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The Gradual Acquisition of English /l/

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1. Introduction

One of the fundamental issues in developmental phonology is why some speech sounds are acquired early whereas others are acquired much later (e.g. Prather, Hendrick, and Kern, 1975; Hare, 1983; Dyson, 1988; Smit, Hand, Freilinger, and Bernthal, 1990). We speculate that there are at least two issues at play: articulatory control and learning the phonology of the native language.

With respect to the need for articulatory control, we posit that children must develop proper motor control over the primary speech organs, including the tongue, lips, vocal folds (required for voicing) and velum (required for nasal consonant and vowel contrasts). It is plausible that motor control for some organs takes longer to develop than others, either due to inherent physiological difficulty of manipulation, or due to frequency of use in non-speech contexts.

Children must develop a phonology appropriate to their native language community. In particular, they must develop contrasts between speech sounds used by adults of their speech community, and lose contrasts that are not relevant to their speech community. Language users often contrast sounds that are acoustically similar, and it has been shown that these contrasts can take longer than others to develop (e.g., Narayan, Werker, and Beddor, 2010).

In this study, we are primarily interested in children's articulatory control over the tongue. One property common to many of the most protracted sounds in acquisition, such as the liquids /l/ and /ɹ/ and the affricates /tʃ/ and /dʒ/, is that they involve the coordination of multiple lingual gestures. That is, in the speech of adults, typical production of these sounds requires movement of the tongue to form more than one constriction against the palate. In contrast, some of the earliest acquired speech sounds, the nasal stops /m/ and /n/, and the labiovelar glide /w/, involve coordination of a single lingual gesture with another non-lingual gesture. In production of the nasal stops /n/ and /m/, speakers must simultaneously lower the velum, allowing airflow to be rerouted through the nasal cavity, and form an oral closure, provided by the lips in /m/ and by the tongue tip in /n/. The glide /w/ requires partial constriction of both the lips and of the tongue body with the palate (Ladefoged, 1993; Johnson, 2003).

Laterals are particularly relevant, due to their articulatory complexity and protractedness of acquisition, with word-initial (onset) /l/ typically acquired

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between 3;0 and 4;0, but word-final (coda) /l/ not generally acquired until after 5;6 (Smit et al., 1990)[1]. Our primary goal in this study was to better understand how and when onset and coda /l/s are acquired by examining the children's development of articulatory gestures in singleton onset laterals (e.g. *leap*) and coda laterals (e.g. *peel*).

Most research in phonological development to date has focused on impressionistic judgments of segmental accuracy. More recently, however, acoustic analyses of children's speech have unearthed some of the inadequacies of impressionistic coding of child speech. In particular, several studies have shown that children are capable of producing native phonemic contrasts that are imperceptible by adult listeners, but are revealed to be acoustically distinct through spectral analysis (Macken and Barton, 1980a,b; Scobbie, Gibbon, Hardcastle, and Fletcher, 2000; Li, Edwards, and Beckman, 2009). We posit that if quantitative analysis of acoustic recordings can reveal such "covert" contrasts, articulatory imaging should be capable of revealing even more about phonetic and phonological development.

While methods for directly measuring lingual motion during speech have been utilized in speech research for decades, such work has been almost exclusively performed on adult speakers, due to the inherent intrusiveness of these technologies (e.g. X-ray palatography, Sproat and Fujimura, 1993; cinefluorography, Giles and Moll, 1975). More recently, speech researchers have been capturing vocal tract motion in speech using relatively non-invasive techniques such as ultrasound (Gick, 2003; Gick, Cambpell, Oh, and Tamburri-Watt, 2006) and real time MRI (Byrd, Tobin, Bresch, and Narayanan, 2009) imaging, including with children (e.g. Song, Demuth, Shattuck-Hufnagel and Ménard, 2010; Scobbie, Lawson, and Stuart-Smith, 2012). During ultrasound imaging of the tongue, a transducer is placed against the participant's chin pointing upwards into his or her oral cavity. The transducer emits ultrasound waves into the participant's skin and flesh, which are reflected off air above the tongue, and subsequently interpreted by the ultrasound engine as a bright line in the center of the resulting image. For comfort and safety, we elected to use ultrasound imaging for data collection in this study.

2. Methodology

2.1. Participants and stimuli

Data from seventeen children between the ages of 3;0 and 7;11 (6M, 11F; mean age 4;7) are presented in this study. All participants were typically developing monolingual leaners of Australian English recruited from the greater Sydney region, and were thus generally exposed to a variety of Australian English without post-vocalic /l/-vocalization (Horvath and Horvath, 2002). Data from four additional child participants were collected but not analyzed, as they

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[1] Smit et al. (1990) defined "typically acquired" as over 80% of utterances being transcribed as being perceived as accurate by phonetically trained adult transcribers.

were unable to complete the task. Five adult monolingual speakers of Australian English raised in or around Sydney were also recruited to provide adult comparisons. The adult speakers were all undergraduate volunteers with no reported speaking or hearing impairments. The number and gender of participants in each age group are listed in Table 1.

Table 1. Age and gender of child and adult participants.

	Age (years)					
Sex	3	4	5	7	Adult	**Total**
Female	4	3	3	1	5	**16**
Male	3	1	0	2	0	**6**
Total	**7**	**4**	**3**	**3**	**5**	**22**

The elicited stimuli, listed in Table 2, were high-frequency, imageable monosyllabic CVC words, where either the onset or coda was the lateral /l/. We also included two CVC words with /w/ onsets, to act as controls, as onset /w/ is one of the earliest acquired segments in English phonological development (Smit et al., 1990). In every target /lVC/ or /CVl/ stimulus, the non-target consonant was at either the labial or velar place of articulation. This helped minimize the potential coarticulatory effects of alveolar consonants on tongue tip motion in the target lateral. For similar reasons, in each /wVC/ stimulus word, the coda consonant was the alveolar stop /t/.

Table 2. Elicited stimuli and typical IPA pronunciation for adult Australian English speakers.

/w/ onset		/l/ onset		/l/ coda	
wheat	[wiːt]	*leap*	[liːp]	*peel*	[pʰiːɫ][2]
weight	[wæɪt]	*lake*	[læɪk]	*mail*	[mæɪɫ]
		lip	[lɪp]		
		lap	[læp]		

2.2. Procedure and equipment

Stimuli were collected from participants using an elicited imitation task. Participants sat in front of a computer monitor and were presented with a cartoon image representing the target stimulus, without an orthographic representation, which was accompanied by an audio prompt. The audio prompts were pre-recorded productions of the target stimuli spoken in isolation by a female native speaker of a non-vocalizing variety of Australian English. Participants were asked to repeat the word in the audio prompt, and were rewarded with stickers and praise. Prior to the task, participants were given up to

[2] Coda /l/s are generally transcribed as the "dark" variety [ɫ] while onset /l/s are transcribed as the "light" variety [l] in Australian English transcriptions, despite evidence that both onset and coda /l/s in Australian English are often perceptually "dark."

two practice trials in order to familiarize them with the task and stimuli. Presentation stimuli were blocked and randomized, and between three to five repetitions of each item were elicited from each participant.

While participants produced target stimuli, midsagittal (bisecting the oral tract into right and left) ultrasound images of participants' tongues were recorded using a Terason t3000 ultrasound system running Ultraspeech 1.1 (Heuber, Chollet, Denby, and Stone, 2008). Ultraspeech simultaneously recorded video of the participants' lip movements as well as audio of their speech. Both lip motion and lingual ultrasound videos were recorded at 60 frames per second, and were synchronized with the audio stream with a margin of error of one frame, or up to ±16.67 ms. The ultrasound transducer was stabilized in relation to the heads of adult participants using an ultrasound stabilization helmet from Articulate Instruments, Ltd. However, due to their young age, the helmet was not used with child participants. In lieu of mechanical stabilization, the first author held the transducer under the child's chin, while monitoring the ultrasound and video images to ensure that the transducer remained positioned properly. The task took each participant approximately 10-20 minutes to complete. Figure 1 shows sample video ultrasound images from one child participant. The bright white curve in the center of the ultrasound image is the trace of the tongue, with tongue blade and tip towards the right and tongue root towards the left.

2.3. Analysis: Perceptual coding

Audio from all utterances were perceptually coded by two phonetically trained transcribers for the presence of the target segments, /l/ and /w/. Both transcribers listened to the audio recordings via high-fidelity Sennheiser headphones. When target segments were not present, they noted whether the segment was omitted altogether or if it was substituted by another segment, noting the identity of the substitution. Inter-coder reliability was 91%.

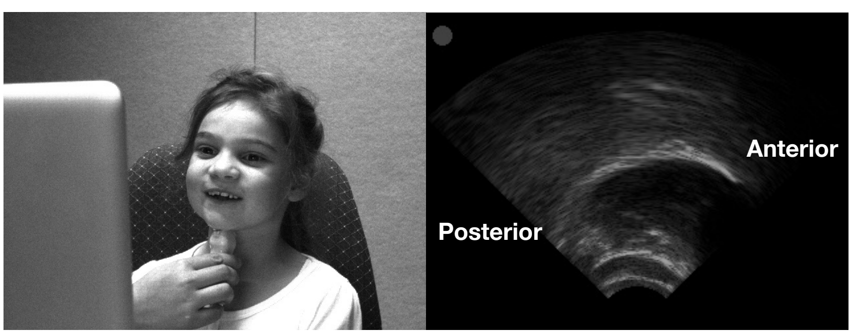

Figure 1. Sample video image (left) and ultrasound image (right) from participant aged 7;5 years.

Table 3. Gestures engaged during adult production of target segments in Australian English.

Gestures Engaged	onset /w/	onset /l/	coda /l/
Tongue tip raising (TT)	no	yes	yes
Tongue dorsum retraction (TD)	yes	yes	yes
Lip rounding (LAB)	yes	no	no

2.4 Analysis: Articulatory coding

A trained articulatory phonetician examined ultrasound and video frames from each utterance for the presence or absence of adult-like articulatory gestures. Across the three target segments, (onset /w/, onset /l/ and coda /l/) there are three relevant gestures: tongue tip raising[3], tongue dorum retraction, and lip rounding. Every utterance collected during this study was visually inspected for the presence or absence of all three relevant gestures.

In our data from the adult participants, coda /l/s were produced with tongue tip raising and tongue dorsum retraction 92% of the time, onset /l/s were produced with both tongue tip raising and tongue dorsum retraction 96% of the time, and onset /w/s were always produced with tongue dorsum retraction and lip rounding. We are thus comfortable in asserting that the gestures engaged during adult production of /l/s and /w/s are as summarized in Table 3 and are consistent with previous findings for other varieties of English (e.g. Giles and Moll, 1975; Sproat and Fujimura, 1993; Gick, 2003).

Figure 2 illustrates several potential lingual and labial configurations, as demonstrated by a 7;5-year-old child participant. Based on the presence or absence of gestures utilized by adults, each child-produced utterance was rated as either "adult-like" or not. For instance, an "adult-like" production of a /w/ must engage both the tongue dorsum and lips, but not the tongue tip. Similarly, an "adult-like" production of /l/ must engage both the tongue tip and tongue dorsum, but not the lips.

2.5. Predictions

Based on previous surveys of English speaking children, we predict:

1. Onset /w/s should be both perceptually and articulatorily adult-like for all children. (This segment was included in this study as a control.)
2. Onset /l/s should be perceptually and articulatorily adult-like earlier than coda /l/s, but we should find between-speaker variation, such that older children produce greater proportions of adult-like /l/s, in both onset and coda positions.
3. Perception should be correlated with articulation for all three segments.

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[3] The tongue tip itself is not typically visible in ultrasound images due to interference from the mandible. However, the most anterior region of the tongue blade is frequently used as an indicator of tongue tip position.

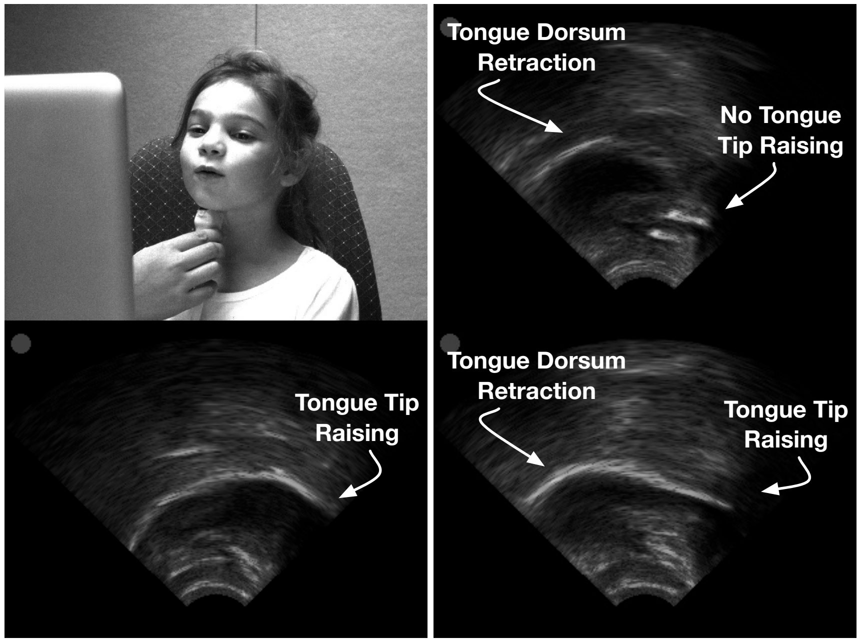

Figure 2. Video and ultrasound images showing lip rounding (top left), tongue dorsum retraction with tip raising (top right), tongue tip raising only (bottom left), and tongue dorsum retraction only (bottom right).

3. Results and discussion

Figure 3 illustrates the relationship between age and proportion of utterances perceived as adult-like (left), and utterances produced with adult-like gestures (right). To determine the relationship between age and adult-like perceptions, linear models[4] were fit between age and proportion of utterances produced with adult-like gestures, for words in the three contexts separately.

For onset /w/s, we found no significant relationship between age and proportion of adult-like perceptions (β=0.0165, t=1.01, p=0.3295, r^2=0.0019) and, as exhibited in Figure 3 (top left), this is likely due to even the youngest participants producing most adult-like /w/s. This ceiling effect was mirrored in the adult-likeness of children's productions (β=0.0165, t=1.01, p=0.3295, r^2=0.0019; Figure 3 (top right)). These results for onset /w/ are entirely in line with our expectations.

[4] Linear regression may not be the most appropriate model for these data. However, given the relatively small number of data points, we can't be certain if another model would be more appropriate at this stage in the research, and the linear regression at least gives us an idea of whether children's speech becomes more adult-like with age.

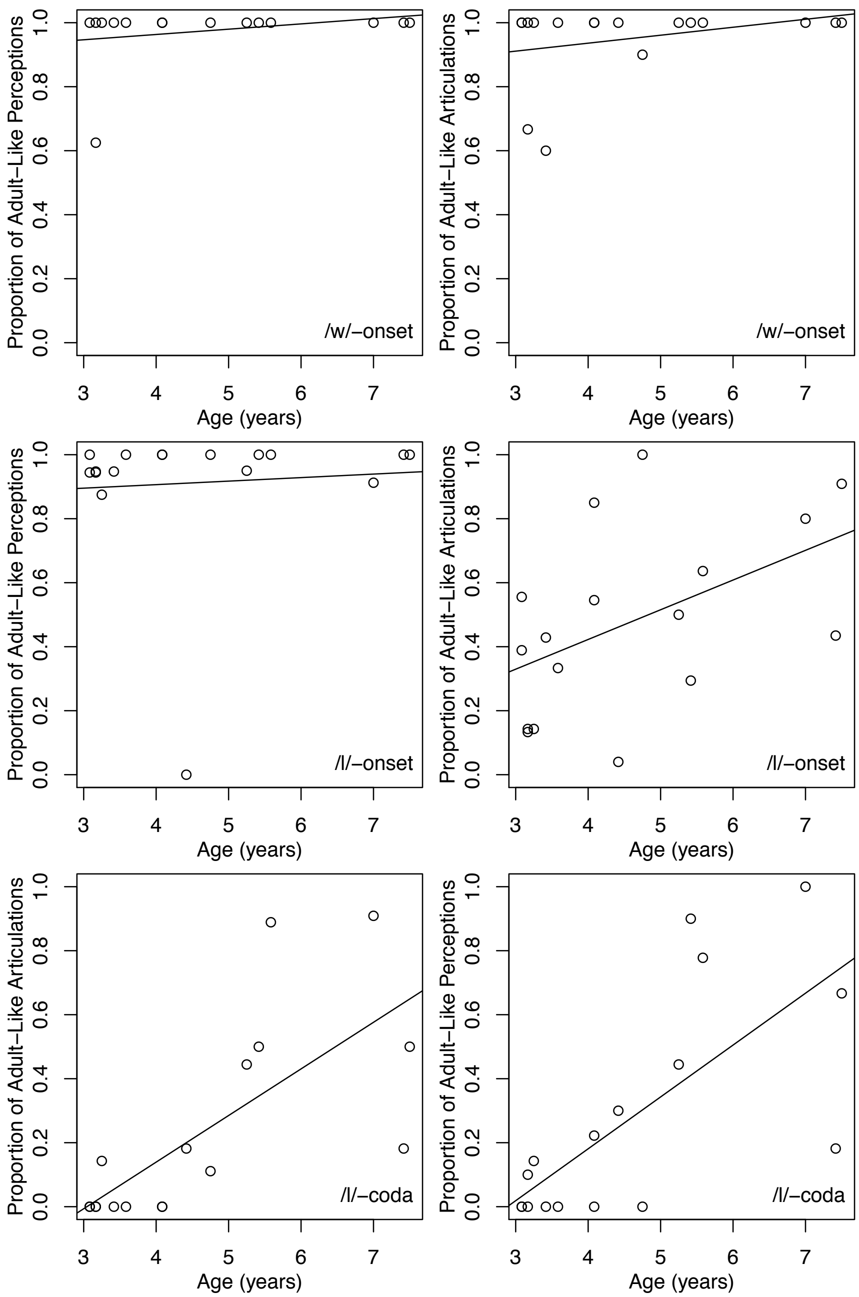

Figure 3. Proportion of utterances perceived as adult-like (left) and having actual adult-like gestures (right), for /w/-onset (top), /l/-onset (middle) and /l/-coda (bottom) stimuli; best-fit linear models superimposed.

We found a similar equivalence between perception and production of coda /l/s, as shown in Figure 3 (bottom). Age and adult-liked-ness were significantly correlated for both perception (β=0.1621, t=3.96, p=0.0013, r^2=0.4782) and production (β=0.1457, t=4.04, p=0.0011, r^2=0.4890), such that older children produced more adult-like utterances. Note the similarity in the slope estimates, suggesting a strong connection between how coda /l/s are produced and whether they are perceived to be /l/s by adult listeners.

In contrast, we found a mismatch between children's productions of onset /l/s and adult-perception of said productions. Articulatorily, children's productions of onset /l/s improved with age (β=0.0929, t=2.19, p=0.0444, r^2=0.1924), but these same /l/s were almost completely perceived to be adult-like, regardless of age (β=0.0110, t=0.28, p=0.7867, r^2=-0.0613).

3.1. Perception

Our findings provide both support for as well as intriguing differences from previous studies on the timeframe for acquisition of the English lateral /l/. For adult perception of /l/s, our data shows that the child participants in our study performed well above these norms for onset /l/s, and slightly behind for coda /l/s. Onset /l/s produced by our child participants were nearly uniformly perceived by the adult transcribers as being /l/s[5], despite our youngest participants being just 3;0. We posit two potential factors for why our children appear to be substantially more advanced than expected. First, according to a post-study survey filled out by participants' guardians, the children in our study came from relatively well-educated families, likely owing to our recruitment drive at the university. Second, and perhaps more importantly, due to technical limitations, the data collected in our study were single words spoken in isolation, rather than the spontaneously produced speech used by Smit et al. (1990). Words spoken in isolation by adults may be produced differently than words produced in simultaneous speech (e.g. Labov, 1972), and we expect that the same is true for children.

On the other hand, the coda /l/s produced by our child participants were typically perceived either as adult-like /l/, or vocalized as /w/ or a /w/-like vowel. The trajectory of this developmental curve, as shown in Figure 3 (bottom left), suggests that these Australian English learning children may not acquire adult-like coda /l/s until 7;0 or older, substantially later than the 5;6 reported by Smit et al. (1990). Whenever the coda /l/s were not perceived by the transcribers as adult-like, they were perceived as vocalized. It is possible that despite these children being raised in an environment not known for strong post-vocalic /l/ vocalization, exposure to vocalized /l/s in media may have postponed development of typical /l/ articulations. It is also possible, and potentially more

[5] The single child, aged 4;5, whose onset /l/s were perceived as not being adult-like consistently glided them into /j/s.

likely, that the two oldest children in the study simply have idiosyncratically higher proportions of vocalization than is typical for children their age.

3.2. Articulations

For coda /l/s, children's articulations and adult perception of said productions tracked very neatly. Generally, children with a high proportion of adult-like coda /l/ articulations also induced a high proportion of adult-like coda /l/ perceptions in the adult transcribers. Figure 4 (right) shows proportion of adult-like perceptions plotted against the proportion of adult-like productions for coda /l/s. The correlation between production and perception is quite strong, and a linear model showed that this correlation was significant (β=1.0505, t=10.19, p<0.0001, r^2=0.8653), with an estimated slope that is nearly 1. Additionally, half of the coda laterals produced by the primary outlier (C15; aged 5;5) in this context were produced with all three gestures (tongue tip raising, tongue dorsum retraction and lip rounding), as shown in Figure 5. This demonstrates that she had knowledge of the adult-like gestures involved in /l/ production, despite using an additional gesture. For this particular child, if coda lateral productions utilizing all three gestures were to be counted as being adult-like, the ratio between her production and perception improves from 0.5:0.9 (0.56) to 1.0:0.9 (1.11).

However, for onset /l/s, the correlation between production and perception was quite different. As shown in Figure 4, adult perception of onset /l/s was not well correlated with the adult-liked-ness of children's articulations. Nearly all of the children in our study were capable of producing onset /l/s that were perceived as adult-like by our transcribers, but there was substantial variation in whether these onset /l/s were produced with adult-like articulations. By and large, the onset /l/s that were coded as not being articulated with adult-like

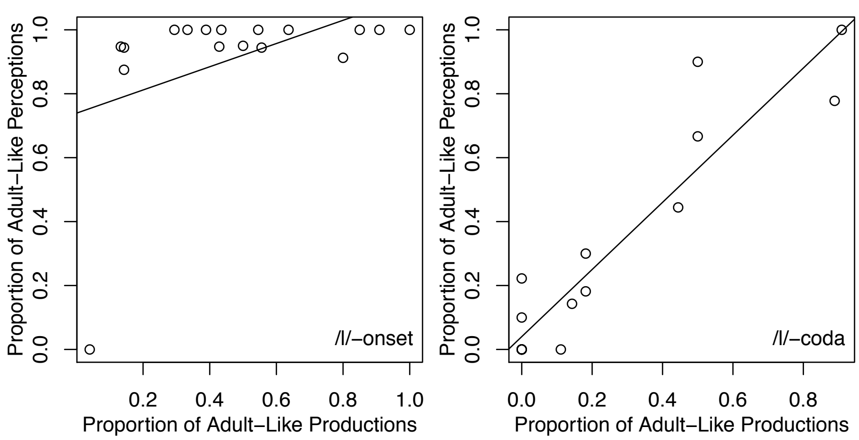

Figure 4. Proportion of adult-like productions against adult-like perceptions for onset /l/s (left) and coda /l/s (right).

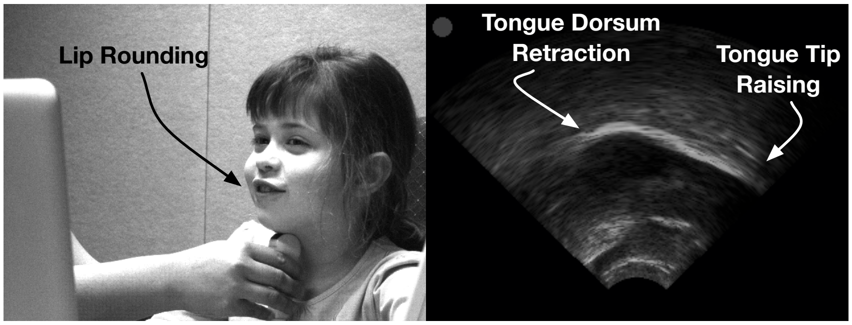

Figure 5. Production of coda /l/ from participant aged 5;5, demonstrating engagement of all three gestures.

gestures were produced with a single tongue tip raising (or tongue blade) gesture, rather than with both tongue tip raising and tongue dorsum retraction. This tongue configuration is similar to that utilized in "clear" laterals in some languages, such as Mandarin (Gick et al., 2006) or Spanish (Proctor, 2011), and it is therefore not surprising that they are perceived as being perfectly reasonable onset laterals.

What makes this result especially intriguing is that, as shown previously in Figure 3 (middle right), children do eventually develop adult-like onset /l/ articulations. Moreover, there is substantial intra-speaker variation, suggesting that development of adult-like onset /l/s is not necessarily bimodal. That is, it is not the case that once a child is capable of producing adult-like onset /l/s, he or she produces all onset /l/s in an adult-like manner.

3.3. Disconnect between adult-like production and perception

Why would children develop production of onset /l/ with two lingual gestures when single-gestured onset /l/s, which are presumably less complex, are perceptually sufficient for adult perceivers? We offer three potential explanations.

One possibility is that despite onset /l/s and coda /l/s being phonologically and phonetically distinct (e.g., Sproat and Fujimura, 1993), learners collapse them into a single phonemic category. This could lead to the extension of gestures required to produce coda /l/s onto onset /l/s as well. However, children in our study appear to be able to produce adult-like /l/ articulations in onset position before they are able to produce them in coda /l/s. Thus, this account doesn't appear to fit our data adequately.

More likely, "clear" single-gesture onset /l/s are perceptually sufficient to induce an /l/ percept, but are not actually perceptually equivalent to adult-like English onset /l/s. As children gain experience with English, they may become more capable of producing the adult-like double-gesture /l/s in both onset and coda positions. We plan to examine this hypothesis in future studies by analyzing the acoustics of single- and double-gesture onset /l/s, and by testing their perceptual equivalence as perceived by both children and adults.

We posit a third possibility, that development of an articulatory complex onset /l/ may be necessary for the production of onset consonant+/l/ clusters, which begin to appear around 4;0 (Templin, 1959; Smit et al., 1990), especially /C_{velar}l-/ clusters such as in *clap* or *glue*. That is, coarticulation from an initial velar consonant onto a following lateral may result in the introduction of a tongue dorsum retraction gesture during production of these /l/s. This may then become generalized across all onset /l/s, including singleton /l/. This is a particularly intriguing possibility, in light of Gierut and O'Connor's (2002) claim that faithful onset cluster production is linked to the acquisition of liquid (/l/ vs. /r/) contrast. This hypothesis would predict a rise in production of adult-like onset /l/s that correlates with a rise in production of onset clusters in general. Furthermore, this hypothesis predicts that onset /l/s in languages which do not allow onset consonant+/l/ clusters would be more likely to be produced with the single tongue tip raising gesture, and further cross-linguistic articulatory data would provide support or counter-evidence for this hypothesis. Interestingly, and potentially problematic for this account, neither Templin (1957) nor Smit et al. (1990) report substantial differences in acquisition times for /C_{velar}l/ compared to /C_{labial}l/. However, both studies report on acquisition over a relatively wide age range (4;0-5;0 and 4;0-5;6, respectively), and this adoption of coarticulatory effect across all /l/ contexts may well occur on a shorter time scale.

4. Conclusions

Two of our three predictions, repeated in Table 4, were confirmed by our data. First, almost all of the children in our study produced onset /w/s that were nearly uniformly adult-like both articulatorily and perceptually. Second, our data establishes that, for our participants, coda /l/s are acquired later than onset /l/s, and that older children produce greater proportions of adult-like /l/s, in both onset and coda positions. Additionally, we found that when onset /l/s were not adult-like, they tended to be glided, and coda /l/s tended to be vocalized when not adult-like. We therefore conclude that development of onset and coda /l/s in

Table 4. Summary of predictions and conclusions.

Predictions	Upheld?
1. Onset /w/s should be both perceptually and articulatorily adult-like for all children.	Yes
2. Onset /l/s should be perceptually and articulatorily adult-like earlier than coda /l/s, but we should find between-speaker variation, such that older children produce greater proportions of adult-like /l/s, in both onset and coda positions.	Yes
3. Perception should be correlated with articulation for all three segments.	Partially (see text)

Australian English follow similar (though not identical) norms as established by studies of American English speaking children.

Our third prediction, that perceptibility of /l/s should correlate with their articulatory similarity to adult /l/s, was confirmed for coda /l/s, but not onset /l/s. The disparity in the production and adults' perception of singleton onset /l/s produced by children in our study highlights an intriguing conceptual issue: what does it mean to have acquired a segment (or phonological structure)? Certainly, discrimination between segments precedes the ability to reliably produce discriminable segments. But even when limiting our definition of acquisition to the ability to *produce* segments, we found a distinction between the ability to produce adult-like articulations and the ability to induce target segments perceptually.

With modern technology improving the accessibility of articulatory data from children's speech, we believe it reasonable to begin formulating articulatory norms, to exist in conjunction with perceptual norms. Our understanding of how speech sounds are acquired will surely benefit from knowledge of whether other segments undergo perceptual/articulatory disconnects similar to our findings, and if so, what universals exist within that set of sounds.

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