

Acoustic cues to stop-coda voicing contrasts in the speech of 2-3-year-olds learning American English

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Stevens (2002) postulates that speakers represent words in terms of distinctive features, with different acoustic cues signaling the feature contrasts in different contexts. Imbrie (2002) suggests that children use cues differently from adults in word-onset consonants. This paper explores these differences for word-final stops, using detailed acoustic analyses of cues to the voicing contrast in 2 children (2;5 and 3;2). Voiced coda stops were associated with a long voice bar during closure and an epenthetic vowel after release; voiceless coda stops with noisy and/or glottalized voice quality toward the vowel end, suggesting that incomplete control of gestural coordination, immature planning ability, or non-adult-like decisions about enhancing feature cues, may persist even after the child is producing recognizable stops.

1. Introduction

One of the most striking characteristics of early child productions is their variability in form. Even for a CVC monosyllable like *dog*, a child's production may vary widely over time even within the same day or same conversation (e.g. *dog* → [dɔ:] ~ [dɔg^h] ~ [dɔdɔ] ~ [dɔgə]) (e.g. Vihman & Velleman 1989; Demuth, Culbertson & Alter 2006). One barrier to understanding the nature of children's variable productions has been the reliance on perception-based segmental transcription to capture the child's output. This generally requires the transcriber to make a categorical decision regarding the sound or segment the child produced. This approach has produced substantial insights into the patterns of speech and language development, but it also has several limitations. First, it may not capture all of the phonemic contrasts that the child is signaling, due to the phenomenon of covert contrast, in which the child systematically produces differences that

are not apparent to the adult (Macken & Barton 1980; Scobbie et al. 1998, 2000). Second, it does not support quantitative analysis of the presence and magnitude of the various individual feature cues that signal a target sound. Finally, segmental transcription does not provide a means for describing which individual cues the child is using, and how well the child's productions approximate the systematic variation in the acoustic shape of a phoneme across different contexts that characterizes adult speech.

Stevens' (2002) feature-cue-based model suggests a way of overcoming these limitations. This model proposes that a given feature contrast may be signaled by a number of different acoustic cues, and that the precise set of cues that a speaker employs may vary depending on the other features in the feature bundle (i.e. the phonemic segment), as well as on the segmental and structural context in which the feature occurs. This model separates the acoustic cues in the speech signal into acoustic Landmarks (robustly-detectable abrupt changes in the acoustic signal which provide information on the articulator-free features (Halle 1990; Stevens & Hanson 2010) that correspond roughly to the manner of articulation), and an additional set of cues to the articulator-bound features (such as voicing and place of articulation), which are found in the vicinity of the Landmarks (Keyser & Stevens 2006; Stevens & Keyser 2010). An advantage of this approach is that, for a given set of articulator-free features, only a limited number of articulator-bound features are relevant, and so only this limited set must be specified. This organization is illustrated in Table 1, for the word *back*.

Table 1. Distinctive features for the word *back*

	b	æ	k
<i>articulator free</i>	-sonorant -continuant	+vowel	-sonorant -continuant
<i>articulator bound</i>	+voiced +labial	+low -back	-voiced +velar

On this view, it is possible to ask not only which of the target *segments* a child produces for a given word, and which target *features* of the segment the child is signaling (as in a segment-based transcription), but also which *acoustic cues* the child is using to signal each of those features. This approach requires a more fine-grained acoustic analysis of the speech signal than does segmental transcription, and so can be time-consuming, but it has the potential to capture critical details about variation patterns in child productions, and to reveal how these details may

differ from those of the adults who provide the speech input that drives the child's developing competence. Since the appropriate selection and magnitude of cues is part of the phonological and phonetic knowledge of the adult language that the child must eventually master, we propose that this level of analysis of child speech is a critical element in the research toolbox.

Moreover, determining the nature of cue variation between parent and child, as well as among tokens produced by the child, may also help to distinguish among various models of the developmental process by which it arises. Many such models can be envisioned, with different causes for the variation that is observed. For example, the child may have an incomplete lexical representation of the word, so that the incomplete aspects may be 'filled in' differently on different occasions. Or, there may be incomplete command of various aspects of the process by which the lexical representation is translated into a set of articulatory commands, and then into acoustic form (including both planning and motor implementation). Alternatively, the child may actively choose to signal a contrast by using acoustic cues that are different from those conventionally used by the adult members of the speech community. Detailed information about the individual acoustic cues that children use to signal a contrast may help to evaluate the contribution of these different factors to the patterns of variation that we observe during development. For example, as noted above, acoustic studies have shown that children may make 'covert' (non-adult-like) acoustic contrasts in onset position; e.g. they may produce systematically different VOTs for voiced & voiceless onsets, even if both distributions are within the voiceless region for adults and are therefore not perceived by transcribers as contrastive (Macken & Barton 1990). Similarly, a child may produce a reliable acoustic distinction between /s/ & /s/+stop onsets, even though both productions are perceived as simple fricatives by adult listeners (Scobbie 1998; Scobbie et al. 2000). These observations raise the possibility that the feature contrasts for these onset segments are fully represented in the child's lexicon, even though adult listeners do not perceive all of the contrasts that the child is signaling, because of differences in the patterning of individual feature cues.

Most of the work on covert contrast has been carried out for onset consonants, but one might ask whether this kind of phenomenon occurs for coda consonants as well. Recent work by Song & Demuth (2008) suggests that this is the case. Drawing on data from the Providence Corpus (Demuth et al. 2006), they examined three children's early attempted productions of CVC target words. An example from one child is given in Figure 1, where the coda consonant was omitted in the target word *dog* (at 1;2.7 years), with an associated long vowel (CV:), but was produced at 1;4.18 as a CVC.

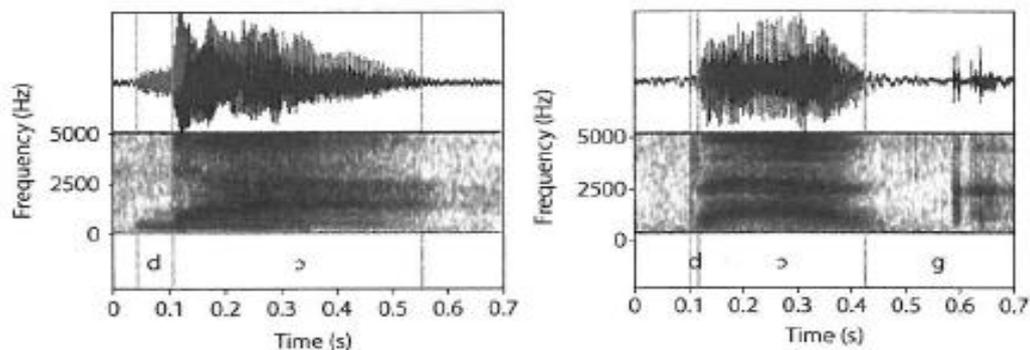


Figure 1. The same child's productions of *dog*, without a coda consonant at 1;2.7, and with coda consonant at 1;4.18

Careful examination of the duration of the vowels in the two kinds of utterances revealed a considerably longer duration for the early utterances that included no discernable coda closure or release. This suggests that the child's lexical representation included at least some information about the coda, and that she was producing compensatory vowel lengthening to signal the presence of this segment (possibly independent of coda voicing). Perhaps this can be thought of as an enhancement process, providing some feature cues that a final consonant exists, even if the articulatory/acoustic realization of these cues is not adult-like. This raises the possibility that other children who do not yet produce any coda consonants might also do the same. That is, even at a stage of development where children apparently produce no codas, there may be acoustic and/or articulatory evidence that at least some aspect of the coda segment is part of the child's lexical representation. This might be especially true for those older children (e.g. 2-year-olds) who appear to be phonologically impaired in coda production. Careful acoustic analysis could reveal if this is truly a deficit at the level of the lexical representation, or merely the lack of complete articulatory closure and/or execution of feature contrasts during production.

Moreover, such acoustic analysis may also shed light on the course of emergence of adult-like use of vowel duration to signal the voicing feature of a following coda consonant. We know that very young children show good control of vowel length (Krause 1982; Stoel-Gammon & Buder 1999); recent research has shown that even children below the age of two are capable of using extrinsic vowel duration differences to indicate contrastive coda voicing (Krause 1982; Stoel-Gammon & Buder 1999; Ko 2007). But the development of adult-like vowel duration differences associated with coda voicing has not been tracked. In preparation for such future studies, this paper examines the acoustic cues to coda stops in older children i.e. in 2-3-year-olds who are producing them in most of their target codas. We know from the work of Imbrie (2005) that children are still developing

aspects of motor control for stop consonants in onset position at the age of 3;6. Although the spectrum of the stop burst resembles adult speech, there is still poor coordination of gestures and glottal control (indicated by long VOT and variable F0) and poor control of subglottal pressure (indicated by variable amplitude across the vowel). These observations for word onset consonants raise questions about what might be found for codas.

The findings on covert contrasts noted above suggest that the variability observed in child productions of coda consonants may not always be due to incomplete lexical representations. What about immature planning or articulatory mechanisms as factors? We know that the production of grammatical morphemes can be influenced by the complexity of their phonological context; for example, articles are more likely to be produced when they can be prosodified as part of a two-syllable foot, so that the word *the* is more likely to be produced in sentences like *he [hits the] [ball]* than like *he [catches] the [ball]* (Gerken 1996, Demuth & Tremblay 2008, Demuth & McCullough 2009). Moreover, the 3rd person singular morpheme is more likely to be produced when the verb occurs in phrase-final compared to phrase-medial position, and in verbs ending in a vowel (with no coda) (e.g. *cries*) compared to verbs that contain a coda (e.g. *runs*) (Song, Sundara & Demuth 2009). Again, this is independent of the voicing of the final consonant. It would be of interest to know whether such contextual/planning constraints govern the production of non-morphemic codas as well.

Finally, another possible account of adult-child production differences is that children may enhance the acoustic cues to some feature contrasts by producing additional gestures. That is, they may produce fully voiced closures (with post-release vowel epenthesis) for voiced coda stops, but silent closures (with heavy post-release noise) for voiceless coda stops. These contrastive cues are not typically observed in adult speech, although they can sometimes occur. (We note that these additional cues may provide information about place contrasts as well: vowel epenthesis provides more cues to the place features of the stop consonant in the formant transitions after the coda stop release, while multiple release bursts provide strong place cues.) One line of evidence that appears to support this possibility is the finding reported by Demuth et al., (2006) that some children's early utterances containing coda stops (around age 1;2) showed non-adult-like patterns of epenthetic vowels and heavy aspiration at the release, and that these additional cues disappeared as the child reached the age of 1;5 (see also Vihman & Velleman 1989). This is shown in Figure 2. Informal observation suggests that the epenthetic vowels were more commonly produced following voiced codas, with the heavy release noise more commonly produced before voiceless codas. This observation would be consistent with an enhancement view. One of the goals of the present study is to confirm this observation by acoustic measures of tokens with both voiced and voiceless stop codas.

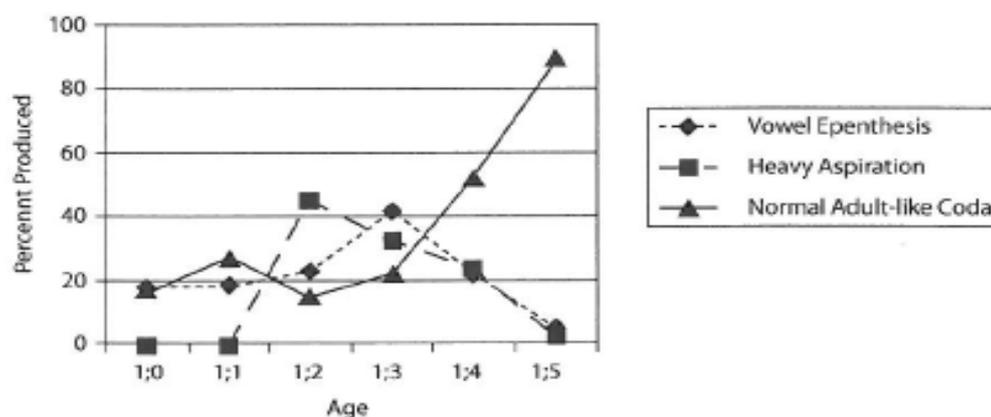


Figure 2. One child's realization of CVC target words as epenthesized (e.g. [dɔgə]), heavily aspirated (e.g. [kæt^h]), or a normal (e.g. [dɔg], [kæt]) coda releases

Our approach is to identify candidate cues for the voicing feature of coda stops in child productions and observe how often each is produced for voiced vs. voiceless codas. These binary observations of presence vs. absence of a cue will provide one kind of quantitative information, and will also facilitate the future development of acoustic measures to quantify differences in the strength of individual cues. Our assumption is that by focusing on the individual *feature cues*, rather than the segments, these studies will provide insights into the nature of the child's lexical representations, and into the mechanisms that underlie surface variation. We focus on coda consonants here, because they have been little studied in comparison to onsets, and because they are the locus of English grammatical morphology (e.g. the plural marker for nouns, and the third person singular and past tense markers for verbs). The substantial variability that has been observed in the production of these morphemic markers during development (e.g. Brown 1973) may also interact with the acquisition of the general ability to produce codas and coda clusters. This information will therefore be important for constructing a developmental model of planning and production. In this study we examine the acoustic cues that children produce for the voicing contrast in coda stop consonants during the 6 months just after the age of 2;6 (child F1) and 3;2 (child M1), i.e. at a point when these children were producing audible coda stop segments.

2. Methods

The data we examined were drawn from the Imbrie Corpus (Imbrie 2005), which consists of recordings from 10 children learning American English. The present study included data from 2 children (a girl – F1, age 2;6, MLU (Mean Length of

Utterance) = 4.4 words, and a boy – M1, age 3;2, MLU = 3.7 words). These two children were recorded every 4–6 weeks for 6 months. A set of 20 target words was elicited multiple times in each session, via interactive play using pictures and objects. In this study we examined data from codas at two places of articulation, velar and labial, in utterance-final position. The target words include four high-frequency CVC monosyllables with the same vowel: two with velar codas /g/-/k/ (*bug* vs. *duck*, 53 and 70 tokens respectively), and two with bilabial codas /b/-/p/ (*tub* vs. *cup*, 63 and 72 tokens respectively). To ensure that a coda was present, only those tokens with a coda release were included. All were taken from final position to ensure comparable position effects. Any item with poor acoustic quality due to background noise was excluded from the analysis. The presence vs. absence of five separate acoustic cues to voicing of the coda consonant was coded by hand. These are outlined in (1).

1. Acoustic cues coded

- Voice bar (VB): low-frequency periodicity during closure (i.e. continued periodicity after the abrupt drop in amplitude that signals closure for the coda consonant); cf. Figure 3
- Epenthetic vowel at release of coda (epen): voicing with vowel-like formants after release, cf. Figure 3
- Presence of noise at the end of the V before closure (noi): often called pre-aspiration in the literature; cf. Figure 4
- Substantial noise after the release of the coda (coded as *asp*, although its source is still uncertain and may include considerable frication); cf. Figure 4
- Glottalization in V (glot): irregular, creaky-sounding pitch periods during the vowel; cf. Figures 5a and 5b

An example of the voiced coda /g/ in the target word *bug* is shown in Figure 3, which illustrates a voice bar (VB) after the abrupt diminution of amplitude and disappearance of the second formant that indicates closure, and a post-release epenthetic vowel (epen).

In contrast, Figure 4 provides an example of the word *duck*, which shows a closure period with no voice bar, followed by a heavy post-release noise (*asp*) and no epenthetic post-release vowel. Interestingly, this token also shows a period of noise at the end of the vowel (*noi*), just before the silent closure period; similar phenomena have sometimes been called pre-aspiration (e.g. Gordeeva & Scobbie 2007).

Another acoustic cue associated with voiceless codas in American English is the occurrence of irregular ('glottalized') pitch periods. In adult American English speech, a glottalized region at the end of the vowel in a CVC is quite common

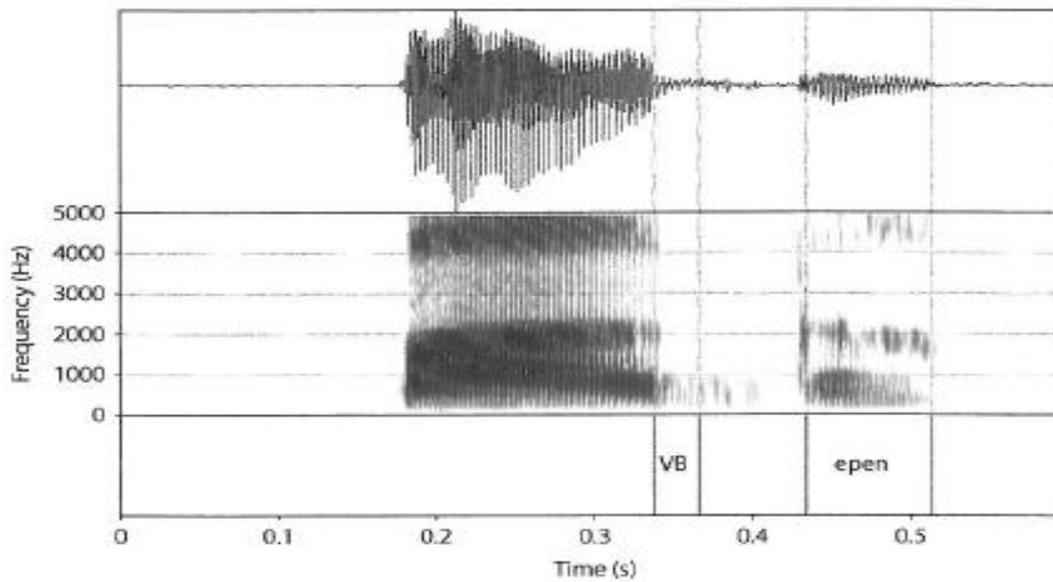


Figure 3. *Bug* with voice bar (VB) and post-release epenthetic vowel (epen) (child F1)

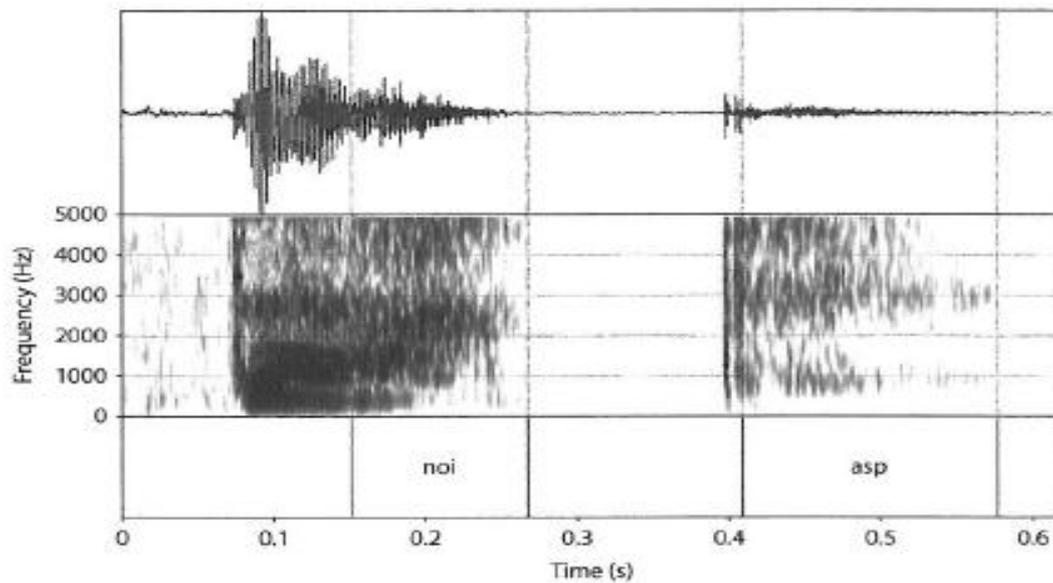


Figure 4. *Duck* with pre-aspiration (noi) and heavy post-release noise (asp) (child F1)

when the coda consonant is a voiceless stop, particularly /t/, but the developmental course of the emergence of this cue in child speech has not been investigated. An example from child F1 is shown for the target word *duck* in Figure 5 (normal (a) and expanded (b) views).

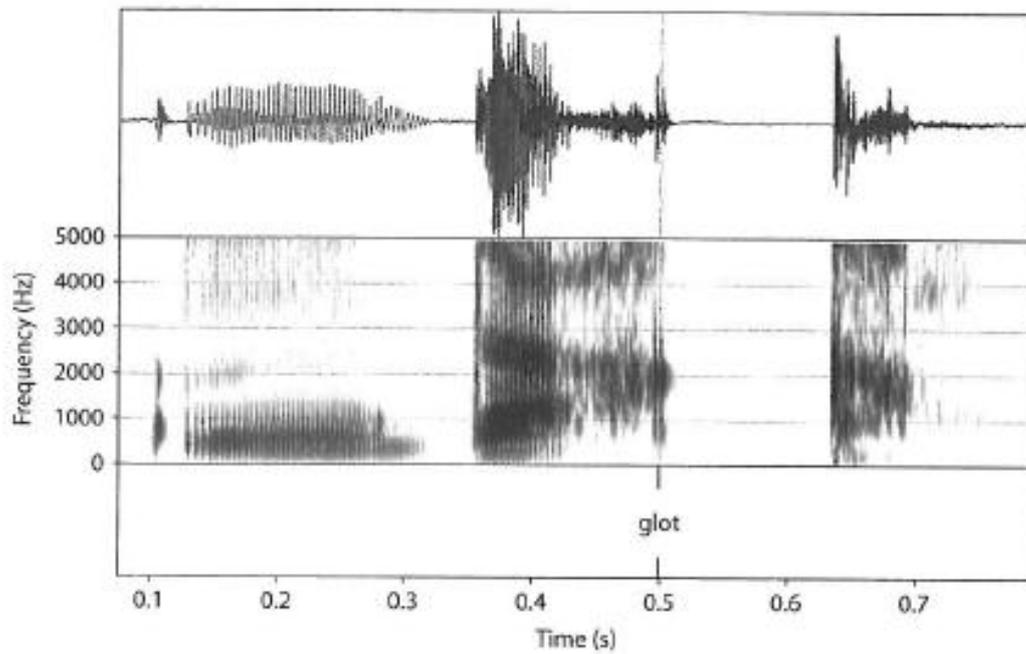


Figure 5a. Final voiceless velar stop with glottalization (target word *duck*, at 3 to 7 seconds, produced by child F1)

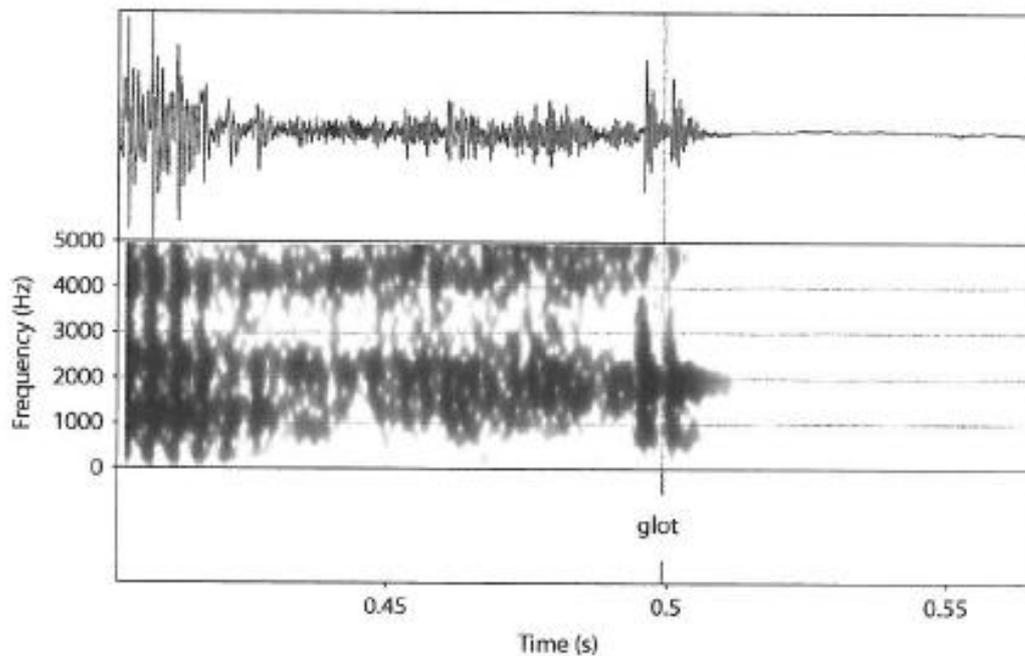


Figure 5b. Expanded view of final voiceless velar stop, showing long decay time of the two final glottalized pulses

Using a combination of visual inspection of the waveform and spectrogram, and auditory perception of the signal, the labeler coded each word token for the presence or absence of each of the 5 cues. A second coder labeled 15% of the data,

with 93% agreement. We predicted that voice bar and epenthesis would be most likely to occur in the context of voiced codas, whereas noise and aspiration would be most likely to occur in the context of voiceless codas. It was not clear in which context glottalization would be most likely to appear, because all tokens were utterance-final, and this is a location in which irregular pitch periods are likely to occur in general. However, adult patterns suggested an additional preference for irregular periods with voiceless coda stops in English. We also did not know what percent of voiced/voiceless tokens would be accompanied by these acoustic cues, and the extent to which this would be similar across the two children.

3. Results

In general, the results showed that both children were producing contrasting sets of cues for the voiced vs. voiceless coda stops. This is shown for the velar codas /g, k/ for child F1 and child M1, in Figures 6a and 6b, respectively.

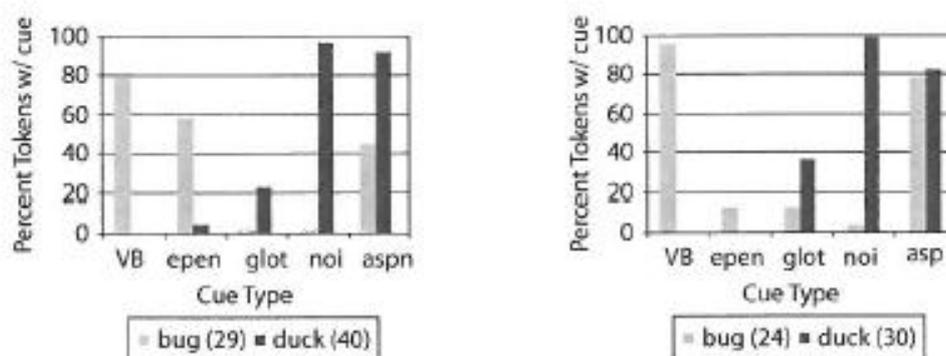


Figure 6. (a) F1's cues to velar voicing contrasts; (b) M1's cues to velar voicing contrasts

For F1, as expected, when a voice bar occurred, it was associated with voiced velar coda /g/ contexts. Many of these /g/s also have an epenthetic vowel after release. Both of these cues can be thought of as increasing the acoustic evidence for the feature [+voice]. In contrast, noise at the end of the vowel before the silent closure period is associated with the voiceless velar coda /k/; in fact, most of the /k/ codas have this noise, and also show post-release noise. In addition, slightly more of the voiceless than voiced velar codas show some evidence of glottalization during the vowel, but this distinction is not as extreme as for the other four cues. Similar results are shown for M1, although his voiced velar codas show fewer epenthetic vowels than those of F1, and have approximately the same frequency of post-release noise as his voiceless velar codas.

In summary, these two children exhibit systematic cues to voicing contrasts for velar codas. That is, for the voiced coda they tended to produce a substantial voice

bar at the beginning of (or throughout) the stop closure, and an epenthetic vowel after the release, whereas for the voiceless codas they tended to produce noise at the end of the vowel and (for F1) heavy noise after the release, with a tendency to favor glottalization before voiceless codas. Moreover, this cue distribution is somewhat different from what is typically reported in adults: F1 produced epenthetic vowels liberally for voiced codas, and both produced substantial noise at the end of the vowel for voiceless codas. To help interpret these results and maximize their possible value in distinguishing models based on articulatory/planning immaturity vs. feature enhancement mechanisms, we need to know how robust these cues are across place of articulation. For example, if the noise at the end of the vowel that we observe for the voiceless velar consonant /k/ is produced by oral constriction (i.e. by early movement of tongue dorsum toward velar closure during the vowel, producing a constriction which causes turbulence noise), then it may not occur for labial stops. In contrast, if this noise is the result of aspiration produced at the vocal folds, then it may occur for the labial stops as well for the velars.

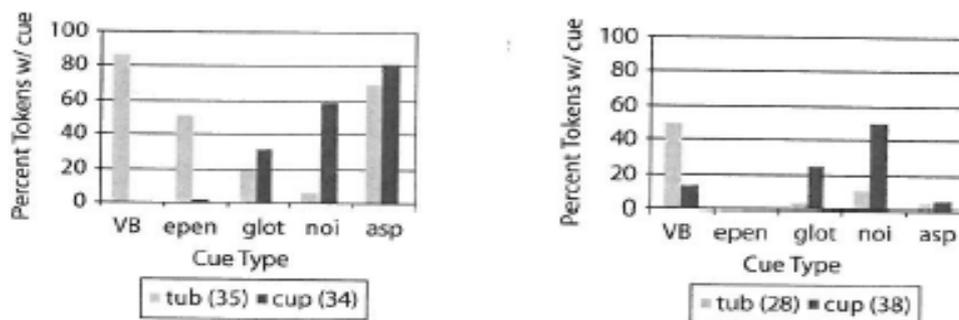


Figure 7. (a) F1's cues to labial voicing contrasts; (b) M1's cues to labial voicing contrasts

Figure 7 shows the pattern of noise at the end of the vowel (noi) for the labial coda stops: as for the velar codas, more of the voiceless stops show this cue than of the voiced. Note that for F1, as in M1's velar codas above, noise after the coda release (asp) occurs in a high percentage of tokens for both voiced and voiceless codas, while for M1, a noisy release is not produced for either voiced or voiceless labial codas; it appears that the two children differ substantially in their production of this cue, but only F1's results for velar codas are consistent with the possibility that it is used to signal the voicing contrast. In other respects the results for the labial codas are similar to those for the velars: many of the voiced codas show a voice bar, and (for F1) many have an epenthetic vowel after the release, whereas most of the voiceless codas do not exhibit either of these two cues. Finally, glottalization occurs less frequently than some other cues, although both speakers have more glottalized tokens for voiceless /p/ codas than for voiced /b/, just as was true for the velars.

In sum, the feature cues produced by these children appear to enhance voicing contrasts, across the two places of velar and labial articulation. However, we note that for M1, the contrasts for the labials are weaker than they are for his velars, perhaps indicating a still-developing voicing contrast for this place of articulation. In addition, the degree to which noise follows the release of the coda consonant appears to be unstable across both subject and place. It does not appear that either of these two children is using this cue systematically to signal the distinction between voiced and voiceless stops.

4. Discussion

One of the goals of this study was to determine which acoustic cues to voicing contrasts (other than extrinsic vowel length) young children use. The second goal was to determine from these findings, if possible, the source of these acoustic cues, and whether any unexpected cues were due to aspects of the coordination of articulatory gestures, or due to processes of feature cue enhancement. For example, what is the source of the noise produced at the end of the vowel before voiceless codas by these children? In adult English, the release of unvoiced aspirated stops is typically modeled as having three phases (Hanson & Stevens 2003):

Phases of adult release of unvoiced aspiration stops

1. the **transient**, when the pressure behind the constriction is released and the resulting abrupt increase in volume velocity *excites the entire vocal tract*;
2. a period of **frication**, when turbulence noise generated at the supraglottal constriction *excites primarily the cavity in front of the constriction*;
3. a period of **aspiration**, when turbulence noise generated near the approximating vocal folds *excites the entire vocal tract*.

These 3 phases are expected to overlap somewhat in time, but each is expected to be marked by the dominance of one type of excitation. Close examination of stop releases in the Hanson & Stevens (2003) study reveals that the aspiration phase (3) is more complicated than has been assumed: some speakers produce a mix of frication and aspiration during the third phase, rather than a clearly-defined sequence of these two noise sources. The additional frication that overlaps with the aspiration appears to be generated at the original supraglottal constriction; that is, its spectral characteristics are similar to those of the burst. This raises the question of where in the vocal tract the noise at the end of the vowels produced by these children is being generated. That is, is it generated at the larynx, as aspiration, or at the still-forming supra-glottal constriction for the coda, as frication? If it is the latter,

then it may represent the early formation of the constriction for the coda stop consonant; if the former, then it may represent a non-adult-like coordination between the supra-glottal and laryngeal articulations. If this noise is generated via early spreading of the vocal folds, then it would suggest that final voiceless stops may have a different mechanism for cutting off vocal fold vibration than initial stops.

The fact that this noise can occur near the moment of closure for both labial coda /p/ and velar coda /k/ raises the possibility that, for these children, it serves as an enhancing cue for the feature [-voice]. Future work examining the occurrence of such noise cues near the closure for the coda in the speech recorded from the adult caretakers of these children, as well as spectral analysis and articulatory measures (using ultrasound), may help to delineate the articulatory source of this noise, and shed some light on its significance for models of phonological and phonetic development.

In examining the child's use of acoustic cues to distinctive features, we must first ask what the child is doing with her larynx and vocal tract, as indicated by the acoustic result of these articulatory gestures. We can then ask, why are these events occurring, particularly when they are different from those we observe in adult speech. Do they arise from immature motor control, planning abilities, or lexical representations? Or are they the result of the child's decision to enhance feature contrasts in early word production? The results presented here are consistent with the hypothesis that children often signal feature contrasts by producing voice bars and/or epenthetic post-release vowels for voiced /b, g/ codas, and noise or irregular pitch periods at end of the vowel for voiceless /p, k/; the distribution of heavy post-release noise is less reliably governed by the voicing contrast. These results are robust across the two children observed at this age (between 2;6 and 3;9), and many of the same phenomena have been observed in younger children as well (Demuth et al. 2006). Substantially more detailed and quantitative acoustic analysis is needed to fully evaluate these proposed mechanisms of variation across children, at different periods of development, and across different languages. However, even in its current preliminary stage, this work illustrates our belief that, in order to determine the nature of children's early lexical representations and processing capacities, it is necessary to analyze the *individual feature cues* in the signal, rather than the features and segments alone, and to take account of *variation in these cues* across tokens, contexts and speakers.

Acknowledgments

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