

High functional load inhibits phonological contrast loss: A corpus study

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## Abstract

For nearly a century, linguists have suggested that diachronic merger is less likely between phonemes with a high functional load – that is, phonemes that distinguish many words in the language in question. However, limitations in data and computational power have made assessing this hypothesis difficult. Here we present the first larger-scale study of the functional load hypothesis, using data from sound changes in a diverse set of languages. Our results support the functional load hypothesis: phoneme pairs undergoing merger distinguish significantly fewer minimal pairs in the lexicon than unmerged phoneme pairs. Furthermore, we show that in the absence of minimal pairs, greater relative phoneme frequency is correlated with merger. Finally, within our dataset we find that minimal pair count and phoneme frequency better predict merger than change in system entropy at the lexical or phoneme level.

*Keywords:* functional load, phoneme, frequency, minimal pair, corpus, entropy

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## 1 Introduction

Spoken languages make use of a system of individually meaningless, contrastive sound categories, often termed *phonemes*, in combination to create distinctive words (Hockett, 1960; Studdert-Kennedy & Goldstein, 2003). Despite the central role phonemes play in carrying contrast between words, phonemes can be lost from a language when, for example, two phonemes merge with one another (Labov, 1994, ch. 11). For example, in many regions of North America the historically contrastive vowels in the words *cot* and *caught* have merged, with the result that these words are now pronounced the same. Phoneme merger often, but not always, results in some previously distinct words becoming homophonous.

Nearly a century ago, Gilliéron (1918) first proposed that the probability of phoneme loss should be inversely related to the amount of ‘work’ that the phoneme does in distinguishing words in communication. Termed the functional load hypothesis by Jakobson (1931), Mathesius (1931), and Trubetzkoy (1939) and developed further by Martinet (1952) and Hockett (1967), the idea that change in a system of phonemes is related to their role in information transmission has held great intuitive appeal for language-change researchers over the last century. However, clear evidence supporting this hypothesis has not been found. Previous work has focused on individual case studies due to limited access to data and computational resources, and results of these studies have been equivocal or contradictory (Blevins & Wedel, 2009; Kaplan, 2011; King, 1967; Silverman, 2010; Surendran & Niyogi, 2006). This is perhaps not surprising: even if functional load does influence the probability of phoneme loss, many other systemic and phonetic (Blevins, 2004; Labov, 1994) as well as social (Labov, 2001) factors also influence sound change. As

a consequence, we would expect to find many individual ‘exceptions’ to the functional load hypothesis even if functional load can contribute significantly to the course of sound change. Instead, testing the functional load hypothesis requires a larger sample of data in which effects can be assessed statistically.

In this paper, we present the first such analysis of a dataset comprising a large number of phoneme mergers from a diverse set of languages. We show for the first time that simple measures of functional load within a system of phonemes *do* significantly predict patterns of phoneme merger, and that this effect is in the hypothesized direction: the greater the contribution a pair of phonemes makes to word differentiation, the less likely those phonemes are to merge over the course of language change. Further, we show that in the case that a phoneme pair does not distinguish many words, relative phoneme frequency is a significant predictor of merger.

## 2 Corpus study

### 2.1 Database

The rate of phoneme merger over the course of language change tends to be low, with the result that often only a small number of historically recent phoneme mergers are attested in related variants of any given language. Consequently, in order to obtain enough data for statistical analysis, we pooled data from multiple languages. The languages represented in the dataset are English (Received Pronunciation and Standard American), Korean, French, German, Dutch, Slovak, Spanish, and Hong Kong Cantonese. A summary of the contents of the database is presented in Table 1.

The dataset consists of 18 groups of phoneme pairs from these 8 different languages. Each group of phoneme pairs consists of phonemes within a single structural class such as ‘vowels’ or ‘consonants’, and the phonemes within each pair are phonologically similar,

differing in only one phonological feature such as *voice* or *place of articulation*. Each set contains at least one phoneme pair that has merged in some dialect of the language, as well as all other phonologically similar phoneme pairs in that structural class. In total, the dataset contains 56 phoneme pairs that have merged, and 578 that have not. Within mergers, 33 are consonant-consonant mergers as opposed to vowel-vowel mergers, and 27 are conditioned by phonological context, as opposed to context-free. A context-free merger eliminates a phoneme contrast from a language altogether, while a context-sensitive one eliminates a contrast only in certain phonological environments. The North American English *cot* ~ *caught* merger is an example of a context-free merger, while the *pin* ~ *pen* merger, which occurs in southern dialects of American English, merges [ɪ] ~ [ɛ] only before nasals. As a consequence, the words *pin* and *pen* are homophonous in these dialects, while *pit* and *pet* are not.

Each language is represented by a phonemically-transcribed word list from a corpus. Inflected forms are listed separately (for all languages except Korean) and are associated with token frequencies from their source corpus. No grammatical or function words were included in the dataset. These corpora are different on a number of dimensions (e.g., size and source genre), as are the languages they represent (e.g., complexity of phoneme inventory, syllable structure, complexity of morphology). As described in section 2.3, we used hierarchical modeling to model the differences between languages as random effects. The fact that these models represent “partial pooling” of results across the languages makes our results more generalizable than simple logistic regression (Gelman & Hill, 2007) and therefore should be fairly robust against the heterogeneous nature of the languages and corpora.

An unavoidable issue in using corpora to study language change is that a corpus will fail to perfectly reflect whatever features of the language may have been causally relevant over the time-course of the change. For example, the corpora used here provide information

about the frequencies, pronunciations, and patterns of usage in the source material, which will be different to some degree from the state of the language at the time and location where a particular merger originated and spread. By concentrating only on mergers that are historically recent or in progress in some speech community, we attempt to minimize the lack of fit between the corpora and the “true” linguistic context of the merger.

Furthermore, it is unlikely that particular differences between a corpus and the linguistic context of a merger would be systematically repeated across the different mergers and languages in such a way as to give rise to spurious relationships between our variables and the probability of merger.

## 2.2 Predictor Variables

There are many possible operationalizations of the notion of functional load (Hockett, 1967; Kaplan, 2011; King, 1967; Silverman, 2010; Surendran & Niyogi, 2006), differing in relation to unit size, role of frequency, word-category and other variables. A particularly simple measure is the number of lexical minimal pairs in a language distinguished by a phoneme pair.<sup>1</sup> Martinet (1952) and Hockett (1955) proposed that word frequency should be taken into account as well, and Hockett (1967), Surendran and Niyogi (2003), and Surendran and Niyogi (2006) described a general framework for assessing functional load of phonemic contrasts in terms of system entropy at varying levels of analysis. At the word level, we compare the number of minimal pairs in the corpus defined by a phoneme pair to the change in word-level entropy of the corpus upon merger of the phoneme pair

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<sup>1</sup>Given two sounds X and Y, a minimal pair for those sounds is a pair of words of the same length such that the two words are identical except for one segment, where one word contains X and the other contains Y.

<sup>a</sup>The CMU pronouncing dictionary lacks frequency information. Frequencies for this dataset were taken from CELEX.

Language	Corpus	Phoneme Types / Context	Actual Mergers	Notes	References
English ( <i>RP</i> )	CELEX (Baayen et al., 1995)	V ~ V  C ~ C	aɪ ~ ɔɪ ʊə ~ ɔ: ɪə ~ eə ɛ: ~ eə θ ~ t θ ~ f θ ~ s	PRICE ~ CHOICE CURE ~ THOUGHT NEAR ~ SQUARE NURSE ~ SQUARE	Wells (1982)
English ( <i>American</i> )	CMU pronouncing dictionary <sup>a</sup>  (Weide, 1995)	V ~ V V ~ V / <u>  </u> ɪ V ~ V / <u>  </u> n V ~ V / <u>  </u> l	a ~ ɔ ɔɪ ~ eɪ a ~ ɔ ɪ ~ e ɪ ~ i ʊ ~ u ʊ ~ oʊ ʌ ~ a ʊ ~ ʌ ʌ ~ w	LOT ~ THOUGHT  START ~ NORTH PIN ~ PEN HILL ~ HEEL PULL ~ POOL BULL ~ BOWL HULL ~ HALL BULL ~ HULL	Labov et al. (2006)
German	CELEX (Baayen et al., 1995)	V ~ V	e ~ e:	GEBE ~ GÄBE	Wiese (2000)
Dutch	CELEX (Baayen et al., 1995)	C ~ C	s ~ z f ~ v x ~ ɣ		Kissine et al. (2003)
French	Lexique (New et al., 2001)	V ~ V	ẽ ~ œ e ~ ε œ ~ ø ~ ɔ	VIN ~ UN ÉPÉE ~ ÉPAIS	Fagyal et al. (2006)
Spanish		C ~ C	ʎ ~ j s ~ θ		Penny (2002, 106) Harris (1969)
Slovak	Slovak National Corpus (Šimková, 2006)	C ~ C V ~ V	ʎ ~ l æ ~ a æ ~ e		Krajčovič (1988)
Korean	Korean National Database (Lee, 2006)	C ~ C / [-son] <u>  </u>  C ~ C / <u>  </u> ]σ	p ~ p' t ~ t' s ~ s' tʃ ~ tʃ' k ~ k' p ~ p <sup>h</sup> t ~ t <sup>h</sup> ~ s ~ s' ~ tʃ ~ tʃ <sup>h</sup> ~ h k ~ k <sup>h</sup> ~ k'	post-obs. tensing  coda neut.	Sohn (1999, 173)  Sohn (1999, 165)
Cantonese ( <i>Hong Kong</i> )	Hong Kong Cantonese Corpus (Kang Kwong, 2004)	C ~ C / # <u>  </u> C ~ C / <u>  </u> # T ~ T	n ~ l n ~ ŋ 2 ~ 5		Zee (1999) Zee (1985) Mok and Wong (2010)

Table 1

*Summary of the database constructed for this study: languages included, corpora from which data were taken, phoneme pairs included, and known actual mergers.*

(Surendran & Niyogi, 2006). Similarly, at the segment level<sup>2</sup> we compare relative phoneme

<sup>2</sup>For the purposes of this analysis, we treat tone in the Hong Kong Cantonese data as a segment-level property of a syllable, rather than, for example, as a feature of a vowel.

token frequency to change in the segment-level entropy upon merger of the phoneme-pair (Hockett, 1967). Phoneme frequencies are divided by total corpus segment token frequency to provide a relative frequency, and then summed over each phoneme pair. The results we report here use the natural logarithm of this sum to reduce the influence of very high frequency phonemes, but the untransformed measure provides the same basic results.

We compare the minimal pair and relative phoneme frequency measures to the word- and sound-level entropy measures, respectively, because while they are comparable in their levels of analysis they differ in the degree to which properties of the system as a whole are taken into account. The minimal pair and phoneme frequency measures are *local* in the sense that they do not depend on the number or frequency of other word or phoneme types in the system. The entropy measures do take these relationships in the rest of the system into account, and as such the two types of measures imply different models for mechanisms underlying an effect of functional load on phoneme merger. While a thorough analysis comparing the predictive power of other functional load measures is beyond the scope of this short report, the general pattern of results reported here holds for most of the formulations we have investigated.

## 2.3 Results

In this section, we report a model using the predictors discussed in the previous section in a hierarchical (or *mixed-effects*) logistic regression model (Baayen, 2008; Gelman & Hill, 2007; Jaeger, 2008). The grouping factor (i.e., *random effect*) in the hierarchical model is phoneme pair group, defined above in section 2.1.<sup>3</sup> The use of a hierarchical model is appropriate for this kind of structured data, and should allow our results to generalize to

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<sup>3</sup>It is possible to treat this factor as nested within levels of language/corpus. However, this did not improve any of the model fits we investigated, and therefore we will only report the simpler models with phoneme pair group as the only grouping factor.



other languages and corpora more successfully than simple logistic regression.<sup>4</sup>

We begin with a discussion of the minimal pair and phoneme frequency measures. When included in a model with only simple effects, both are significantly predictive of phoneme merger, in opposite directions. That is, the more minimal pairs, the less likely merger is, but the more frequent the phonemes, the more likely merger is. In addition to the simple effects of the minimal pair count and phoneme frequency, we also investigated their interaction. Interestingly, while the linear interaction between these two continuous variables proved non-significant ( $p = 0.47$ ), closer inspection revealed that there was an abrupt shift in the effect of phoneme frequency between the pairs showing no minimal pairs vs. those with minimal pairs. In the model presented here, this is captured by including a dichotomous predictor with the levels ‘minimal pairs’ and ‘no minimal pairs,’ which is allowed to interact with phoneme frequency. A near-significant  $\chi^2$  likelihood ratio test suggests that this more complex model may be warranted over the simpler model with only the simple effects of minimal pairs and phoneme frequency ( $\chi^2 = 5.88$ ,  $df = 2$ ,  $p = 0.053$ ). The parameters of the final model described thus far are given in table 2.

Predictors	Estimate	Std. Error	z value	p value
(Intercept)	-3.34	0.43	-7.70	0.0000
Minimal pairs	-3.44	0.96	-3.60	0.0003
Segment frequency	0.36	0.24	1.53	0.1249
Absence of min. pairs (binary)	-0.13	0.47	-0.27	0.7851
Segment freq. by absence of min. pairs	1.27	0.64	1.97	0.0484

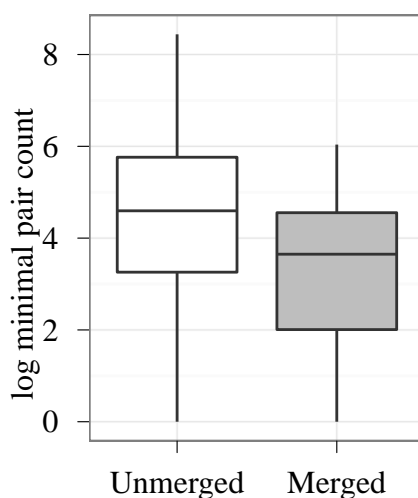
Table 2

*Fixed effects in logistic mixed-effects model.*

The simple hypothesis of functional load was supported: the negative effect of minimal pairs is consistent with the claim that a greater role in distinguishing words

<sup>4</sup>We examined all possible models of different random effect structures, including all random slope effects. Model selection based on AIC, BIC, and  $\chi^2$  likelihood ratio tests all arrived at the same conclusion, that a model with only a random intercept (no random slopes) was the best-fitting model. We therefore report the only the fixed effects from this simpler model.

decreases the probability of phoneme merger. This effect can be seen graphically in the boxplot in figure 1, where the merged pairs have lower minimal pair counts than the unmerged pairs. The continuous predictors were centered and standardized prior to model-fitting, and positive values indicate increased probability of merger. Thus the coefficients in table 2 can be interpreted as the change in the log-odds of merger for a change of one standard deviation in the predictor. For example, if the probability of merger was otherwise estimated as 5% (log-odds -2.94), a one-standard-deviation increase in the number of minimal pairs would change the estimate by -3.44, which translates into a decrease from 5% down to 0.17%.



*Figure 1.* Relationship between minimal pair count and merger

The effect of phoneme frequency is more subtle because of its interaction with the presence/absence of minimal pairs. In the model in table 2, the presence of minimal pairs is taken as the ‘baseline,’ and so the non-significant simple effect of phoneme frequency is interpreted to mean that for phoneme pairs which have minimal pairs in the language, phoneme frequency does not play a reliable role in predicting merger. However, the significant interaction indicates that where there are no minimal pairs, merger is more

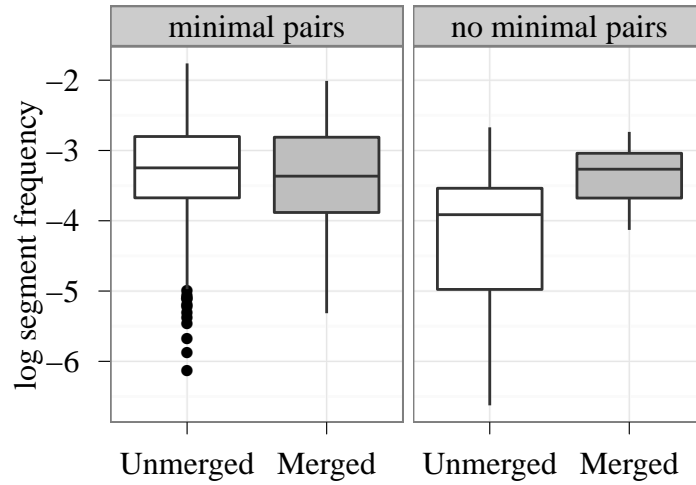


Figure 2. Relationship between segment frequency and merger, by presence of minimal pairs

likely for higher-frequency segments. Figure 2 shows this graphically.

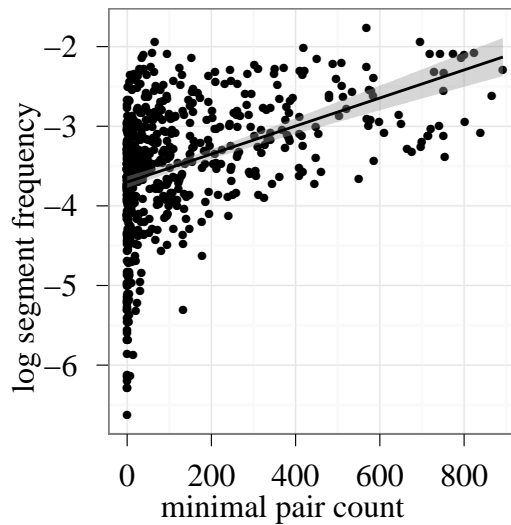


Figure 3. Relationship between segment frequency and merger, by presence of minimal pairs

While we have modeled this using the binary distinction between presence and absence of minimal pairs, we do not claim that the effect of segment frequency really is “all

or nothing” depending on the presence of minimal pairs. Our results do indicate that the interaction is nonlinear, and this binary distinction appears to be a good way to capture this nonlinearity in a simple fashion. We note that as expected, relative phoneme frequency and number of minimal pairs are positively correlated, as shown by the scatterplot in figure 3.<sup>5</sup> The fact that these two predictors are related, and that they show effects in opposite directions, raises concerns about collinearity. In order to rule out the possibility that the model was adversely affected by collinearity, we residualized the segment frequency variable on the minimal pair variable and refit the model. The results were virtually identical to those in table 2, suggesting that collinearity is not a major concern.

Having established the model in table 2, we ask whether entropy-based measures improve the model. We consider two measures of entropy, word-level entropy and segment-level entropy, as described in section 2.2. Because word-level entropy is more correlated with our minimal pairs variable than the segment frequency variable (0.72 vs. 0.42, respectively), we considered whether word-level entropy was a more effective predictor than minimal pairs. Conversely, segment-level entropy is more correlated with segment frequency in our data (0.71 vs. 0.6 with minimal pairs), so we considered these two predictors as competitors.<sup>6</sup>

To assess the relative effectiveness, we first fit a superset model including both competitors. We then fit an alternative model substituting the entropy variable in place of the competitor in our model in table 2. Using  $\chi^2$  likelihood ratio tests, we compared both our model in table 2 and the entropy-based model to the superset model. In the case of word-level entropy vs. minimal pairs, model comparison indicated that the superset model was significantly better-fitting than the word-entropy model ( $\chi^2 = 9.97$ ,  $df = 1$ ,  $p = 0.002$ ),

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<sup>5</sup>This figure excludes observations with extreme values of minimal pair counts (over 900 minimal pairs; excluding 32 observations, none of them cases of merger), in order to more clearly depict the graphical pattern. The results are the same when these observations are included.

<sup>6</sup>Treating segment-level entropy as a competitor to minimal pairs instead produced the same results as those reported in the main text.

but not significantly better than the minimal pairs model without word entropy ( $\chi^2 = 0.43$ ,  $df = 1$ ,  $p = 0.511$ ). Similarly, the superset model including both phoneme frequency and segment entropy was significantly better-fitting than the segment-entropy model, ( $\chi^2 = 19.27$ ,  $df = 2$ ,  $p = 1e-04$ ), but not better than the phoneme frequency model without segment entropy ( $\chi^2 = 3.11$ ,  $df = 2$ ,  $p = 0.211$ ). In summary, entropy-based formulations of functional load at the word level or segment level did not improve on the model presented in table 2.

### 3 Conclusions

This paper reports the first statistical evidence that functional load is indeed correlated with phoneme merger, as predicted for nearly a century. We accomplished this by employing a statistical analysis of a relatively large dataset drawing on a variety of languages, rather than on individual case studies. Within this dataset, we find that the more minimal pairs defined by a phoneme pair, the less likely that phoneme pair is to have merged. These results provide the first clear support for the general intuition behind the functional load hypothesis, which is that merger is less likely between phonemes which contribute more to distinguishing words. Further, we find that in case there are few or no minimal pairs distinguished by a phoneme pair, greater relative phoneme frequency is significantly associated with merger.

These findings are consistent with models that propose a causal chain linking individual utterances to long-term change in the abstract, sublexical category system of a speech community (Beckner et al., 2009; Blevins, 2004; Blevins & Wedel, 2009; Bybee, 2001; Kirby, 1999; Labov, 1994; Ohala, 1989; Pierrehumbert, 2001, 2003; Walsh, Möbius, Wade, & Schütze, 2010; Wedel, 2007). More specifically, Wedel (2004, 2006) describes a multi-level exemplar model (Walsh et al., 2010) for a general linking mechanism between

biased variation in word production/perception events and long-term change in phonetic distributions within sound categories. In this model, any mechanism in production or perception favoring phonetically more contrastive tokens of minimal pair members will promote maintenance of a phonetic distinction between the phonemes defining that minimal pair. Consistent with the proposed existence of such mechanism(s) (reviewed in Baese & Goldrick, 2009, Scarborough, 2010), many studies have reported that in production, phonetic cues to word identity are exaggerated when a word has more close competitors, i.e., when there are more words in the lexicon that are pronounced similarly (Aylett & Turk, 2004; Baese & Goldrick, 2009; Munson, 2007; Munson & Solomon, 2004; Scarborough, 2010; Wright, 2004).

Hockett (1967), followed by Surendran and Niyogi (2003, 2006), note that the change in system entropy upon loss of a contrast is the most direct index of that contrast's contribution to the overall information transmission capacity of the system (Shannon, 1948) and argue that it is, by extension, the appropriate measure of functional load. In this dataset, however, we find that the more local measures of minimal pair count and relative phoneme frequency do a significantly better job of predicting merger. There are two possible reasons for this finding. One is simply that the properties of the corpora on which the dataset is based, in particular their frequency information, may not correspond sufficiently well to the language context during the merger process. The other is that a putative contrast-maintenance mechanism may not directly take the contrast properties of the entire system into account (as is implicit in the use of an entropy-based measure), but instead may operate on the basis of, for example, a more local competition between individual words (Baese & Goldrick, 2009) and phonemes (Pierrehumbert, 2001). We note, however, that any mechanism maintaining contrast at these more local levels will tend to indirectly maintain the information-transmission capacity of the system as a whole.

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