstressed word onsets)
c. caboose support suppose kebab (b/p are stressed 2nd syllable onsets)
d. cabin soapy supper cobble (b/p are unstressed 2nd syllable onsets)

In all cases, errors between the similar consonant pair or the dissimilar pair resulted in non-words. Words which repeated vowels after pairs of target or non-target consonants were avoided as much as possible. It was possible to create stimuli for 9 sets of consonants, resulting in 36 unique twisters. The entire set of twisters is given in the Appendix. In order to obtain a sufficient amount of data for analysis, each twister was reordered by swapping adjacent pairs of words to create a second block of 36 twisters.

The stimuli were blocked and randomized so that no adjacent stimuli contained the same target consonant pair or had the same target position. Participants read and repeated each twister a total of six times. The subjects were recorded on audio cassette, and the recordings were used for error tabulation. Errors were scored based on the perceptions of the author. A total of 31 Northwestern University undergraduates participated in the experiment. They received payment for their participation.

Errors between either the similar consonant pair or the dissimilar consonant pair were tabulated. All other errors were ignored. Errors clearly involving units larger than the onset consonant were not counted, and the lack of repeated vowels in most cases aided in determining the size of the error unit. All exchange errors were counted as one error on the first consonant, as Dell & Reich (1981) have shown differences between the first error in an exchange and the second that suggest that the second error is not an independent mistake.

The total error counts between similar and dissimilar consonants for each prosodic position are shown in Table X.6. Results of the ANOVA are reported with both stimuli and participants as factors. Word onsets were errors more often than second syllable onsets ($F(1,17) = 30.7$, $p < 0.01$; $F(1,30) = 48.7$, $p < 0.01$). Unstressed syllable onsets were errors more often than stressed syllable onsets ($F(1,17) = 16.4$, $p < 0.01$; $F(1,30) = 23.7$, $p < 0.01$). Similar consonants were errors more often than dissimilar consonants ($F(1,17) = 21.6$, $p < 0.01$; $F(1,30) = 34.6$, $p < 0.01$). There was a significant word position by stress interaction. For word onsets, unstressed syllables were errors more often than stressed syllables, but there was no difference for 2nd syllable onsets ($F(1,17) = 20.6$, $p < 0.01$; $F(1,30) = 30.1$, $p < 0.01$). There we no other interactions.

Table X.6. Total errors in the experiment for similar and dissimilar consonants by position. #S/#D is the ratio of similar to dissimilar errors for that position.

| Position in word | Stress | #Similar | #Dissimilar | #S/#D |
|---|---|---|---|---|
| Word onset | Stressed | 124 | 30 | 4.1 |
| Word onset | Unstressed | 226 | 163 | 1.4 |
| 2nd syllable onset | Stressed | 89 | 31 | 2.9 |
| 2nd syllable onset | Unstressed | 79 | 27 | 2.9 |

To highlight the differences between similar and dissimilar consonant pairs, the ratio of the number of errors between similar and dissimilar consonant pairs is shown in the rightmost column of Table X.6. These ratios reflect two distinct influences of the surrounding context of the consonant on the importance of consonant similarity in speech errors. For unstressed word onsets, the following vowel was almost always /ə/. This was not the case for unstressed 2nd syllable onsets. The shared vowel context greatly reduced the influence of consonant similarity on error rate (cf. Dell, 1984). In fact, it is not certain that these errors were consonant errors, and not whole syllable errors. The overall high error rate for word initial unstressed consonants may reflect some of each.

There is a second effect of context, the difference between stressed word onset errors and 2nd syllable onset errors. There is a trend toward more errors between similar stressed word onsets than similar stressed 2nd syllable onsets (across participants, $t = 1.8$, $p = 0.04$, df = 30; across stimuli, $t = 1.1$, ns, df = 17). There is clearly no difference for dissimilar consonants (across participants, $t = 0.17$, ns, df = 30; across stimuli, $t = 0.09$, ns, df = 17). In a temporally organized lexical representation, the second syllable onset of a word has the first syllable as preceding context.

The effect of position in word on the importance of consonant similarity in speech errors is not limited to errors made while producing tongue twisters. Frisch (1996) also found an interaction of position in word and similarity in an analysis of a naturally occurring error corpus. Errors involving word onsets had significantly greater mean similarity and significantly less variance in similarity than errors involving consonants later in the word.

Thus far, it has been shown that in both the case of the phonotactic dissimilarity constraint and phonological speech errors, similarity is a greater factor early in the word than it is later in the word. The parallelism in similarity effects in both phonotactics and speech production can be accounted for if phonological encoding, following the natural time course of a word from beginning-to-end, gives special status to word initial consonants.

### X.6 Word onsets in phonological encoding

The account of the fact that word onsets have special status in similarity phenomena is based on two generally accepted claims about the phonological encoding of information in an activation/competition model of the lexicon. First, segmental information is accessed and encoded sequentially (as in the perception model of Marslen-Wilson, 1984, and the production model of Sevald & Dell, 1994, among others). Second, the access and encoding of segments activates phonologically related words and segments (as in the perception model of Norris, 1994, and the production model of Dell, 1986, among others).

The general account is as follows:

1. Encoding of the initial segments activates all possible completions.
2. This activation degrades similarity effects through competition/interference.
3. There is no left-hand context for the initial segment, and less context for early segments, giving them special status.

In the case of speech errors, viable intrusions for a word onset come from an unrestricted space of possibilities. Within this space, similar consonants are likely to be the most activated, and thus most likely to appear as intrusions. For later consonants, the preceding context (the segments which have already been encoded) activate a set of competing completions, which may or may not be similar to the target. The set of most likely intrusions can thus come from either the space of similar consonants or the space of possible completions (and most likely from their intersection). The effect of similarity on segmental speech errors is diluted by context.

The pattern is much the same for the phonotactic dissimilarity constraint OCP-Place. Consonants which are similar to one another become highly activated in comparison to consonants which are not similar. The effects of consonantal similarity are most robust for initial consonant pairs, as the initial segments are accessed first. Similar initial consonant pairs are highly activated compared to other consonant pairs. Later consonants pairs are accessed only after initial consonants are activated. Once again, the activation of initial segments activates a set of related words and their segments. Given the contextually created activation, the difference in activation levels between similar and dissimilar consonant pairs later in the word is reduced.

### X.7 Discussion and conclusion

Phonotactic patterns in the Arabic verbal roots demonstrate that the mechanism of lexical access has an influence on patterns traditionally considered a part of linguistic competence. Functional cognitive constraints, associated with language processing in speech perception and production, can provide a basis for explaining phonological patterns. There is a complementary and growing body of research highlighting the importance of functional phonetic constraints in phonology. Together, constraints on articulation, audition, speech production, perception, and language processing can provide the basis for a psycholinguistically plausible theory of phonology. Under this view, phonology results from the human nervous system organizing and categorizing the continuous and variable input received from the articulatory and auditory systems.

Such a phonological theory weakens the traditional distinction between competence and performance. However, evidence for this view can only be found if gradient phenomena can be analyzed and accounted for in a rigorous, formal manner. The analysis presented here is intended to serve as an example. Gradient phenomena are a rich source of data that can be exploited effectively to test current models of linguistic theory, and provide new theoretical insights. Broadening the scope of phonological analysis to mathematical, instrumental, and experimental research insures that the theory is not constrained merely by the choice of data that is presupposed to be relevant.

Current phonological formalisms are not necessarily incompatible with these conclusions, if we consider the *implementation* of these theories in a computational model. Traditionally, linguistic formalism is grounded in discrete symbolism. A linguistic formalism implemented using connectionist methods gains the potential for similarity and frequency effects, and gradience in general, *for free*. These concepts are part of the formalism, and need not be added explicitly or built up from primitive elements. In addition, an important component of connectionist models is their ability to self-organize, learn, and generalize. This is precisely the role of phonological system in a functional phonological theory.

## Appendix

Tongue twister stimuli:

Similar pair b,p; Dissimilar pair k,s
beacon possum piercing bookie
became pursue percent bouquet
caboose support suppose kebab
cabin soapy supper cobble

Similar pair b,d; Dissimilar pair k,s
docile backer booking decent
descend because becalm deceit
sedate combine combust sedan
sided cabbage carbon sadden

Similar pair f,p; Dissimilar pair s,l
fossil pillow pilot facile
facade polite police forsake
suffuse lapel lampoon suffice
siphon leper lipid sofa

Similar pair p,b; Dissimilar pair s,d
passive bundle bedding person
percent bedeck bedew pursue
surpass debase debate superb
super debit double sappy

Similar pair l,r; Dissimilar pair k,s
Lisa wrinkle racket lasso
LaSalle recant raccoon Lucille
Celeste career corrupt saloon
Sally carrot courage salad

Similar pair s,f; Dissimilar pair r,b
sorry phobic feeble serum
serene forbid forbode surround
recite befoul before receipt
racy barfing beefy wrestle

Similar pair p,k; Dissimilar pair r,d
parent coddle kidding parish
parole cadet condone Peru
repeal discard decay riposte
ripen decade decoy romper

Similar pair l,r; Dissimilar pair k,m
rumor lucky liquor roaming
remain locale LaCoste remote
maroon collapse collide morass
mirror colon cooling marrow

Similar pair m,r; Dissimilar pair s,p
massive ripple rapid messy
myself repeat repulse masseuse
cement parade peruse surmount
summer porous purring salmon

## References


Bender, M. L. & H. Fulass (1978). *Amharic verb morphology*. East Lansing, MI: Michigan State University African Studies Center.

Berkley, D. (1994). Variability in Obligatory Contour Principle effects. *CLS* 30: 1-12.

Broe, M. (1993). *Specification theory: the treatment of redundancy in generative phonology*. Ph.D. thesis, University of Edinburgh.

Broe, M. (1995). Specification theory and Ngbaka co-occurrence constraints. Paper presented at the Mid-Continental Workshop on Phonology. Ohio State University, Columbus, OH.

Buckley, E. (1993). Tigrinya root consonants and the OCP. Paper presented at the 16th annual Penn Linguistics Colloquium. Philadelphia, PA.

Cowan, J. (1979). *Hans Wehr: a dictionary of modern written Arabic*. Wiesbaden: Otto Harrasowitz.

Dell, G. S. (1984). Representation of serial order in speech: evidence from the repeated phoneme effect in speech errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 10: 222-233.

Dell, G. S. (1986). A spreading activation theory of retrieval in sentence production. *Psychological Review* 93: 283-321.

Dell, G. S. & P. A. Reich (1981). Stages in sentence production: an analysis of speech error data. *Journal of Verbal Learning and Verbal Behavior* 20: 611-629.

Frisch, S. (1996). *Similarity and frequency in phonology*. Ph.D. thesis, Northwestern University.

Frisch, S., M. Broe, & J. B. Pierrehumbert. (1997). Similarity and phonotactics in Arabic. Manuscript submitted for publication.

Greenberg, J. H. (1950). The patterning of root morphemes in Semitic. *Word* 6: 162-181.

Hayes-Roth, B. & F. Hayes-Roth (1977). Concept learning and the recognition and classification of exemplars. *Journal of Verbal Learning and Verbal Behavior* 16: 321-338.

Hayward, K. M. & R. J. Hayward (1989). "Guttural": arguments for a new distinctive feature. *Transactions of the Philological Society* 87: 179-193.

Koskinen, K. (1964). Kompatibilitat in den dreikonsonantigen hebraishen wurzeln. *Zeitschrift der Deutschen Morgenlandischen Gesellschaft* 144: 16-58.

MacKay, D. G. (1970). Spoonerisms: the structure of errors in the serial order of speech. *Neuropsychologica* 8: 323-353.

Marslen-Wilson, W. (1984). Function and process in spoken word-recognition. In H. Bouma & D.G. Boudwhuis (eds.), *Attention and performance X: control of language processes*. Hillsdale, NJ: Lawrence Earlbaum. 125-150.

McCarthy, J.J. (1994). The phonetics and phonology of Semitic pharyngeals. In P. Keating (ed.), *Phonological structure and phonetic form: Papers in laboratory phonology III*. Cambridge: Cambridge University Press. 191-233.

Medin, D. L., R. L. Goldstone, & D. Gentner (1993). Respects for similarity. *Psychological Review* 100: 254-278.

Mester, R. A. (1986). *Studies in tier structure*. Ph.D. thesis, University of Massachusetts-Amherst.

Norris, D. (1994). Shortlist: A connectionist model of continuous speech recognition. *Cognition* 52: 189-234.

Padgett, J. (1995). *Stricture in feature geometry*. Stanford, CA: CSLI Press.

Pierrehumbert, J. B. (1993). Dissimilarity in the Arabic verbal roots. *NELS* 23: 367-381.

Pierrehumbert, J. B. (1994). Syllable structure and word structure. In P. Keating (ed.), *Phonological structure and phonetic form: Papers in laboratory phonology III*. Cambridge: Cambridge University Press. 168-190.

Sevald, C. A. & G. S. Dell (1994). The sequential cueing effect in speech production. *Cognition* 53: 91-127.

Shattuck-Hufnagel, S. (1987). The role of word onset consonants in speech production planning. In E. Keller & M. Gopnick (eds.), *Motor and sensory processing in language*. Hillsdale, NJ: Lawrence Erlbaum. 17-51.

Shattuck-Hufnagel, S. (1992). The role of word structure in segmental serial ordering. *Cognition* 42: 213-259.

Van den Broecke, M. P. R., & L. Goldstein (1980). Consonant features in speech errors. In V. Fromkin (ed.), *Errors in linguistic performance: Slips of the tongue, ear, pen, and hand*. New York: Academic Press. 47-65.

Yip, M. (1989). Feature geometry and cooccurrence restrictions. *Phonology* 6: 349-374.