# Functional Load and Frequency as Predictors of Consonant Emergence across Five Languages

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## Abstract

Frequency often predicts when children will acquire units of language such as words or phones. An additional predictor of language development may be a phone's functional load (FL), or the contrastive work a sound performs in a language. A higher FL may correlate with earlier phone emergence in child speech as children selectively converge upon the most meaningful contrasts in their input. This hypothesis is tested across five typologically diverse languages that vary by phone inventory size and structure as well as word composition. Consonant FL was calculated over more than 390,000 words of child-directed speech. Results demonstrate that the relationship of frequency and FL to speech development is dependent upon the language of exposure. Models fit to bootstrapped corpus data suggest that frequency may be the stronger of the two parameters.

**Keywords:** language acquisition; child development; functional load; modeling; entropy

## Introduction

Many factors predict when a child will first start using a sound of their native language: articulatory difficulty, frequency in the input, and even word structure. Though all likely contribute to the reliable production of a consonant, or CONSONANT EMERGENCE, the relative influence of each factor may vary by language. For example, with an articulation towards the front, and at times back, of the mouth, the lateral approximant /l/ has a complex articulation. It is, accordingly, late to emerge in child English (Lin & Demuth, 2015). However, children acquiring Quiché Mayan begin to use laterals like /l/ fairly early in development, as soon as 1;7, perhaps because /l/ is highly frequent in the ambient language (Pye, Ingram, & List 1987).

Beyond frequency, another predictor of when children start using a consonant sound may be functional load (FL). Formally, FL has been defined as the entropy reduction a system undergoes due to minimal pair loss (Hockett, 1955). In implementation, FL can measure the effect of removing a phoneme from a language by quantifying how many minimal word pairs that phoneme distinguishes (e.g. pat~bat). Interest in FL as an explanatory device for sound mergers in language change has recently resurfaced (Oh et al., 2013; Surendran & Levow, 2004; Surendran & Niyogi, 2006; Wedel, Jackson, & Kaplan, 2013). Its potential as a metric in speech development is often suggested, though not implemented (So & Dodd, 1995) or conflated with frequency (Amayreh, 2003). The few studies that have applied FL to speech development used disparate methodologies for collecting corpora, calculated FL differently, and came to different conclusions regarding its role for development (Pye et al., 1987; Stokes & Surendran, 2005; Van Severen et al., 2013).

In addition to FL, frequency is a useful predictor of speech development (Edwards, Beckman, & Munson, 2015). It is also a natural correlate with FL. Unlike frequency, FL encompasses semantic contrast and mental lexicon structure. This may be critical for development since phonetic categories derived from the lexicon, over those inferred purely from input distributions, have resulted in more robust category acquisition, at least in models of infant learners (Feldman et al. 2013).

The relationship between FL and speech development is intuitive. As children selectively focus upon contrasts in their ambient language, they acquire phones that differentiate the most words (Dietrich, Swingley, & Werker, 2007). Still, it is not clear if the contrastive importance of a phone always reinforces consonant emergence. Data from several unrelated languages show conflicting evidence. Like the relationship between the speech sound emergence and articulatory complexity of /l/, the role of FL may differ by language. For example, Stokes & Surendran (2005) attributed the low predictive power of FL in Cantonese consonant development to word structure: with six tones, Cantonese has many segmental homonyms. This could lower the FL of individual phones. But Van Severen et al. (2013) found that FL was a better predictor of productive consonant use in Dutch than frequency alone. Thus, how individual languages incorporate the roles of FL and frequency for development is unclear. Finally, there are multiple approaches to FL calculation – its role in speech emergence has not been uniformly evaluated. A standard FL calculation, measured over several languages, can address the universality of FL for consonant emergence.

Understanding the varied parameters of speech development has clear clinical implications. But is the contribution of FL and frequency the same for all children? Or does it depend on the language of exposure? Furthermore, though the negative correlation of FL and age of consonant emergence is intuitive, the reason why a child prioritizes highly contrastive phones in phonological learning is less straightforward. In fact, this distributional learning mechanism may differ by language. Here this is addressed by computing FL and phone frequency over the child-directed speech (CDS) of five typologically diverse languages that vary by phone inventory size and structure as well as word composition. This cross-linguistic comparison evaluates the potentially language-specific role of FL and frequency in child consonant emergence.

## Formalizing Functional Load

FL has been defined as the system entropy reduction resulting from minimal pair loss (Hockett, 1955). Following Surendran & Niyogi (2006), here it is formalized as information loss:

$$FL_U(a) = \frac{CL_U - C(L_U^{-a})}{CL_U}$$

where $a$ is the linguistic unit (phone or word), $C$ is entropy, and $L_U$ is the lexicon. This calculation was made at the word level, but phoneme level FL is another alternative. Phone frequency was measured as the number of occurrences in the corpus divided by the number of total phones in the corpus. Van Severen et al. (2013) found that FL and frequency calculated on word types correlated more strongly with phone acquisition than word tokens. Consequently, both FL and frequency were calculated for consonants over type frequencies (English [N=1,321], Japanese [N= 10,412], Mandarin [N=2,200], Spanish [N=2,304], and Turkish [N=2,216]).

FL was measured over the entire consonant inventory of each language (Table 1) except Japanese geminate stops such as /pp/[1] and Japanese /ʃ/. There was not developmental data on these segments. Spanish /s/ was also excluded because the CDS corpus is a *ceceo* dialect and the developmental data reports on non-*ceceo* dialects (see Lipski 1994). Finally, nasals like /n/ and /m/ are excluded because they are ubiquitous from early babbling, likely emerging too early to be lexically meaningful.

Table 1: Consonants measured

| LANGUAGE | STOPS | FRICATIVES |
|---|---|---|
| English | p, t, k, b, d, g | f, v, θ, ð, s, z, ʃ, ʒ |
| Japanese | p, t, k, b, d, g | s, z, h |
| Mandarin | p, t, k, pʰ, tʰ, kʰ | s, f, ʂ, ɕ, x |
| Spanish | p, t, k, b, d, g | f, x |
| Turkish | p, t, k, b, d, g | s, f, v, ʃ, ʒ, ɣ, h |

| LANGUAGE | AFFRICATES | LIQUIDS/GLIDES |
|---|---|---|
| English | tʃ, dʒ | l, ɹ, w, j |
| Japanese | ts, tʃ | r, w, j |
| Mandarin | ts, tsʰ, tʂ, tʂʰ,<br>tɕ, tɕʰ | ɻ, l |
| Spanish | tʃ | l, ɾ, r, ʝ |
| Turkish | tʃ, dʒ | l, r, j |

There is disagreement concerning best practices for FL calculation. Stokes & Surendran (2005) justify the choice to calculate FL only in word-initial position since "children pay attention to the onsets of words (581)." However, this is not universal. For example, in early word production, French children actually tend to omit word-initial segments, likely due to exclusive word-final stress in French (Vihman, 2013). Consequently, here FL is calculated over all segments. Elsewhere, FL calculations are limited to the lemma (Wedel et al., 2013). But since Turkish, a highly agglutinating language, is included in this analysis, all inflected and derived forms in the remaining languages are also. Unfortunately, including this morphology biases the occurrence of /s/ and /z/ in English – the plural allomorphs – and they are extreme outliers. Consequently, it was decided to exclude /s/ and /z/ from the English analysis. A larger work will compare the effects of frequency and FL across morphologically complex and decomposed forms and will include English /s/ and /z/.

## Methods

### Corpora Preprocessing

FL and frequency were calculated over naturalistic, monolingual corpora of American English (Bernstein-Ratner [Bernstein-Ratner, 1987] & Brent-Ratner corpus [Brent & Cartwright, 1996]), Japanese (MiiPro corpus [Miyata, 2012]), Shenzhen Mandarin (Tong corpus [Deng & Yip, 2017]), Peninsular Spanish (Aguirre corpus [Aguirre, 2000]), and Turkish (Aksu [Slobin, 1982] & Altinkamis corpus [Türkay, 2005]) available in CHILDES (MacWhinney, 2000). These languages were selected because they were either 1) already phonologically transcribed or 2) relatively orthographically transparent which permits algorithmic grapheme-to-phoneme conversion. Only CDS directed towards the child from 1;0-3;0 and from the target child's mother, father, grandparents, and adult interlocutors was included. Though sibling input undoubtedly impacts development, sibling utterances were excluded since age and presence was corpus-dependent. To further increase corpus generalizability, the following were also removed: all proper nouns, with the exception of familial terms (e.g. "Mama"), child- and family-specific forms, second language items, and investigator speech. This resulted in the following token counts/corpus: English (N=32,993), Japanese (N=235,705), Mandarin (N=72,908), Spanish (N=44,440), and Turkish (N=10,977). Discrepancies in corpus size are counteracted in a bootstrap procedure before model fitting in Results.

The Mandarin (Pinyin transcription), Spanish, and Turkish corpora underwent a grapheme-to-phoneme conversion utilizing the Montreal Forced Aligner (McAuliffe et al., 2017). Forms without a representation in the corresponding dictionary were discarded. These unknown words made up 0.39%, 0.86%, and 10.71% of

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[1] The only developmental data available was acoustic (Kunnari, Nakai, & Vihman 2001). For consistency, emergence calculation was limited to diary data.

the Spanish, Mandarin, and Turkish corpora, respectively. Only the relationship of segments and FL is analyzed here so tone was removed from the Mandarin corpus. The Brent-Ratner corpus for English was already transcribed phonologically and the MiiPro Japanese corpus was transcribed in Hepburn Romanization which is orthographically transparent (Miyata p.c.).

### Developmental Data

Age of consonant emergence (AoE) was determined from previous peer-reviewed works of developmental phonology for each language. Studies have employed distinct metrics to qualify a consonant as "emerged" in a child's phonological repertoire: if the sound was present in the child's inventory at least two times in a given speech sample (Dinnsen et al., 1990) or, in larger studies, if 90% of the children produced the sound one time (Prather, Hedrick, & Kern, 1975; So & Dodd, 1995). Data collection methodologies – naturalistic, elicited, etc. – also differ by study. Table 2 lists studies referenced and the metrics employed. When an age range was specified (e.g. 18-22 months), the mean month was taken as AoE.

Table 2: Metric for consonant emergence

| Language | Reference | Metric for emergence |
|---|---|---|
| English | Prather et. al (1975) | 75% of children (*N*=147) used consonant in initial and final position |
| Japanese | Nakanishi (1982);<br>Ota (2015) | mean age of first appearance across (*N*=10) children |
| Mandarin | Hua & Dodd (2000)[3] | 90% of children in each age group (~*N*=20) produced sound one time |
| Spanish | Cataño, Barlow, & Moyna (2009) (metanalysis) | occurred at least two times in a given speech sample from *N*=16 children |
| Turkish | Topbaş (1997) | produced in all 7 possible word positions by *N*=22 children |

Given the discrepancy between studies, the metric for consonant emergence is not standard. For example, consonants appear to emerge much later in the English data but this is due to the more stringent emergence criterion that Prather et al. (1975) used. As a result, AoE is not directly comparable between languages but it was consistent within each language.

## Results

Figure 1 maps the relationship of normalized FL to age of emergence (AoE). To compare FL measurements between languages, FL was normalized by the sum of all FL calculations within each language: $FL(a) \ / \sum Fx_i$. The negative correlation of FL and AoE for each language varied: English (Pearson *r* = -.50), Japanese (*r* = -.29), Mandarin (*r* = -.04), Spanish (*r* = -.13), and Turkish (*r* = -.58) and meaning that in some languages, children tend to acquire phones with higher functional load first.

Frequency negatively correlated with AoE in each language: English (*r* = -.39), Japanese (*r* = -.20), Mandarin (*r* = -.47), Spanish (*r* = -.58), and Turkish (*r* = -.29). FL correlated more strongly than frequency with AoE for three out of the five languages. This suggests that FL plays a role in consonant emergence for some languages, but frequency is most predictive.

To confirm the generalization from correlational statistics, a bootstrapping with replacement procedure was employed over each of the CDS type-frequency language corpora in one hundred 750-word samples.[2] FL was then normalized over the sum of phone FL measurements within each sample.

Stepwise cumulative link mixed effects models, similar in implementation and interpretation to other hierarchical (e.g. mixed effects) models but specified for ordinal response variables, were fit to the bootstrapped data for each language using the `clmm` function in the R package `ordinal` (Christensen, 2015). Multivariate linear and even logistic models cannot perform as well as clmms. Linear models predict values outside of the realistic range of the response variable. Here this means that the model would predict a relationship before the age children begin producing consonants. Since AoE does not evoke a continuous developmental period, but rather discrete, chronologically ordered developmental stages, it was binned into developmental periods of 3 months (e.g. 0;11-1;1, 1;2-1;5) Forwards stepwise model fitting was evaluated through log-likelihood tests and AIC comparison.

When discussing child phonology, an obvious concern about motor limitations arises. No model of emergence is complete without an articulatory complexity metric but it is surprisingly difficult to quantify. The scale used for the model parameter **articulatory_complexity** is adopted with modification from Stokes & Surendran (2005) (Table 3).

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[2] In Japanese, samples < 750 resulted in a FL of 0 for almost all segments/sample. This is likely due to heterogeneous phonotactics and distinct lexical strata in Japanese so a sample size of at least 750 is required to gauge FL (Itô & Mester, 1999).

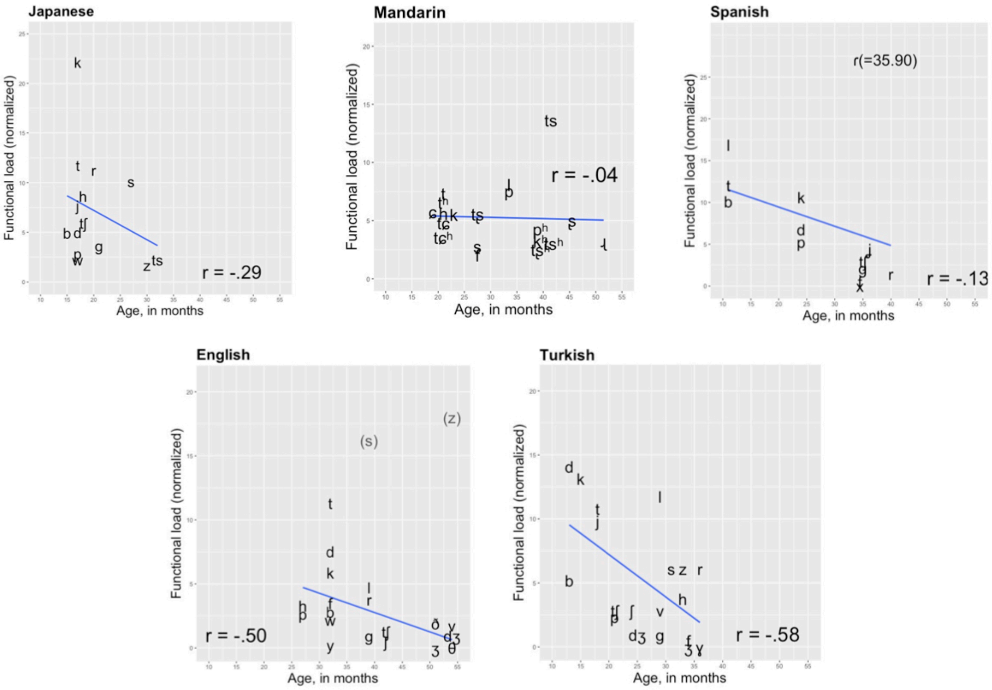

Figure 1: Functional load by age of emergence

Table 3: Articulatory complexity metric

| LEVEL | DESCRIPTION | PHONES |
|---|---|---|
| 1 | -Rapid/ballistic movement<br>-Slow/progressive movement | p, w, h |
| 2 | -Some lingual control for frication<br>-Velar place of articulation<br>-Laryngeal mastery | t, k, b, d, g, j, f, pʰ, tʰ, kʰ |
| 3 | -Tongue tip and dorsum manipulation | r, ɹ, ɻ, ɾ, l |
| 4 | -Complete lingual control for fricatives<br>-Transition from ballistic to frication | s, z, ʃ, ð, θ, v, ʝ, ʒ, x, ɣ, tʃ, dʒ, ts, tsʰ, ʂ, tʂ, tʂʰ, ɕ, tɕ, tɕʰ |

Best model fits resulted in parameter values for **frequency** and **FL** that varied by language (table 4).[3] **Articulatory_complexity** was modeled as a random effect for each language. Negative coefficients signify that as children age, phone FL/frequency decrease. Best model fit for English was quadratic so a negative coefficient instead indicates a rising, concave trajectory. Coefficients are scaled via z-score normalization to compare the relative importance of FL and frequency for emergence.

Table 4: Model fits by language

| | FREQUENCY, SCALED | FUNCTIONAL LOAD, SCALED |
|---|---|---|
| English | β = -3.12, *** | β = -1.43, *** |
| Japanese | β = -0.33, *** | n.s. |
| Mandarin | β = -1.16, *** | n.s. |
| Spanish | β = -3.86, *** | β = -1.03, *** |
| Turkish | β = -0.44, *** | β = -3.86, *** |

The significance of FL and frequency for these models indicates that, alone, articulatory complexity does not explain when children first produce consonants. For example, Turkish-, Spanish-, and English-learning children learn higher FL and higher frequency phones before lower-FL and lower frequency phones, even after controlling for articulatory complexity. However, FL does not have this predictive effect in Mandarin or Japanese. Furthermore, the normalized coefficients permit comparison between model parameters. So frequency is more predictive than FL in both English and Spanish. However, FL is more predictive for emergence in Turkish.

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[3] Coefficients in table report on Mandarin model without /ts/ and Spanish model without /ɾ/. Alone, these phones changed their respective language model fits. The coefficients for a Mandarin model with /ts/: (**frequency**=-1.30 ***, **FL**=0.43 ***) and Spanish model with /ɾ/: (**frequency**=-2.14 ***, **FL**=1.17 ***).

# Discussion

Phone frequency influences consonant development in children's speech. The more children hear a sound, the faster they can focus attention to imitating its articulation and ensuing acoustic signal. Yet this intuitive relationship has limitations. Edwards et al. (2015) cite the example of English /ð/. Due to words like 'the' and 'that', /ð/ has exceptionally high token frequency, but low type frequency in English. This explains, in part, why /ð/ emerges relatively late for children learning English. So while frequency is correlated with development, alone, it cannot complete the picture of speech development.

Likewise, child phonology is rife with examples of phones that emerge late due to motor limitations and immature physiology (McGowan, Nittrouer, & Manning, 2004; Nittrouer, 1993). But cross-linguistically, the same segment can emerge in child speech at different developmental stages (Edwards & Beckman, 2008). So articulatory demands also cannot fully predict when sounds emerge in child speech.

The model here incorporates both of these factors and tests an additional parameter: functional load. Even when controlling for type frequency and articulatory complexity, children learning English, Turkish, and Spanish manipulate the semantic information in the input to inform their timeline of early phone production. At least at the segmental level, children acquiring Japanese and Mandarin do not use this information. This supports previous findings about the primacy of the lexicon for speech development in models of English learners (Feldman et al., 2013). There is of course a natural circularity to any argument about ambient language effects and language acquisition. It follows a chicken-or-the-egg logic: do children acquire segments because they are more frequent in the input or more frequently contrast words? Or are those sounds more frequent because they are more "naturally" acquired or easier to articulate? Both explanations are valid and models here suggest that, cross-linguistically, universals and language-specific parameters govern speech development.

FL did not predict consonant emergence in Mandarin, replicating Stokes & Surendran (2005)'s finding from another tonal language, Cantonese. There, the authors attributed the finding to the high load of tone in Cantonese. The same explanation could be offered for the Mandarin model outlined here. However, it is also possible that, like Mandarin-speaking adults, Mandarin-speaking children have a different phoneme awareness than English- or Spanish-speakers. For example, Mandarin-speaking children may instead transact contrasts at the syllable level. Though Japanese is not a tonal language, its consistent syllable structure (primarily CV) may also mean that children rely upon this reliable syllable shape, instead of individual phones, to bootstrap into phonological categories.

In both Spanish and English, frequency was a stronger predictor for speech sound emergence than FL. This is not a surprising conclusion given the typological and structural similarity between the languages. However, FL was a stronger predictor than frequency for Turkish. This could be due to the agglutinating nature of Turkish. Instead of computing contrasts over the entire lexicon, children may instead compute only across semantically meaningful words such as nouns and action verbs, ignoring function and grammatical words. (Note that Wedel et al. (2013) opted to remove function words entirely from their FL analysis.) In a language like Turkish, the information typically expressed in function words – tense, aspect, prepositional relations – is expressed in suffixes attached to root words. In Spanish and English, however, function words are separate lexemes. Computing FL over datasets with and without grammatical and function words could be a way to test this hypothesis empirically. Future analyses into the relationship between emergence and ambient effects should also compute FL over morphologically decomposed corpora to better understand which parts of the lexicon children use to acquire speech sounds.

In conclusion, the intuition that ambient frequency predicts consonant development was confirmed for all languages studied. In addition, the ability to contrast words, calculated by phone FL, also predicts when speech sounds emerge in Spanish, English, and Turkish. These relationships are constant even after controlling for the articulatory demands of phones. These results reaffirm the dual contributions of environment and physiology on early language production.

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