Language-Specific Sources of Acoustic Stability in Phonological Development

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1. Introduction

Acoustic variability in adult speech is rampant and largely chalked up to reduction and coarticulation. Variability in child speech production, however, can be attributed to physiological development: anatomy or underdeveloped motor routines explain why a child's spectral patterns vary from one production to the next (Lee et al. 1999; Vorperian & Kent 2007). Adult-like variability, for example the acoustic dispersion of individual phoneme categories, is only attained around age 12.

Phonetic mastery clearly poses a challenge throughout childhood, but it is essential for phonological development. Acoustic competence leads to efficient adult communication (Aylett & Turk 2004) and phoneme category stability results in more intelligible speech (Ménard et al. 2007). The acoustic vowel space is even used as a metric of speech development (Schenk et al. 2003). Given the importance of acoustic stability in development, we examine another potential source of variability in child speech: phonological inventory.

Previous conclusions on child phoneme variability were drawn from languages with relatively large vowel inventories such as English (Lee et al. 1999) and French (Ménard et al. 2007). But vowel inventory size and intra-category variability – how dispersed each phoneme category's productions are from the mean – may be negatively correlated in adults (Recasens & Espinosa 2006). Do children learning a language with fewer vowel contrasts achieve adult-like levels of phoneme category stability earlier? Additionally, children first master consonants that are frequent in the ambient language (Edwards & Beckman 2008). Consequently, we expect that in systems with fewer vowel contrasts, where each vowel is more frequent, children may master vowel

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distinctions sooner. We expect children to be equally, if not more, variable with dispersed phoneme categories than adults when acquiring a language with few vowel contrasts. Our secondary hypothesis is that linguistic structure affects development of acoustic stability; if so, children will master vowels at different rates throughout morphologically complex words. We test these hypotheses in Chuquisaca Quechua, a language with three vowel contrasts and highly agglutinative morphology.

2. Acoustical development

Production patterns such as cluster reduction and place assimilation that characterize early child phonology rapidly subside as typically developing children attune their motor planning skills. Yet children will still undergo years of variable phonetic production. We refer to this process of attaining adult-like levels of phoneme category variability as ACOUSTICAL NARROWING, following the well-known phenomenon of perceptual narrowing.

Acoustical variability in speech production, even for adults, is ubiquitous. Variability in child speech, however, stems from anatomical difference from adults (Denny & McGowan 2013) and underdeveloped coarticulatory and gestural movement (Nittrouer 1993). These differences can have acoustic consequences. Peterson & Barney (1952) and Eguchi & Hirsh (1969) studied children's production of vowel formants, or resonances within the vocal tract that distinguish speech sounds. They found that English-speaking children 3;0-13;0 had acoustically more dispersed vowel categories than adults. Hillenbrand et al. (1995) and Lee et al. (1999) replicated this evidence for acoustical narrowing. In a large cross-sectional study of American English vowels in N=436 children aged 5;0-17;0, Lee et al. (1999) found that variability in formant frequency production, fundamental frequency (pitch), and length of vowel duration decreased with age. Children attained adult-like levels of stability around age 12.

The consistent pattern of acoustical narrowing is most often attributed to anatomical maturation. If acoustical differences between children and adults have anatomical origins, vowel development should not differ cross-linguistically. The results of Ménard et al. (2007) support this claim. They examined French vowel formant production by adults and children (3;7-4;2, 7;9-8;3) and found that younger speakers had more variable spectral productions with more dispersed phoneme categories. Non-rhotic vowels are some of the earliest segments that children produce, but these results suggest that children do not master vowel formant frequencies at adult-like levels until early puberty.

Other studies have found exceptions to acoustical narrowing patterns. Nittrouer (1993) elicited the sequence /ə/-consonant-/a, i, or u/ in English-speaking adults and children (3;0, 5;0, 7;0). Child formant variability did not unilaterally reduce with age. In fact, as early as 3;0, the children demonstrated minimal, almost adult-like levels of formant 1 (F1) variability. Formant 2 (F2) variability, however, continued to decrease well after this age. Nittrouer explained this as a function of non-uniform motor development: children may master vertical jaw movement early, but other gestures (e.g. tongue dorsum fronting) require further maturation. Nittrouer did, however, find that the children produced a longer duration schwa than the adults.

McGowan et al. (2014) examined naturalistic, adult-directed speech in the vowels of six American English children (1;6-4;0). While children's production was variable with highly-dispersed phoneme categories, front vowels were more stable than back. Furthermore, the variability did not change over time suggesting that it may not always correlate negatively with child age.

With the exception of some inter-vowel differences, and McGowan et al. (2014)'s naturalistic speech finding, acoustical narrowing appears widespread. This is perfectly cogent: child variability stems from immature motor development and the transient articulatory-acoustics mapping that children must continuously update as their anatomy changes. However, there are other factors that influence phonetic production. For example, word duration and frequency are negatively correlated in adult speakers (Gahl 2008) and phonological neighborhood density interacts with acoustic reduction (word duration) (Gahl, Yao, & Johnson 2012). We examine phonological structure, a language-internal factor that could also mitigate acoustical narrowing.

3. Current study

3.1. Chuquisaca Quechua

This study analyzes data elicited from Quechua-speaking children and adults in the rural highlands of the Chuquisaca department in Bolivia. In 2001, 220,739 speakers in Chuquisaca identified Quechua as their native language (UNICEF and FUNPROEIB Andes 2009).[1] The second author postulates that Chuquisaca Quechua (CQ) is a relatively conservative variety of South Bolivian Quechua, a Quechua-II/C language with over 1.6 million speakers in southwest Bolivia and northwest Argentina (Simons 2009). CQ is mutually intelligible with Cuzco Quechua, the lingua franca of the Inca Empire.

CQ is a subject-object-verb language with highly agglutinating morphology. Suffixes encode arguments and grammatical functions in addition to agreement (1).

(1) uhut'a-chi-chka-Ø-n
sandalia-CAUS-PROG-3OBJ-3SUJ
'S/he is making her/him put the sandal on.'

South Bolivian Quechua varieties have three peripheral vowels /a, i, u/ with allophonic mid-vowels [e, o] derived in uvular contexts (Gallagher 2016). A consonant inventory is listed in appendix 1. The developmental trajectory for allophonic versus phonemic vowels likely differs. However the mid vowels [e,

[1] Most recent population data available.

o] were isolated to certain words in our corpus (e.g. *q'ipi* "package") and were not frequent enough to analyze. This language contributes to the study of phonetic development not simply because it, and all other Quechuan languages, is almost entirely unrepresented in L1 phonology, but also because of its relatively small three-vowel inventory and distinctive morphological structure.

3.2. Objectives

We test acoustical narrowing assumptions in a new phonological system:

1) Do vowel formant frequencies undergo acoustical narrowing in a language with a relatively small vowel inventory?

Since CQ has three vowels, children will acquire adult-like levels of category variability earlier than children learning languages with large vowel inventories (English, French). Languages with larger vowel inventories seem to show that phoneme categories are less dispersed in acoustical space (Manuel & Krakow 1984; Recasens & Espinosa 2006) or the difference in inventory size must be extreme to affect variability (Recasens & Espinosa 2009). However, others found that intra-vowel category acoustic variability does not vary by inventory size – languages with large and small inventories show similar acoustic dispersion (Bradlow 1995). These studies reported on adult speech, but vowel inventory size may impact child speech variability as well.

The trajectory of phonetic development is an important question for developmental researchers who may, for example, use the acoustical space as a metric of development (Schenk et al. 2003). Studying how typically-developing children progress to adult proficiency in cross-linguistic contexts is critical to a complete theory of phonological development.

2) Does the rate of acoustical narrowing depend on morphological status?

A series of recent studies have documented a morphology-phonetics interaction in English and Dutch. Orthographic word representations display affixes equidistantly around the root. However, these studies suggest that morphemes may actually be acoustically reduced relative to the root form. The closer an affix is fused to a root, the more it reduces. Frequency plays a role in this phenomenon: Losiewicz (1995) demonstrated that English past tense *-ed* was longer in duration on low-frequency verbs than high. Suggesting a lexical effect, Baker et al. (2007) demonstrated that true prefixes (e.g. ***mis****trust*) were longer in duration than pseudo-prefixes (e.g. ***mis****take*). Most recently, Plag et al. (2014) measured the acoustic properties of English morphemic (e.g. plural) and non-morphemic /s/ and /z/ and found that plural and non-morphemic /s/ and /z/ were longer than other /s, z/ affixes such as person marking.

Evidence for the morphology-phonetics interplay is limited to adult speech, but it may apply across the lifespan. Acoustical narrowing of formants in child speech will not occur uniformly throughout the word. Rather, since increased fusion leads to shorter duration morphemes, suffixes will be reduced relative to roots in the form of a smaller overall acoustic space.

4. Methods

4.1. Participants

The second author and a team of native-speaker field partners collected recordings for the corpus data used in this study (Kalt, 2009; Kalt, to appear). The recordings are part of a larger comparative corpus of interviews from rural Cuzco, Peru and Chuquisaca, Bolivia. Bolivian speakers were recorded in two agro-pastoralist communities in the Chuquisaca department of Bolivia,[2] each located approximately two hours hiking from the small town of Tarabuco. At the time of recording, there were not more than 120 households in either community and CQ was the dominant language. We examine a subset of the child corpus, recorded in 2009: Bolivian children under 10;0. Two participants were excluded because of breathy speech. *N*=26 children and *N*=2 adults remained (table 1). The children were divided into groups by age. The remoteness of the communities limited our team's access, resulting in unbalanced age groups.

Table 1: Speaker demographics

	5;0-6;0	7;0-8;0	9;0-10;0	ADULTS
FEMALE	5	2	7	1
MALE	1	3	8	1

In the communities, children learn and speak CQ in the home and begin to learn Spanish in kindergarten (5;0). Children interviewed may be classified as sequential Quechua-Spanish bilinguals, but CQ dominant. Both adult speakers, recorded in 2016 in the same communities, stated that they did not speak Spanish. The adult female (age 34) reported six years of primary education (in Spanish) and the adult male (age 78) reported one month of primary education.

4.2. Corpus collection

Child interactions were videotaped with a Canon Vixia HF-100 Camcorder and audio was recorded utilizing an Audio Technica AT899 lavalier microphone at 20 kHz sampling rate. Adults were recorded with a Zoom Q4 video recorder at 44.1 kHz. Data were collected in an empty classroom at the community's school or in participants' homes. Child participants completed a picture selection and description task with culturally-appropriate images and contexts designed to measure comprehension and production of simple declarative sentences with transitive, ditransitive, and reflexive argument structure (Kalt et al. 2009). Adults narrated the Duck Story, an original, open-ended comic strip

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[2] Names rescinded for confidentiality.

we designed to elicit multi-utterance narratives (Kalt et al. 2009; 2015; to appear). All interviews were conducted by native or fluent heritage speaker interlocutors. This resulted in semi-naturalistic and contextually-consistent data across speakers, despite different instruments and tasks for adults and children.

4.3. Phonetic analysis

Native speakers of Bolivian and Peruvian Quechua transcribed and morphologically segmented the narratives under supervision of the second author. The first author wrote a Python script *ad hoc* to parse the morphological transcriptions into phone-level representations which were hand-corrected in Praat (Boersma & Weenink 2016). Acoustical measurements (duration, formants 1, 2, & 3, and fundamental frequency [pitch]) for all vowels were automatically extracted at five evenly-spaced time points in the vowel using a script running Inverse-Filter Control Formant (Watanabe 2001). The estimated resonant vocal tract frequencies (adult male versus adult female versus child) were specified prior to measurement. See Watanabe (2001) for additional details.

Spectral analysis of child speech poses a unique challenge. In addition to a propensity for breathiness, the high frequencies of child voices mean harmonics are widely dispersed so it is easy to undersample the spectral shape. Consequently, the bands of energy that represent formant frequencies may not manifest in the spectrogram. There have been different approaches to this problem: automatically track formants and exclude outliers beyond 2SDs (Lee et al. 1999) or exclude problematic tokens and average measurements from hand-verified linear predictive coding (LPC) spectra and spectrograms (Sussman et al. 1996). For this analysis, following automatic formant tracking, the first and last time points were removed to avoid coarticulatory influence. Then, audio was resampled at 14kHz. The first author, a trained phonetician, hand-verified and corrected F1 and F2[3] measurements via comparison with peaks in LPC spectra (displayed with a 12ms Gaussian window) and spectrograms with and without formant overlay in Praat. The number of peaks specified for the LPC spectra varied from 8-14 (usually 12), depending which displayed formants clearest.

In all, N=192 tokens of child speech and N=37 adult were removed, generally because breathiness or frication rendered a formant immeasurable. The first author also removed tokens if she could not disambiguate formants, even after specifying a different number of spectral peaks. Because we are examining the relationship between F1 and F2, if it was not possible to measure a formant, the entire vowel was removed. N=8106 child vowels tokens and N=1698 adult remained (table 2).

Vowel category dispersion was computed via the Mahalanobis distance:

$$D^2 = (x-\mu)^T \Sigma^{-1} (x-\mu)$$

[3] Like many languages without contrastive rounding, F1 and F2 serve to distinguish all vowel contrasts in CQ.

where μ is category mean, T the number of observations, and Σ the covariance matrix. Mahalanobis distance is a normalization metric that can reflect oblong dispersions common in 2D acoustical space (Kartushina & Frauenfelder 2014). It improves upon standard deviation alone by taking into account covariances *between* vectors. Dispersion was calculated separately for each vowel of each speaker.

Table 2: Token counts by vowel

	5;0-6;0	7;0-8;0	9;0-10;0	ADULTS	TOTAL
/a/	996	1164	2454	924	5538
/i/	279	345	810	393	1827
/u/	336	501	1221	381	2439
TOTAL	1611	2010	4485	1698	9804

5. Results
5.1. Vowel category analysis

Statistical analyses were carried out in R (R Core Team 2015) using the `lme4` (Bates et al. 2015), `lmerTest` (Kuznetsova et al. 2013), and `phonR` (McCloy 2016) packages. Figure 1 displays the acoustical space and vowel categories of each age group, Bark normalized. The direction of some vowel categories' dispersion changes over development. For example /a/ is more stable in the adult speakers than any of the child groups, particularly along the F1 axis. However the adults have a more dispersed /u/ category than most children.

To test the significance of these differences, a linear mixed effects model was fit to the category dispersion measurement (Mahalanobis) (see 4.3). A low Mahalanobis score means that the measurement is closer to the category mean. The model was fit in a forwards testing procedure, beginning with a baseline model (only random effects). Parameter selection was determined via AIC values and log-likelihood comparison. Alone, none of the fixed effects of **age group**, **vowel** (/a, i, u/), or (normalized) **vowel duration** improved model fit – the final model only included the interaction **age_group*duration**, with random slopes for each speaker's vowels. This indicates that, counter to acoustical narrowing, CQ vowel category dispersion does not reliably differ by age. Instead, the significant interaction of age and duration means that differences in dispersion by age group depend on vowel duration.

Figure 2 maps the relationship between duration and dispersion by age group. 5;0-6;0 children's categories are a bit more dispersed than the other age groups' for 150-350ms vowels. However, overall, the age groups pattern closely. The only significantly different pattern that the model predicts is 9;0-10;0 have more dispersed categories for the shortest vowels. Note that the interaction with vowel was not significant so this is consistent across /a, i, u/. This finding runs counter to most findings concerning acoustic reduction in fast speech (Ernestus 2014) as well as the other age groups' patterns.

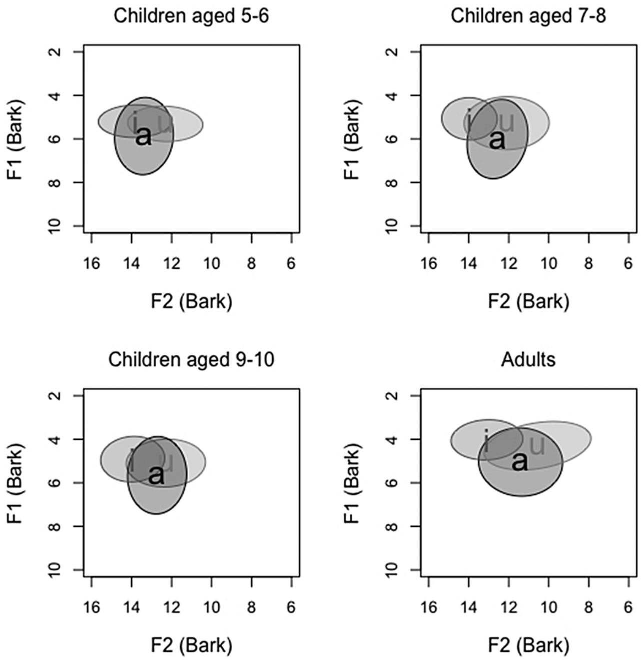

Figure 1: Vowel category dispersion, all speakers. Ellipses represent 1 SD from category mean (represented with IPA symbol).

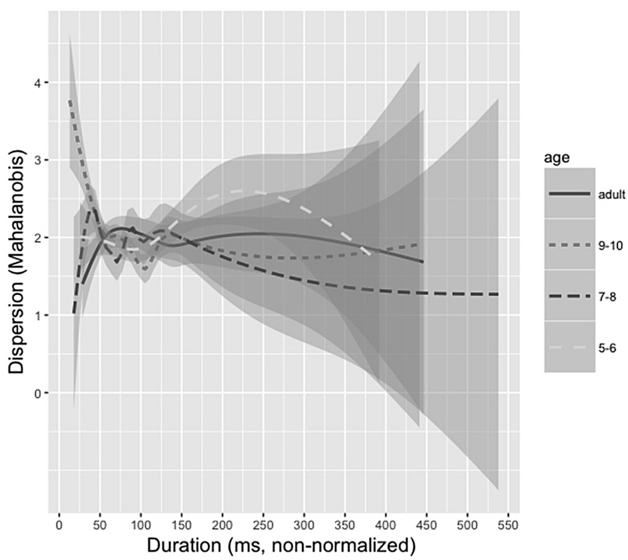

Figure 2: Vowel category dispersion by duration, raw data. Gray bands represent 95% confidence intervals.

5.2. Morphological analysis

The second analysis tested the effect of word structure on each phoneme’s dispersion. Figure 3 demonstrates how suffixes make up a smaller portion of the acoustic space and the vowel categories overlap more. This suggests that the vowels in suffixes may be more acoustically reduced than in roots.

To test these differences, a second linear mixed effects model was fit with the same procedure as in 6.1 but included the binary variable **morphological status** (suffix or root). Best model fit included the interaction of **morphological_status*age_group*vowel** fit with random slopes for each speaker’s vowels (table 3). This interaction indicates that while there may be a reliable relationship between morphological status, root or suffix, and category dispersion, there are important caveats by age group and vowel.

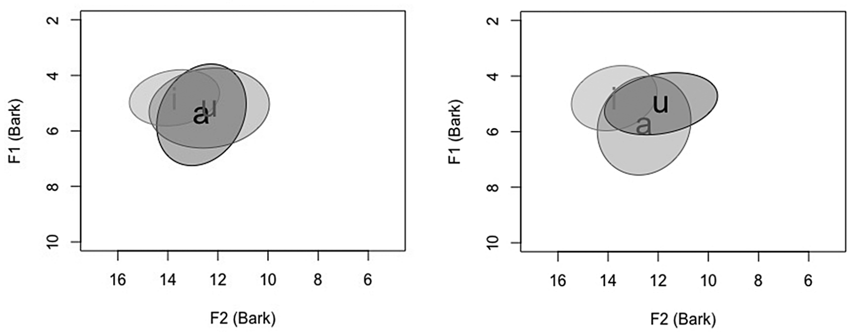

Figure 3: Dispersion by morphological status: suffixes (L), roots (R). Ellipses represent 1 SD from category mean (represented with IPA symbol).

Table 3: Fixed effects structure: Morphological factors model[4]

VARIABLE	β	*SE*	*t*	*p*
(INTERCEPT)	1.99776	0.09849	20.284	***
MORPH*5;0-6;0*/i/	-2.17275	0.54387	-3.995	***
MORPH*5;0-6;0*/u/	-0.07697	0.47493	-0.162	n.s.
MORPH*7;0-8;0*/i/	-1.68674	0.68664	-2.457	*
MORPH*7;0-8;0*/u/	1.01686	0.44483	2.286	*
MORPH*9;0-10;0*/i/	-1.87659	0.47476	-3.953	***
MORPH*9;0-10;0*/u/	0.56655	0.38110	1.487	n.s.

To illustrate this interaction, figure 4 plots category dispersion by age and vowel. Vowels in suffixes are more dispersed than vowels in roots but this is specific to adults and children 7;0-8;0. 5;0-6;0 actually show the reverse. Furthermore, while /i/ shows similar amounts of dispersion across suffixes and

[4] Only parameter levels of the interaction **morphological_status*age_group*vowel** listed.

roots, /u/ is more dispersed in suffixes than roots. Overall, the results seem to confirm that category dispersion differs between stems and morphemes, but the effect is far from universal in the language or across speakers.

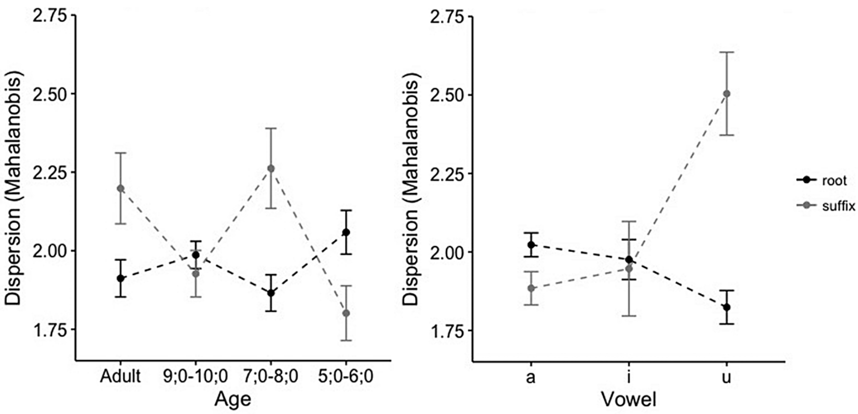

Figure 4: Mean dispersion by morphological status and age (L), vowel (R). Error bars represent standard error from the mean.

6. Discussion & Conclusion

This study tested two hypotheses. The first questioned a robust finding from developmental phonetics which we termed acoustical narrowing: as children age, spectral variability in their vowel production decreases. We asked if this same pattern applied in a language with fewer vowel contrasts and results suggest that vowel inventory size mitigates child speech variability. To avoid category overlap and perceptual confusion, languages with large vowel inventories, like English and French, evolved to constrain their acoustic variability. It takes children acquiring these systems many years to fine-tune their phoneme categories. For languages like CQ that permit more category dispersion, children can reach adult-like levels at a younger age. Our findings suggest that children learning CQ have mastered category dispersion by 5;0. This means that acoustical narrowing may not stem entirely from children's anatomical limitations, as previous research assumed. We may need to reevaluate findings on acoustical narrowing in the context of the languages that supplied the data.

Future research, including study on vowel development in infants, should heed the conclusion that phonological structure may interact with phonetic development. For example, Polka et al. (2014) synthesized /i/ and /a/ tokens that resembled infant speech and found that infant participants could distinguish vowels in the synthesized infant-like speech. Since all tested infants were acquiring English or French, an interesting follow-up would be if infants exposed to languages with three or five vowel contrasts could also distinguish /i/ and /a/ since their ambient vowel categories may overlap and/or disperse more.

The second hypothesis tested the effects of morphological status on vowel category dispersion. We showed that vowel category size differed across roots and suffixes, but this was dependent upon age group and vowel. For example, /i/ and /a/ showed little difference in category dispersion across stems and suffixes, but /u/ was more acoustically variable. The articulatory demands of a high, back, round vowel could explain this. Unlike /a/ and /i/, /u/ requires both tongue movement (back to the velum) and lip rounding. However, this explanation does not seem likely as 5;0-6;0 /u/ production did not differ significantly from adult /u/. If articulatory maturation explained /u/ variability, we would expect the effect to be greatest in the youngest speakers.

Phoneme frequency could address the /u/ variability. Vowel frequency was measured in a 25,415-word CQ dictionary lexicon (Heggarty 2006) consisting of suffixes (*N*= 251) and roots (*N*=44,183).[5] In the lexicon, /a/ is the most frequent vowel in both suffixes and roots. /i/ is slightly less frequent than /u/ in roots (*N*=19,948 versus *N*=21,486), but in suffixes, /i/ is nearly twice as frequent as /u/ (*N*=122 versus *N*=63). The infrequency of /u/ in suffixes could account for its variability. Speakers have less opportunity to master the required lingual and labial configuration. There is evidence in L1 phonology that children first master segments that are highly frequent in the ambient language (Edwards & Beckman 2008) and that production varies by word position (Gierut & Storkel 2002). We may be seeing evidence of frequency-based formant realizations. This is another reason to factor language-specific structure into developmental studies.

Still, in the analysis of morphological effects, there are confounding factors. Though highly agglutinating – adult nouns and verbs often append four or five morphemes – CQ morphology is exclusively expressed on the ends of words. The finding that vowel dispersion differs between suffixes and stems could just as well originate from the tendency to reduce word-finally. The relationship between predictability and acoustic reduction in agglutinating languages is unexplored. Still, results from adult English speakers show that duration negatively correlates with word predictability (Jurafsky et al. 2001): the more predictable a word, or part of a word, the more reduced it will be. With more developmental data on agglutinating languages, we can evaluate prefixes or infixes as well and control for word position effects. A finer-grained distinction between the form, function, or location of suffixes may elucidate acoustical differences. For example, some suffixes are more frequent than others, and thus more fused to the stem.

Although we demonstrated how a language's structure plays a role in phonetic development, we want to caution against over-interpreting the results. For one thing, there are some methodological differences between this study and those that documented acoustical narrowing. Lee et al. (1999) collected vowel

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[5] CQ is relatively orthographically transparent so dictionary entries correlate well with actual pronunciation.

data from words in carrier phrases and Ménard et al. (2007) analyzed vowels produced in near isolation. We used data from semi-guided narratives conducted in locations familiar to participants (home, school). The naturalistic data in McGowan et al. (2014) showed why this task difference is relevant. In that study, the children's formant variability did not decrease with age. So perhaps acoustical narrowing *is* a universal developmental trend but only manifests in more formal speech registers where adults carefully hit acoustic targets. Still, the children in McGowan et al. were much younger than those studied here or in previous studies. Their data are also more naturalistic than our semi-guided narratives. A future study should study phoneme category variability in elicited tokens to tease apart the effects of task type and language structure.

This study tested if language structure – vowel inventory size and morphological composition – mitigates a developmental trend in 5;0-10;0 speakers of Chuquisaca Quechua (CQ). Our results suggest that if children learn a language with a smaller vowel inventory, they attain adult-like levels of acoustic variability at a younger age than previously reported for languages with large inventories. This effect is also not uniform throughout the word. In CQ, a language with agglutinative morphology, roots contain more acoustically stable acoustic vowel phonemes than suffixes. We attributed this to the frequency of vowels in suffixes versus roots. These findings shed new light on how children acquire adult-like phoneme categories while underscoring the importance of understudied languages for developmental phonology theory.

Appendix 1: Chuquisaca Quechua consonant inventory

	LABIAL	DENTAL	POST-ALVEOLAR	PALATAL	VELAR	UVULAR	GLOTTAL
PLOSIVE	p	t	tʃ		k	q	
ASPIRATE	p^h	t^h	$tʃ^h$		k^h	q^h	
EJECTIVE	p’	t’	tʃ ’		k’	q’	
FRICATIVE		s	(ʃ)				h
NASAL	m	n		ɲ			
TAP		ɾ					
LIQUID		l		ʎ			
GLIDE	w			j			

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