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Research Article

Children's Acquisition of English Onset and Coda /l/: Articulatory Evidence

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Purpose: The goal of this study was to better understand how and when onset /l/ (*leap*) and coda /l/ (*peel*) are acquired by children by examining both the articulations involved and adults' perceptions of the produced segments.
Method: Twenty-five typically developing Australian English–speaking children aged 3;0 (years;months) to 7;11 participated in an elicited imitation task, during which audio, video, and lingual ultrasound images were collected. Transcribers perceptually rated audio, whereas video and ultrasound images were visually examined for the presence of adult-like articulations.
Results: Data from this study establish that for Australian English–learning children, coda /l/s are acquired later than onset /l/s, and older children produce greater proportions of adultlike /l/s in both onset and coda positions, roughly following established norms for American English–speaking children. However, although perceptibility of coda /l/s was correlated with their articulations, onset /l/s were nearly uniformly perceived as adultlike despite substantial variation in the articulations used to produce them.
Conclusions: The disparity in the production and perception of children's singleton onset /l/s is linked to both physiological and phonological development. Suggestions are made for future research to tease these factors apart.

One of the fundamental issues in speech development and developmental phonology is why some speech sounds are acquired early whereas others are acquired much later (Dyson, 1988; Hare, 1983; Prather, Hendrick, & Kern, 1975; Smit, Hand, Freilinger, Bernthal, & Bird, 1990). Developmental linguists have suggested that a number of complex and interacting factors, ranging from physiological (e.g., Kent, 1992) to cognitive (e.g., MacNeilage, Studdert-Kennedy, & Lindblom, 1984) and linguistic (e.g., Song, Sundara, & Demuth, 2009), are at play. This study examines lingual ultrasound imaging data of /l/ production from young (ages 3;0 [years;months] to 7;11) English-speaking children and explores the results in light of children's concurrent physiological and phonological development.

Physiological Development

With respect to physiological development, children must gain sufficient motor control over the primary speech organs, including the tongue, lips, vocal folds (required for voicing), and velum (required for nasal consonants and vowel contrasts), in order to make full use of their language's phonetic inventory. In this study we targeted children's control over the lingual articulations—that is, articulatory gestures using the tongue. One property common to many late-acquired sounds in typical acquisition of English, such as the liquids /l/ and /ɹ/ and the affricates /tʃ/ and /dʒ/, is that they are articulatorily complex. In adults' productions of these sounds, multiple constrictions in the vocal tract are required. Production of /tʃ/, for instance, requires alveolar closure, with the tongue tip against the alveolar ridge, as well as postalveolar constriction (without closure) using the tongue blade.

In contrast, the nasal stops /m/ and /n/ and the labiovelar glide /w/ are some of the speech sounds acquired earliest by English-learning children even though each of these sounds also requires two articulators. Production of the nasal stops /n/ and /m/ requires simultaneous lowering of the velum and formation of an oral closure, and the glide /w/ requires partial constriction of both lips and of the tongue dorsum with the palate (Gick, 2003). These segments involve coordination of two articulators and may therefore be articulatorily complex, like the late-acquired segments described in the previous paragraph. However, unlike the liquids and affricates discussed earlier, only one of the constrictions involved in the production of nasal stops and the

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labiovelar glide is lingual. The protractedness of acquisition of speech sounds requiring multiple lingual constrictions may therefore be linked to lingual differentiation (Gibbon, 1999; Green, Moore, Higashikawa, & Steeve, 2000) during the development of children's fine motor control (Cheng, Murdoch, Goozée, & Scott, 2007; Studdert-Kennedy & Goldstein, 2003).

Furthermore, children undergo phases of rapid skeletal and muscular development throughout their bodies. Vorperian et al. (2005) reported that by 6 years of age, the majority of children's vocal tract structures have reached 65% to 85% of their adult size. However, the structures do not develop uniformly. For instance, rate of tongue growth does not stabilize until after age 5;6, on average, whereas most parameters affecting the size and shape of the oral cavity stabilize between ages 2;0 and 3;0, except for mandibular depth, which stabilizes at approximately age 4;4. As Denny and McGowan (2012) pointed out, this suggests that the size and shape of the oral cavity matures earlier than does the tongue. This in turn suggests that producing an anterior and a posterior constriction simultaneously or in quick succession would be difficult for children younger than age 5;6, providing another physiological reason why development of speech sounds requiring two lingual articulators may be relatively protracted (Studdert-Kennedy & Goldstein, 2003). Indeed, this specific argument has been invoked to explain the protractedness of English /ɹ/ development (Denny & McGowan, 2012; McGowan, Nittrouer, & Manning, 2004) as well as that of English liquids, including /l/ (Gick et al., 2008).

Laterals in English and Around the World

Across multiple languages, there are two main varieties of the alveolar lateral approximant: "light" or "clear" lateral [l] and "dark" or "velarized" lateral [ɫ]. Both varieties are characterized by an anterior constriction, at or near the alveolar ridge, that allows for lateral airflow (Gick, Wilson, & Derrick, 2013). The [ɫ] variety is distinguished from [l] articulatorily by an additional posterior constriction that is either pharyngeal or velar (hence, "velarized"). In terms of acoustics, the additional velar or pharyngeal constriction in dark [ɫ] productions results in a substantially lower second formant frequency (F2) than does clear [l], and F2 value is often used as an indicator of darkness (Recasens & Espinosa, 2005; Sproat & Fujimura, 1993). The anterior constriction typically is created with the tongue tip or anterior portion of the tongue blade, whereas the posterior constriction is created with the tongue dorsum or posterior tongue body. The articulatory movements are therefore often referred to as "tongue tip raising" and "tongue dorsum retraction/raising." Although these terms are appropriate for most adult speakers, it is not clear that they are appropriate for children. Thus, they are referred to in this article generally as "anterior lingual" and "posterior lingual" constrictions or articulations.

The phonemic status of [l] and [ɫ] is largely language specific. Speakers of some varieties of Catalan, for instance, are reported to produce only velarized [ɫ], whereas speakers of French, Italian, and German produce clear [l] (Gick, Campbell, Oh, & Tamburri-Watt, 2006; Recasens, 2004; Recasens & Espinosa, 2005). Many other languages are thought to have a single lateral phoneme that is alternately realized as [l] or [ɫ], depending on context. In most varieties of English, /l/ is often said to be realized as [l] in onsets and [ɫ] in codas. However, despite differences in the phonological behavior of onset compared to coda /l/s (Bladon & Al-Bamerni, 1976; Halle & Mohanan, 1985; Hardcastle & Barry, 1989; Maddieson, 1985), copious articulatory research has established that both onset and coda laterals are typically produced by American English–speaking adults with an anterior constriction as well as a posterior constriction (Browman & Goldstein, 1995; Gick, 2003; Giles & Moll, 1975; Sproat & Fujimura, 1993; Stone & Lundberg, 1996). It is therefore possible to claim that both onset and coda laterals in English are produced as the dark, velarized [ɫ], although the relative magnitude and timing of the two constrictions vary by position. This variability of lateral production has been shown to exist as a continuum rather than as two discrete categories, both within a single language, such as English (Sproat & Fujimura, 1993), and cross-linguistically (Recasens, 2004).

Other cross-linguistic articulatory research has shown that speakers of some languages with reportedly light, nonvelarized [l], such as Spanish, produce these laterals with at least some tongue dorsum constriction (Proctor, 2011). This has led to the proposal that tongue dorsum retraction in alveolar laterals is an articulatory reflex of the primary lateral constriction created by the tongue tip and blade—a reflex that may have developed into an independent and required constriction for lateral production in some languages, such as English and Russian (Gick et al., 2013; Proctor, 2011). This independence has been hypothesized to be integral to postvocalic /l/ vocalization as a sound change in English (Lin, Beddor, & Coetzee, 2014).

Acquisition of English /l/

The time course of /l/ acquisition by English-learning children has been established previously via impressionistic auditory judgments. In particular, there is often reported to be a robust asymmetry in the protractedness of onset compared with coda lateral acquisition. Onset /l/s are typically acquired early (generally indicated by 75% or 80% production accuracy)—as early as age 2;0 (Dyson, 1988) or as late as ages 3;4 to 4;6 (Dodd, Holm, Hua, & Crosbie, 2003; Prather et al., 1975; Smit et al., 1990). In contrast, coda /l/ is acquired later by typically developing children by most accounts, although Prather et al. (1975) found onset and coda /l/ to be acquired at the same age. Smit et al. (1990) reported acquisition of coda /l/ between ages 6;0 and 7;0, whereas Templin (1957) reported acquisition by age 6;0. Prior to acquisition, both onset and coda /l/s are reported to be *glided*—that is, produced as either the labiovelar glide /w/ or the palatal glide /j/. In general, coda /l/s are reported to be substituted by the labiovelar glide /w/ or a back vowel in a process called *vocalization,* which is acoustically similar to the sound change also found in English that shares the same name (Ash, 1982; Hardcastle & Barry, 1989; Horvath & Horvath, 2002). On the other hand, onset /l/s may be vocalized or glided to /j/, sometimes conditioned by the segment's position within a word (Dodd et al., 2003; Smit, 1993). Smit's (1993) data also attested to target onset /l/ production with interdental tongue protrusion, although this substitution is rare.

As suggested previously (Denny & McGowan, 2012; Gick et al., 2008; Studdert-Kennedy & Goldstein, 2003), speech sounds that involve two lingual constrictions should be acquired especially late due to physiological constraints and, more specifically, to the delay in development of the tongue compared with the oral cavity. Given that development of the tongue does not stabilize until age 5;6, whereas the size of the oral cavity stabilizes by age 3;0, we expect that children between ages 3;0 and 5;6 would have difficulty producing laterals with both an anterior tongue tip or blade constriction and a posterior tongue dorsum constriction. Thus, if children are capable of producing auditorily acceptable onset /l/s as early as age 3;0 and sometimes age 2;0, it follows that they may be accomplishing this goal using a different articulatory strategy than that used by adults. We hypothesized that at least some auditorily acceptable onset /l/s are produced with an anterior-dominant constriction, as is classically described for light laterals, instead of with both lingual constrictions, as would be expected for English-speaking adults.

Goals and Hypotheses

Our principal goal in this study was to determine at what age Australian English–speaking children become capable of producing singleton onset laterals (e.g., *leap*) and coda laterals (e.g., *peel*) that are both perceptually and articulatorily similar to adults' productions. We note here that the only substantial documented difference between Australian English laterals and American English laterals is the prevalence of postvocalic /l/ vocalization in some varieties of Australian English; however, /l/ vocalization is not regarded as being common in the greater Sydney metropolitan area, from which our participants were recruited (Borowsky, 2001; Horvath & Horvath, 2002). To be certain, we recruited several Sydney-based adult Australian English speakers to serve as models of adults' speech for this study.

Research in phonological development has historically focused on adults' impressionistic judgments of segmental accuracy based on audio recordings, and such research forms the foundation of many well-established developmental speech production norms (Prather et al., 1975; Smit, 1993; Smit et al., 1990; Templin, 1957). More thorough analyses of children's speech 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 acoustic analysis (Li, Edwards, & Beckman, 2009; Macken & Barton, 1980a, 1980b; Scobbie, Gibbon, Hardcastle, & Fletcher, 2000; Song & Demuth, 2008). Such covert contrasts have also been found articulatorily, even in adults' speech. For example, the rhotic liquid /ɹ/ may be produced in a variety of lingual configurations, including retroflex and bunched (Espy-Wilson, Boyce, Jackson, Narayanan, & Alwan, 2000; Westbury, Hashi, & Lindstrom, 1998). Also, the fricative /s/ has been shown as having either an *apical articulation,* where the primary constriction that results in frication is between the tongue tip and the alveolar ridge, or a *laminal articulation,* in which the tongue blade provides the constriction instead (Dart, 1991; Stone et al., 2013). Articulatory studies have also demonstrated consistent and well-motivated differences between children's and adults' articulations for vowels (Noiray, Ménard, & Iskarous, 2013) and select consonants (Zharkova, Hewlett, & Hardcastle, 2011, 2012) and have shown that variability in children's speech extends through adolescence (Murdoch, Cheng, & Goozée, 2012).

Concerning the development of laterals specifically, Cheng, Murdoch, Goozée, et al. (2007) examined electropalatographic (EPG) data from Australian English–speaking children aged 6;0 to 17;0 as well as adults. The authors reported that the anterior constriction in children's onset /l/ productions is more posterior than in adults' productions and that the constriction becomes progressively more anterior with age. Oh (2005) examined ultrasound images of onset, coda, and intervocalic laterals produced by eight American English–speaking children, aged 3;11 to 5;9, and reported substantial between-subjects variability both in the presence of adultlike anterior and posterior constrictions and in the location and magnitude of the constrictions present. In particular, Oh (2005) found that even though children sometimes produced laterals with both anterior and posterior constrictions, one of the two constrictions often was incomplete or weak compared with adults' productions. It is worth noting that these eight participants were prescreened for audibly accurate lateral productions, as reported by their parents, and might therefore be expected to have a greater proportion of articulatorily adultlike lateral productions than average for those ages. The present study expands on these findings by targeting a wider selection of younger children and by including children whose lateral productions are audibly not adultlike.

Our expectations and hypotheses were as follows: On the basis of previously established norms for American English–learning children, we expected that (a) the proportion of perceptually accurate productions of both onset and coda laterals by Australian English–learning children should increase with age and that (b) onset laterals would be acquired earlier (between ages 3;0 and 4;0) than coda laterals (between ages 5;6 and 6;6). We further hypothesized that (c) at least some perceptually acceptable laterals produced by children would be produced using an anterior-dominant articulation rather than an adultlike anterior–posterior articulation. Finally, because younger children are expected to have more difficulty producing multiple simultaneous lingual constrictions than older children, we expected that

(d) the proportion of lateral productions produced with a single dominant constriction, whether anterior or posterior, should decrease with age. We also provide articulatory data demonstrating that nonvocalizing adult speakers of Australian English produce onset and coda /l/s with articulations that are consistent with established norms for American English–speaking adults.

Method

Participants and Stimuli

Thirty-three children between the ages of 3;0 and 7;11 participated in this study. Data from those who were unable to complete the task ($n = 5$) or who produced fewer than five viable productions in any given context ($n = 3$) were excluded from the analyses. Data from the remaining 25 children (seven boys, 18 girls; $M_{age} = 5;5$) are reported in this study. Five female adults ($M_{age} = 21$ years) also participated in this study. All participants were typically developing (or typically developed, in the case of adults) monolingual speakers of Australian English recruited from the greater Sydney region and were thus generally exposed to a variety of Australian English without postvocalic /l/ vocalization (Borowsky, 2001; Horvath & Horvath, 2002). Table 1 lists all participants (sorted by age) whose data were analyzed, as well as the number of words analyzed from each participant.

Table 1. Number of productions analyzed for each participant, by context.

ID	Age		Gender	Productions per context		
	Months	Category		Onset /l/	Coda /l/	Onset /w/
C13	37	3	M	9	12	5
C03	38	3	F	7	8	9
C08	38	3	F	6	7	6
C11	39	3	F	7	7	5
C04	41	3	M	7	5	5
C19	49	4	M	10	7	8
C10	53	4	F	13	11	13
C23	53	4	F	11	10	9
C12	57	4	F	9	9	10
C21	58	4	F	8	8	6
C17	63	5	F	8	9	8
C15	65	5	F	9	10	10
C26	65	5	F	10	8	11
C29	65	5	F	8	10	7
C05	67	5	F	6	9	10
C28	72	6	F	10	10	11
C30	79	6	M	9	10	10
C25	82	6	M	9	10	10
C22	83	6	F	10	10	8
C27	83	6	F	10	10	9
C18	84	7	M	5	11	11
C24	84	7	F	10	7	9
C20	86	7	F	7	7	5
C16	89	7	M	12	11	10
C14	90	7	M	6	6	6
A1	Adult	Adult	F	10	10	10
A2	Adult	Adult	F	10	10	10
A3	Adult	Adult	F	10	10	10
A4	Adult	Adult	F	10	10	10
A5	Adult	Adult	F	10	10	10

The elicited stimuli were four high-frequency, imageable, monosyllabic /CVl/ and /lVC/ words—two onset /l/s and two coda /l/s. We also included two /CVC/ words with /w/ onsets to serve as controls, as onset /w/ is one of the earliest acquired segments in English (Dyson, 1988; Smit et al., 1990). All participants whose data were analyzed in this study demonstrated greater than 75% auditory accuracy of /w/ productions. Ultrasound images collected from /w/ productions also served as potential comparisons for /w/-substituted /l/ productions. In each context, the vowel was either /i/ (as in *wheat*) or /æ/ (as in *lake*). Back vowels were avoided in the stimuli to reduce the likelihood of auditory transcribers confusing vocalization of coda /l/ with deletion. Avoidance of back vowels reduces the possibility of articulatory overlap in posterior lingual constriction between production of the lateral and vowel. Table 2 lists the target stimuli, along with their typical pronunciation in Australian English (Cox & Palethorpe, 2007), transcribed in International Phonetic Alphabet.

Productions of the stimuli were collected from child participants using an elicited imitation task. Children sat in front of a computer monitor and were presented with a cartoon image of the target stimulus accompanied by an audio prompt. The audio prompts were prerecorded productions of the target stimuli spoken in isolation by a female speaker of a nonvocalizing variety of Australian English. Children were asked to look at the picture and repeat the word in the audio prompt and were rewarded with stickers and praise. Prior to the task, the children were given two practice trials in order to familiarize them with the task and stimuli. Presentation stimuli were blocked and randomized, and between three and six repetitions of each item were elicited from each child participant. If a participant was unable to produce at least three repetitions of each item, his or her data were not used in the analysis.

Adult participants read the same target stimuli presented randomly on a computer monitor, in isolation, without an audio prompt. Substantially more data were collected from each adult speaker (five to eight repetitions per item), and additional filler words were created for the adult participants in order to better obscure the task. Adult participants received credit in their undergraduate linguistics courses for their participation.

Table 2. Control (onset /w/) and test items with International Phonetic Alphabet pronunciation in Australian English.

Onset /w/		Onset /l/		Coda /l/	
wheat	[wiːt]	*leap*	[liːp]	*peel*	[pʰiːɫ][a]
weight	[wæt]	*lake*	[læk]	*mail*	[mæɫ]

[a]In transcriptions of Australian English, coda /l/s are traditionally transcribed as [ɫ] and onset /l/s are transcribed as [l] (Cox & Palethorpe, 2007). Here, we follow that standard, despite evidence that dark and light laterals are merely endpoints of a continuum (e.g., Sproat & Fujimura, 1993).

Articulatory Equipment and Procedure

Although methods for directly measuring articulator 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 or health risks of most instruments measuring articulatory motion—for example, X-ray microbeam (Sproat & Fujimura, 1993), cinefluorography (Giles & Moll, 1975), velotrace (Krakow, 1989), and Electromagnetic (Midsagittal) Articulography (EMA/EMMA; Perkell et al., 1992). Other relatively non-invasive techniques have been employed, such as ultrasound (Davidson, 2005; Gick, 2003; Stone, 2005), EPG (Scobbie & Pouplier, 2010), and magnetic resonance imaging (Byrd, Tobin, Bresch, & Narayanan, 2009; Gick, Kang, & Whalen, 2002; Zhou et al., 2008). These noninvasive techniques have been extended to include child participants (for ultrasound, Bernhardt, Gick, Bacsfalvi, & Ashdown, 2003; Noiray et al., 2013; Scobbie, Lawson, & Stuart-Smith, 2012; Song, Demuth, Shattuck-Hufnagel, & Ménard, 2013; Zharkova et al., 2012; for EPG, Cheng, Murdoch, & Goozée, 2007; Cheng, Murdoch, Goozée, et al., 2007; Gibbon, 1990; Hardcastle & Barry, 1982; Hardcastle, Barry, & Clark, 1987; and for magnetic resonance imaging, Vorperian et al., 2005).

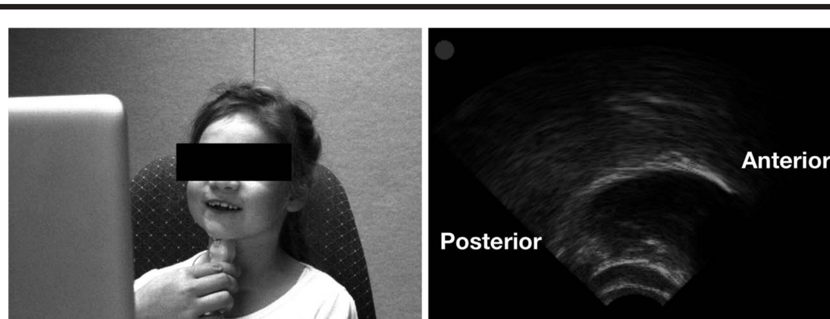
In this study, midsagittal ultrasound images of both child and adult participants' tongues were recorded using a Terason t3000 ultrasound system (Terason, Burlington, MA) running Ultraspeech 1.1 (Hueber, Chollet, Denby, & Stone, 2008). Ultraspeech simultaneously recorded video of the participants' lip movements and audio of participants' speech. Both lip motion and lingual ultrasound videos were captured at 60 frames per second and were synchronized with the audio stream with a margin of error of up to 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 headset from Articulate Instruments Ltd. (East Lothian, United Kingdom). However, the headset was not used with child participants due to their young age. 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. Use of elicited imitation using a visual prompt as well as an audio prompt helped maintain children's focus on the computer screen, thus assisting with manual stabilization (for similar procedures used with young children, see Song et al., 2013). The task took each child participant approximately 10 to 20 min to complete. Figure 1 shows sample video and ultrasound images from one child participant. The bright white curve in the center of the ultrasound image resulted from the change in acoustic impedance between the tongue and the air above the tongue (Stone & Epstein, 2005). In these and all subsequent ultrasound images in this article, the anterior oral cavity is oriented toward the right and the posterior oral cavity is oriented toward the left.

Analysis

In the analyses and results discussed below, all viable target utterances produced by child participants were analyzed, whereas five repetitions of each item produced by adult participants were analyzed. An utterance was considered viable if it had a clear audio signal and ultrasound images and the video provided an unobstructed view of the child's mouth. Examples of acoustic disqualifications include parents' or experimenters' speech or children's clapping overlapping with the target production. Utterances in which the tongue was not easily distinguishable from surrounding tissue in one or more ultrasound frames were not analyzed. In addition, two utterances were not included in the data due to a child's hand blocking the view of the mouth from the camera.

The target segments were then examined for similarity to adults' productions, both perceptually and in terms of the oral constrictions created. The audio recordings from all the target utterances produced by the children 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 (Sennheiser, Wademark, Germany). When the target segments were not present, the transcribers noted whether the segment was omitted or if it was substituted by another segment, noting the identity of the substitution. Intercoder reliability was 91% for child productions and 100% for adult productions. A given target segment

Figure 1. Sample video image (left) and ultrasound image (right) from a child participant.



was considered perceptually accurate if both transcribers agreed that the segment was accurately produced.

Both labial and lingual articulatory videos were then visually examined by two independent coders for the presence or absence of lingual and labial articulations in production of the target segments. Between the three target segments (onset /w/, onset /l/, and coda /l/), there are three constrictions typically reported to be involved in adults' productions: an anterior lingual constriction (tongue tip or blade raising), a posterior lingual constriction (tongue dorsum retraction), and a labial constriction (lip rounding or protrusion). Each target utterance collected during this study, from both child and adult participants, was visually inspected by both articulatory coders for the presence or absence of all three constrictions. Presence of an articulation was indicated by visible motion out of constriction into the following vowel for target onset segments or out of the preceding vowel into constriction for target coda segments. Similar methodology using visual inspection has been used previously by ultrasound researchers studying adults' productions of rhotics (Lawson, Scobbie, & Stuart-Smith, 2013). Intercoder reliability, calculated on the presence or absence of individual constrictions for each item, was 87% for child productions and 98% for adult productions. Reliability in children's articulations was split roughly equally among the constriction types (89% anterior, 85% posterior, and 88% labial) as well as among age groups (85% for 3-year-olds, 90% for 4-year-olds, 85% for 5-year-olds, 93% for 6-year-olds, and 86% for 7-year-olds). Examples of such motion and constriction are demonstrated in Figure 2 by a child participant aged 7;5. In the Results and Discussion sections, we refer to productions that are coded as having both anterior and posterior lingual constrictions as "anterior–posterior" productions. Because the nature of the methods is inherently impressionistic, those that are coded as having a single lingual constriction are referred to as "anterior dominant" or "posterior dominant" rather than "anterior only" or "posterior only."

Adults' Articulations

As the majority of existing English articulatory research has been conducted on varieties of American or British English, we used data collected from the Australian English–speaking adult participants to verify that Australian English speakers do not differ substantially with regard to which gestures are used in the production of /w/s and /l/s. All onset /w/s produced by the adult participants in this study exhibited both tongue dorsum retraction and lip rounding. All coda /l/s and 99% of onset /l/s produced by adults exhibited both a strong anterior constriction and a strong posterior constriction. 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 (Gick, 2003; Gick et al., 2006; Giles & Moll, 1975; Sproat & Fujimura, 1993; Stone & Lundberg, 1996).

Results

Recall our expectations and hypotheses, which were as follows:

- *Hypothesis 1.* The proportion of perceptually accurate productions of both onset and coda laterals by Australian English–learning children should increase with age.
- *Hypothesis 2.* Onset laterals should be acquired earlier (between ages 3;0 and 4;0) than coda laterals (between ages 5;6 and 6;6).
- *Hypothesis 3.* At least some perceptually acceptable laterals produced by children should be produced using a dominant anterior articulation rather than an adultlike anterior–posterior lateral.
- *Hypothesis 4.* Proportion of laterals produced with a single dominant lingual constriction should decrease with age.

All logistic mixed-effects models reported in this section were run using the glmer() function in the lme4 package for R (Bates, Maechler, & Bolker, 2012; R Core Team, 2013).

Perceptual Accuracy

Hypotheses 1 and 2 refer specifically to ratings of accuracy assigned by the transcribers of the audio recordings alone. A logistic mixed-effects model was run with transcribers' accuracy ratings as a binary dependent variable, with Age (continuous, in years) and Position (two levels: onset or coda) as fixed factors, and with interaction terms between age and position included. Subject and repetition were included as random factors. Because vowel quality is known to have an effect on the articulation of English laterals by adults—especially on the posterior lingual constriction (Lee-Kim, Davidson, & Hwang, 2013; Proctor & Walker, 2012)—an initial model with Vowel Quality as a third fixed factor, including full interactions, was also fit to the data and ruled out. A log-likelihood ratio test between these two models showed that inclusion of Vowel as a fixed factor did not significantly improve fit, $\chi^2(4, 10) = 3.44$, $p = .4877$, demonstrating that vowel quality had no significant effect on auditory accuracy in children's lateral productions.

Results from the model showed a significant effect of position on accuracy ratings, with coda laterals having significantly lower accuracy ratings than onset laterals ($B = -7.79$, $SE = 1.55$, $p < .0001$) for the youngest children in our study. The model also showed, for onset laterals, no significant increase in accuracy with age ($B = 0.23$, $SE = 0.30$, $p = .4442$). There was, however, a significant Age × Position interaction ($B = 0.66$, $SE = 0.26$, $p = .0128$), and setting the base comparison level for position to coda revealed that, for coda laterals, Age was indeed a significant factor—children's accuracy in production of coda laterals improved with age ($B = 0.89$, $SE = 0.27$, $p = .0011$). These

Figure 2. Video and ultrasound frames from a child participant demonstrating movement toward and away from labial constriction (top) from onset /w/ production (*weight*), posterior lingual constriction (middle) from vocalized coda /l/ production (*mail*), and anterior lingual constriction (bottom) from onset /l/ production (*lake*). Sequential frames in each series are 100 ms apart.

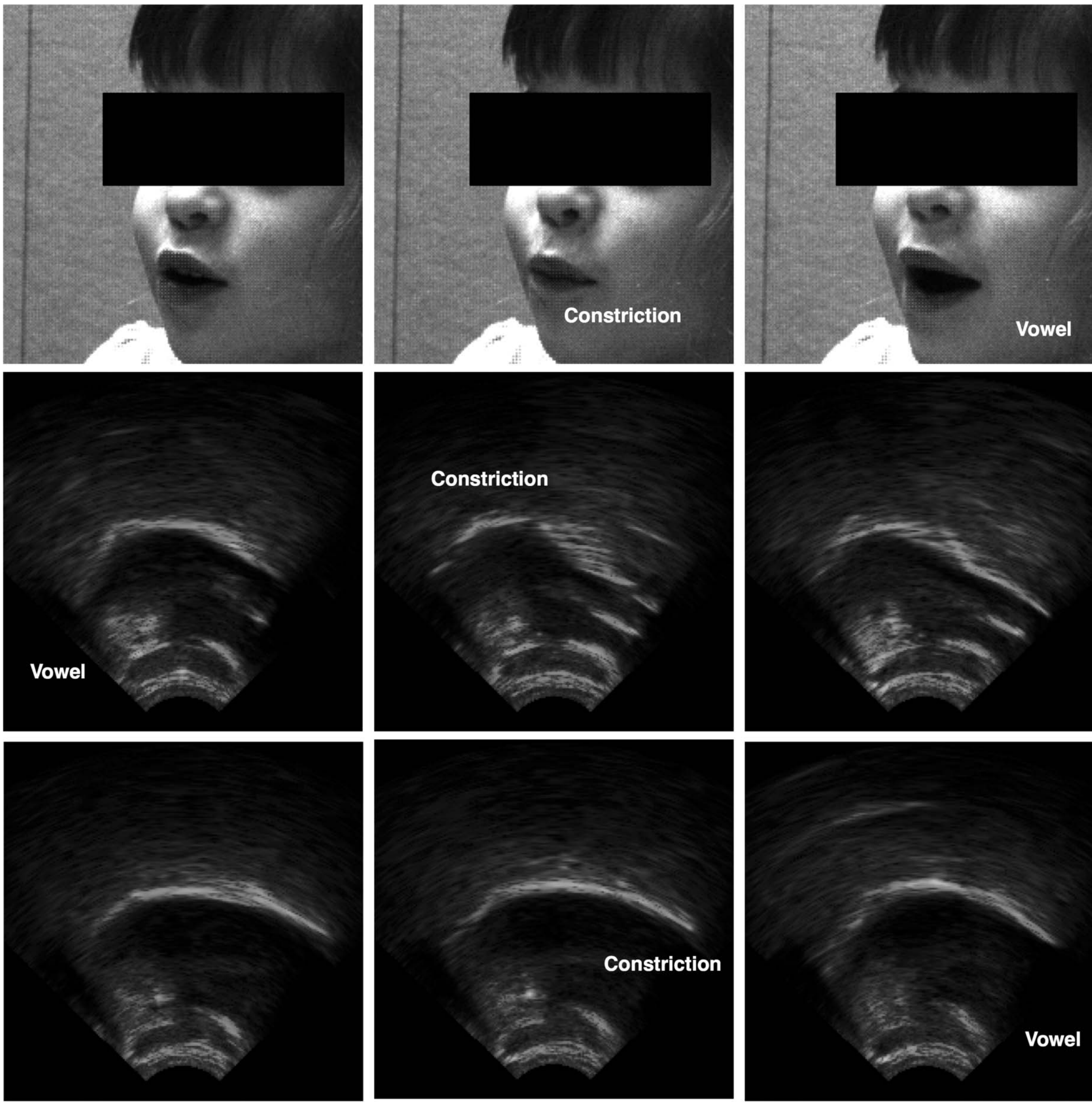
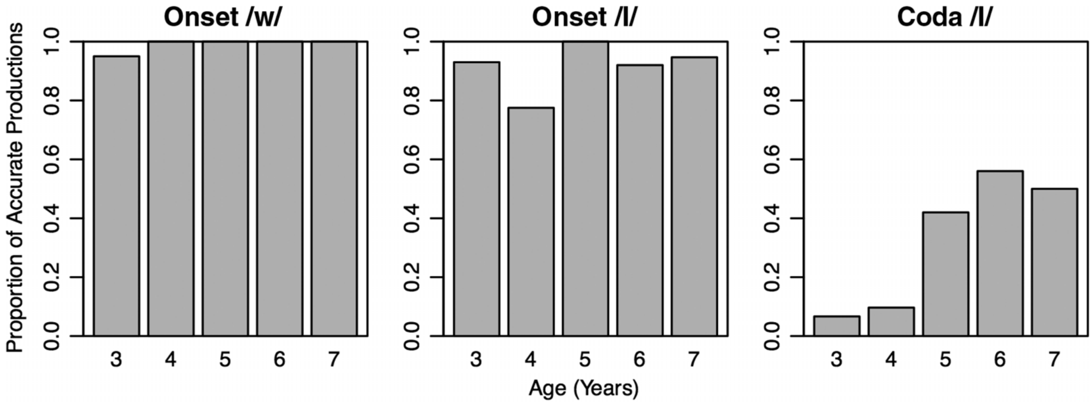


Table 3. Oral cavity constrictions produced by Australian English–speaking adults for target segments.

Typical constrictions	Onset /w/	Onset /l/	Coda /l/
Anterior lingual (tongue tip raising)	No	Yes	Yes
Posterior (tongue dorsum retraction)	Yes	Yes	Yes
Labial (lip rounding or protrusion)	Yes	No	No

data are visualized in Figure 3 along with analogous plots for production of the control consonant /w/. In Figure 3, age is binned by year to improve interpretability, and because participants contributed differing amounts of data to the pool, proportions of accurate productions were calculated separately for each participant and then averaged. Figure 3 demonstrates that the lack of significant age-related improvement of onset lateral production was likely due to even the youngest children in this study producing perceptually accurate onset /l/s. The graphs for onset /l/ progression and /w/ progression bear a strong resemblance to one another except for a dip at age 4;0 in production of onset

Figure 3. Proportion of utterances transcribed as accurate for onset /w/ (left), onset /l/ (middle), and coda /l/ (right) stimuli.



/l/s; this dip is due to a single child, all of whose onset /l/ productions were noted by the transcribers as being glided to /j/. The data visually suggest a nonlinear improvement in coda /l/ accuracy with age, with a jump in accuracy between ages 4;0 and 5;0 and minimal improvement between ages 5;0, 6;0, and 7;0. We note a higher proportion of male participants as the groups advance in age: 5-year-olds, 0% male, 100% female; 6-year-olds, 40% male, 60% female; 7-year-olds, 60% male, 40% female. Thus, this effect may simply be a result of gender imbalance, generally favoring female participants (Kenney & Prather, 1986; Smit et al., 1990; Templin, 1957). The fact remains, however, that transcribers' judgments of coda /l/ accuracy increased with children's age regardless of whether the improvement was linear in nature.

Our expectation that ratings of children's productions of both onset and coda laterals should improve with age (Hypothesis 1) was only partially confirmed. Ratings of coda lateral productions did significantly improve with age, but ratings of onset lateral productions did not. However, the lack of improvement in onset lateral productions is most likely due to even the youngest children in our study being capable of producing perceptually accurate onset /l/s.

In contrast, our expectation that onset laterals should be acquired earlier than coda laterals (Hypothesis 2) was clearly supported by the data. By ages 6;0 and 7;0, the children in our study achieved only 50% to 60% accuracy in coda /l/ productions, whereas they achieved more than 90% accuracy in onset /l/ productions. Of the 25 children whose productions were analyzed in this study, only four—one 5-year-old, one 6-year-old, and two 7-year-olds—demonstrated 75% or better accuracy when producing coda /l/s. In comparison, only three children demonstrated poorer than 75% accuracy in production of onset laterals; two of these three children's productions were less than 5% below the 75% accuracy level.

In all, the data establish that the timeline for acquisition of onset and coda laterals by Australian English children is similar to previously established norms for American English children, although perhaps not identical. Our data show that onset laterals are acquired earlier than age 3;0, whereas coda laterals are acquired after age 7;11. Both of these values are at the extremes (low and high, respectively) of previously reported norms for typically developing American English–speaking children (e.g., Prather et al., 1975; Smit et al., 1990; Templin, 1957). It is of potential relevance to the ceiling effect found in onset /l/ productions that the data collected in our study were single words spoken in isolation, in a laboratory setting, rather than recordings of spontaneously produced speech. Words spoken in laboratory speech studies by adults are known to be produced differently than words produced in spontaneous speech (Bradlow, 2002; Moon & Lindblom, 1994), and it is possible that the same was true for these children, resulting in relatively high overall accuracy in our data compared with how they may have produced laterals in spontaneous speech. (However, for similar results in both conditions, see Song et al., 2009.)

On the other hand, the child participants' coda lateral productions were regularly perceived to be vocalized—transcribed as /w/ or a back vowel. It is possible that despite this study targeting children being raised in Sydney, a region not known for strong postvocalic /l/ vocalization, exposure to vocalized coda laterals in media or via nonlocal relations may postpone development of perceptually accurate nonvocalized coda /l/. As an alternative, this may be the developmental pattern also found in other varieties of English.

Articulatory Variability

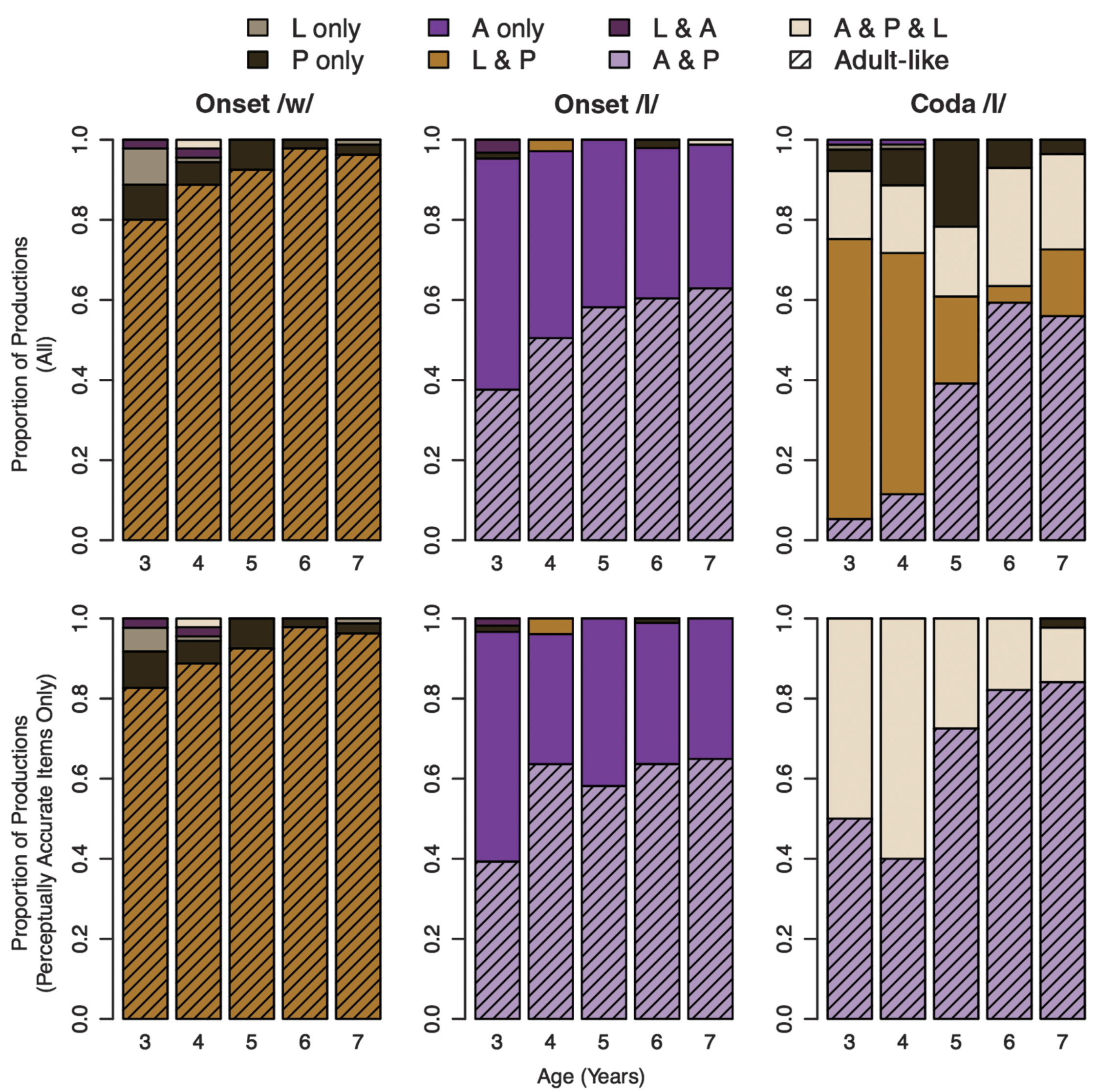
Table 4 illustrates the types of possible combinations of articulations produced by the child participants in this study for onset and coda laterals as well as the control consonant /w/. Figure 4 shows the distribution of these combinations produced by the child participants in this study; the top panel shows all child productions, and the bottom panel shows those productions rated as being perceptually accurate.

Table 4. The six articulatory combinations possible for the three constrictions (anterior, posterior, labial) and percentage of each combination produced by child participants rated as accurate productions of target segments.

	Constrictions			Target segments (%)		
Adult-like	Anterior	Posterior	Labial	Onset /w/	Onset /l/	Coda /l/
	Yes	Yes	Yes	—	—	29
/l/	Yes	Yes		—	99	91
/w/		Yes	Yes	100	—	0
	Yes			—	85	—
		Yes		33	—	7
			Yes	60	—	—

Note. Combinations appearing fewer than five times were not included in this table. Articulatorily adultlike productions are denoted in the left-most column. Dashes indicate data not reported.

Figure 4. Types of constriction combinations produced by children for onset /w/ (left), onset /l/ (middle), and coda /l/ (right) stimuli for all productions (top) and for productions rated as perceptually accurate (bottom). Articulatorily adultlike productions are located at base with diagonal lines. A = anterior lingual; P = posterior lingual; L = labial.



As Figure 4 (bottom panel) demonstrates, several perceptually accurate lateral productions were produced using a dominant anterior lingual constriction, with weak or absent posterior lingual and labial constrictions; this supports our hypothesis that at least some perceptually acceptable laterals produced by children should be produced using a dominant anterior articulation rather than an adult-like anterior–posterior lateral (Hypothesis 3). It is notable that all such productions occurred in onset position, although a single coda lateral production that was rated to be perceptually accurate was also observed by the articulatory coders to have a dominant posterior constriction with no labial constriction.

To test our hypothesis that the proportion of lateral targets produced with a single dominant lingual constriction decreases with age (Hypothesis 4), we ran a logistic mixed-effects model with number of lingual constrictions as the dependent variable, with Age (continuous, in years) and Position (onset or coda position) as fixed factors, and with interaction terms between age and position. The dependent variable (constrictions) was binary, with a value of 1 or 2 regardless of whether the constriction was anterior or posterior. Only one lateral production collected in our data was produced with no observed lingual gestures at all. For the purposes of this analysis, that item was not included. Subject and Repetition were included as random factors. As with auditory accuracy, an initial model with Vowel Quality as a third fixed factor, including full interactions, was also fit to the data and ruled out; a log-likelihood ratio test between these two models showed that inclusion of Vowel as a fixed factor did not significantly improve fit, $\chi^2(4, 10) = 5.94$, $p = .2040$. Thus, although we cannot rule out the possibility that surrounding vowel quality had an impact on the magnitude and position of the labial constrictions, our data did not demonstrate a significant effect of vowel quality on the apparent number of lingual constrictions created during lateral productions and attempts, as visually determined by the articulatory coders.

As predicted, proportion of laterals produced with a dominant lingual constriction decreased with age for both onset laterals ($B = -0.26$, $SE = 0.11$, $p = .0264$) and—by setting base comparison level of position to coda—coda laterals ($B = -1.02$, $SE = 0.15$, $p < .0001$). The model also demonstrated a significant effect of position, such that coda laterals were significantly more likely to be produced using a dominant lingual constriction than were onset laterals ($B = 3.99$, $SE = 0.94$, $p < .0001$) by the youngest children in this study. However, as exemplified by Figure 4 (top panel), these productions were, by and large, /w/ substitutions—coda laterals produced with posterior lingual and labial constriction. The model also revealed a significant Age × Position interaction ($B = -0.76$, $SE = 0.18$, $p < .0001$), such that children's adoption rate for (adultlike) anterior–posterior articulation for /l/ was steeper for coda laterals than for onset laterals. This interaction can be observed in Figure 4 (top panel). In general, the data from this study support both articulatory hypotheses: (a) that at least some productions of laterals rated as perceptually accurate were produced with an anterior-dominant articulation and weak or absent posterior constriction (Hypothesis 3) and (b) that the proportion of lateral attempts (whether deemed auditorily acceptable or not) produced with anterior- or posterior-dominant articulations decreased as a function of age in favor of adult-like anterior–posterior productions (Hypothesis 4).

Additional Articulatory Observations

Several additional observations, based on the articulatory data, are made below. These observations do not directly address the hypotheses but do inform the discussion. As shown by Figure 4 (top panel), onset /w/ productions were almost always (93%) produced with articulatorily adultlike constrictions—a posterior lingual constriction with labial constriction. The most common alternate production (5% of total /w/ productions) involved lip rounding or protrusion only with no lingual constrictions. That lip rounding alone dominates these productions is likely due to the visual accessibility of the labial articulation in /w/ productions, as is suggested for acquisition of rounded vowels (Ménard, Dupont, Baum, & Aubin, 2009; Ménard, Leclerc, Brisebois, Aubin, & Brasseur, 2008). Transcribers' perceptual ratings of these productions were inconsistent, with 63% of these labial-only /w/ productions rated as perceptually accurate. The remaining were transcribed as the back unrounded vowel /ɯ/.

For target coda laterals, by far the most common articulatorily variant that was not articulatorily adultlike (33% of total coda /l/ productions) resembled /w/ and involved a posterior lingual constriction and labial constriction. These were all (100%) transcribed as /w/-, /o/-, or /u/-like, indicating vocalization.

In addition to vocalization, two notable articulatory variants for target coda /l/ were found: posterior dominant with no appreciable labial constriction, or showing all three constrictions (anterior lingual, posterior lingual, and labial). The first of these appeared in 10% of the target coda /l/ productions and was rated as being accurate very rarely (7% of the 10%). All other productions of this variant were transcribed as vocalized. The second variant, involving all three articulatory constrictions, made up 21% of the target coda lateral productions and were rated as being perceptually accurate more often than the posterior-dominant variant (38% of the 21%). These two variants are suggestive of an intermediate phase between vocalized and adultlike coda /l/s, during which children drop labial constriction and add or enhance the adultlike anterior lingual constriction. Although we can only speculate about the precise mechanisms by which this occurs, our data are most consistent with a timeline in which acoustic feedback and articulatory maturation may result in the addition or strengthening of the anterior lingual constriction. Around the same time, lip rounding or protrusion may be dropped in accordance with visual feedback that labial constriction is not typical for coda /l/ production. When these developments are not concurrent, the result is one of these two coda /l/ variants: Dropping of lip rounding before development of anterior constriction results in a posterior-dominant variant, whereas developing the anterior constriction first leads to a variant involving all three constrictions.

It is also possible that children who use posterior-dominant variants of coda laterals with no labial constriction never develop a labial-involved variant for coda laterals at all. These children might develop directly from a posterior-only variant to an adult-like anterior–posterior variant. However, in our data, only two children (ages 5;5 and 6;10) utilized the posterior-only variant more than once, and of these two, the child aged 6;10 produced even more coda laterals with a labial constriction. Thus, although this account is entirely plausible, it appears to be a relatively uncommon developmental pathway to adultlike coda lateral production.

Discussion

Our expectation that the proportion of perceptually accurate productions of laterals would increase with age was upheld for coda laterals. Only 5% of target coda /l/s produced by the 3-year-old group were perceived by our transcribers as sounding accurate; by age 7 years, perceptually accurate production of coda /l/ increased to 52%. In contrast, nearly all target onset /l/ productions were rated as perceptually accurate regardless of participant age, thus placing age of acquisition of onset /l/s before 3;0—closer to the normative age of acquisition provided by Prather et al. (1975) than to that provided by Smit et al. (1990). Accuracy of control /w/ production was similarly uniformly high, as expected.

Onset /l/ Articulation

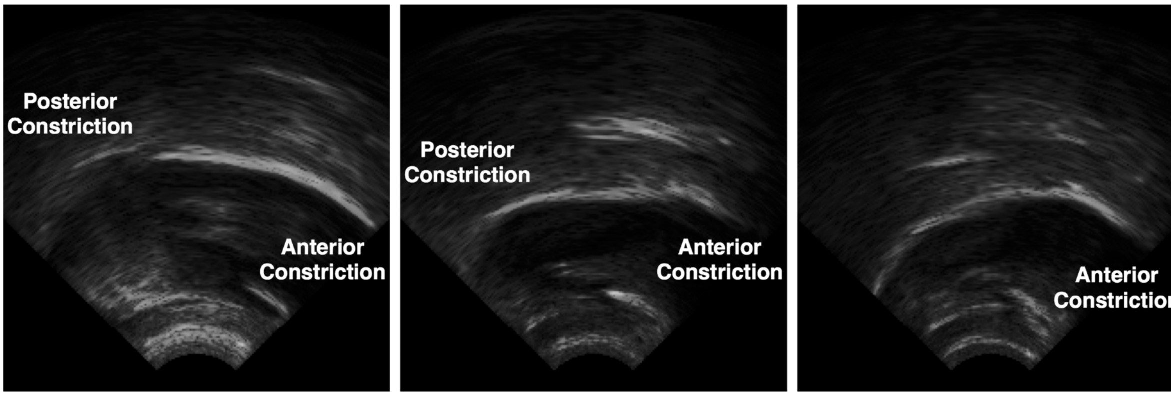
As predicted, several lateral productions rated as being perceptually acceptable by the transcribers were produced with an anterior-dominant articulation rather than with pronounced anterior and posterior articulations. These anterior-dominant productions were overwhelmingly onset /l/s rather than coda /l/s. Also as predicted, the proportion of anterior-dominant productions of onset /l/ decreased with age, whereas anterior–posterior onset /l/ productions became more frequent. Although the anterior-dominant variant of onset /l/s was typically rated as being perceptually accurate, it was rated as being accurate less frequently than the articulatorily adultlike anterior–posterior variants (85% compared with 98%, respectively). The variability in lingual articulation exists both between and within speakers. Figure 5 (middle and right panels) shows ultrasound stills from two onset laterals from two productions of the word *leap* by the same child speaker. The production shown in the middle panel demonstrates both posterior and anterior lingual constrictions (compare this with the adult's production in the left panel of Figure 5), whereas the production on the right shows a pronounced anterior constriction and no visible posterior constriction, strongly resembling a light [l] articulation. This variability is most likely also reflected in the acoustic reality of onset /l/ realizations and suggests that discrepancies between reported age of acquisition of laterals (e.g., Prather et al., 1975, vs. Smit et al., 1990) may be due not only to instrumental or procedural differences but also to intertranscriber differences with respect to what amounts to an accurate lateral. Because light [l] and dark [ɫ] do not contrast phonemically in either American or Australian English, a native speaker of either variety of English may rate [l] and [ɫ] as being equally good. A phonetically trained transcriber may, however, be more sensitive to the differences between these two types of lateral and may rate [l] as being less like adults' speech. The situation is especially muddled because the status of light versus dark laterals falls on a continuum rather than into discrete categories (Recasens, 2004; Sproat & Fujimura, 1993).

Given the difficulties that children (especially those younger than age 5;6) were expected to have with production of two simultaneous lingual articulations, it is striking that our child participants produced as many articulatorily adultlike anterior–posterior onset /l/s as they did. Why would children develop anterior–posterior productions of onset /l/ when anterior-dominant onset /l/s, which are presumably less complex, are perceptually sufficient for adult perceivers? We offer several potential explanations. One possibility is that, despite onset /l/s and coda /l/s being phonologically and phonetically distinct (Giles & Moll, 1975; Sproat & Fujimura, 1993), learners collapse them into a single phonemic category. If articulatory information is shared between the two contexts, the lingual configuration required to produce coda /l/s would become projected onto onset /l/s as well. However, children in our study produced adultlike /l/ articulations in onset position before they produced articulatorily adultlike coda /l/s, so this account does not provide adequate explanatory coverage.

More likely, the anterior-dominant onset laterals produced by many of our child participants are perceptually sufficient to induce an /l/ percept but are not actually acoustically or articulatorily equivalent to adults' productions of English onset /l/s. As children amass experience with adults' speech, their acoustic/auditory targets for laterals may become narrower, and they may in turn be more likely to meet these targets. This hypothesis may be investigated in future studies by analyzing the acoustics of the articulatory variants of onset /l/s and testing their perceptual equivalence with both child and adult listeners.

A third possibility is that development of an articulatorily complex onset /l/ may be necessary for the production of onset consonant + /l/ clusters, which begin to appear around age 4;0 (Smit et al., 1990; Templin, 1957). This should be especially true for /C_{velar}l-/ clusters such as those in *clap* or *glue*. Coarticulation from an initial velar consonant onto a following lateral would result in the introduction of a posterior constriction during production of these /l/s. This may then become generalized across all onset /l/s, including singleton /l/. This is an intriguing possibility in light of Gierut and O'Connor's (2002) linking of faithful onset cluster production with the acquisition of liquid (/l/ vs. /r/) contrast. This hypothesis makes several predictions. First, it predicts that children's productions of articulatorily adult-like anterior–posterior onset /l/s should correlate

Figure 5. Single ultrasound frames from onset lateral production in the word *leap* from an adult speaker (left panel) and one child participant, age 5;5 (middle and right panels). The child's productions varied between articulatorily adultlike (middle) and anterior only (right).



with a rise in production of onset clusters. In other words, children who produce onset /l/s with both anterior and posterior lingual constrictions should be better at producing onset consonant + /l/ clusters than their peers who produce anterior-dominant /l/s.

This hypothesis would also predict that a given child should be able to produce onset labial + /l/ clusters (*blue*) before onset velar + /l/ (*glue*) or onset alveolar + /l/ (*sleep*) clusters. Neither Templin (1957) nor Smit et al. (1990) reported substantial differences in mean acquisition time between velar + /l/ clusters and labial + /l/ clusters. However, both studies report on acquisition over a relatively wide age range (4;0–5;0 and 4;0–5;6, respectively), and adoption of a coarticulatory effect across all /l/ contexts may well occur on a shorter time scale. Furthermore, even after acquisition of consonant + /l/ clusters, children's productions of different types of clusters may still differ. A child who primarily uses an anterior-dominant onset lateral might be expected to produce labial + /l/ clusters with greater gestural overlap than velar + /l/ or alveolar + /l/ clusters. This would manifest in faster articulations and therefore shorter productions of labial + /l/ clusters than velar + /l/ or alveolar + /l/ clusters. In contrast, a child who uses articulatorily adultlike anterior–posterior laterals would be expected to exhibit no significant differences in degree of gestural overlap between labial + /l/ and velar + /l/ clusters. Using EPG data, Cheng, Murdoch, and Goozée (2007) demonstrated that gestural overlap during productions of /kl-/ clusters increases as children age. However, without analogous data for /pl-/ or /sl-/ clusters (because /tl-/ is not a possible English onset cluster), we are unable to speculate further on this topic.

Coda /l/ Articulation

Coda lateral articulation, in contrast, proceeded along the same developmental trajectory as its perception. For the most part, coda laterals that were produced with adultlike anterior–posterior constrictions were perceived to be accurate coda /l/s. Also, nearly all (93%) target coda lateral productions that were rated as being perceptually accurate were produced with adultlike articulation.

It is notable that none of the children in our study adopted an anterior-only production of coda laterals despite the prevalence of this articulatory variant in onset lateral production. Why should this asymmetry exist? Although light and dark laterals in English exist on a continuum, onset and coda laterals do still tend to be perceptually distinct (Sproat & Fujimura, 1993); typically, coda laterals have lower F2 values than do onset laterals, and this low F2 may be enhanced by lip rounding or protrusion. Thus, the early dominance of lip rounding in children's coda /l/ productions suggest that children may place a premium on acoustic/auditory similarity to adults' speech over articulatory similarity.

This may also help explain the steep increase in articulatorily adultlike coda /l/ productions between ages 5;0 and 6;0 compared with the modest increase in articulatorily adultlike onset /l/s. There may be significant auditory/perceptual pressure on children to produce articulatorily adultlike coda laterals as soon as they are capable because the prevailing nonadultlike variants do not pass as perceptually accurate coda /l/s. In contrast, onset laterals produced with only an anterior constriction do typically pass as perceptually accurate onset /l/s.

Conclusions

In this study, we sought to establish an articulatory timeline for the development of onset and coda /l/s in Australian English. Our data suggest that Australian English–speaking children's norms are similar to those established by studies of other English-speaking children. The data also reveal that these children are capable of creating perceptually acceptable laterals that differ in articulatory configuration from adults' productions, consistent with previous findings for children's productions of laterals (Cheng, Murdoch, & Goozée, 2007; Oh, 2005). With technology continuously improving the accessibility of articulatory data from children's speech, we believe that it is reasonable to begin formulating articulatory norms that exist in conjunction with perceptual norms. Of course, one caveat to comparing data from the present study (and similar studies) with existing acoustic and perceptual norms is that our data consisted of isolated /CVC/ words produced in elicited imitation rather than spontaneous productions. Therefore, this relationship can be taken only so far for the time being.

Our understanding of how speech sounds are acquired depends critically on at least three branches of research: development of the passive articulators (e.g., oral cavity, nasal cavity, teeth), development of the active articulators (e.g., tongue, lips, velum), and variability of articulatory configurations during speech development. By linking findings from these three branches of research, we can better understand not only the physiological components of speech development but also how this maps onto cognitive and linguistic representations. For instance, Magloughlin (2013) reported that even identical twins, whose physiologies are presumably very similar, may differ in articulatory strategies for producing English /ɹ/, demonstrating that development of articulatory targets cannot be purely physiological. Data from this study suggest that articulatory strategies vary not only between children but also within productions from a single child, consistent with a high degree of articulatory exploration that persists until the child converges on his or her language community's established articulatory and acoustic/perceptual norms.

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