Three-year-olds' production of Australian English phonemic vowel length as a function of prosodic context

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Durational contrasts are used not only to signal phrasal boundaries and focused constituents, but also to make phonemic distinctions. Boundary and focus effects can therefore interact with phonemic length contrasts, presenting a challenge for learners. Boundary effects are most clearly seen in the syllable rhyme, where the nucleus and coda are longer in utterance-final compared to utterance-medial position, the magnitude of lengthening diminishing leftward from the end of the word. In the case of focus, where the nucleus and coda are also lengthened, the magnitude of lengthening diminishes rightwards toward the end of the word. The goal of this paper was therefore to compare productions of the phonemic vowel length contrast /ɐː/ vs /ɐ/ in adults and 3-yr-old children learning Australian English in the face of competing demands from boundary and focus lengthening. The results showed that the children maintain the /ɐː/ vs /ɐ/ contrast across prosodic contexts. They are also able to implement an adult-like pattern of boundary-related lengthening, but are still developing focus-related lengthening. The findings suggest that these 3-yr-olds have good command of the phonemic vowel length contrast, but are still fine-tuning language-specific aspects of temporal organization (i.e., the *vowel-coda trading* relationship) within the rhyme.
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I. INTRODUCTION

The acquisition of phonemic vowel length contrasts may present more of a challenge for learners than vowel quality contrasts. In a perceptual study, Sato *et al.* (2010) found that Japanese infants were sensitive to vowel quality distinctions at 4 months, but could not distinguish vowel length contrasts until 9.5 months. Speech production studies have found that vowel quality contrasts are acquired early (Templin, 1957; Stoel-Gammon and Herrington, 1990; Salidis and Johnson, 1997), with Templin (1957) reporting 93% correct vowel production for American English-speaking children by the age of three. However, few studies have specifically examined the acquisition of vowel *quantity* contrasts (i.e., phonemic vowel length). Kehoe and Lleó (2003) showed that the three German-speaking children in their study began to distinguish long and short vowels around 2;3–2;6 yrs. Children around this age have also been reported to show an interaction between phonemic and contextual vowel duration. For example, Buder and Stoel-Gammon (2002) examined coda voicing-related durational adjustments for vowels produced by Swedish-speaking and American English-speaking children. Phonemic vowel length was found to emerge in the Swedish-speaking children around 2;6 yrs. At this age the children also started attenuating the articulatory predisposition for vowel duration to be affected by coda voicing (contextual duration). This suggests that, by 2;6 yrs, Swedish-speaking children are attuned to language-specific aspects of phonemic vowel length, beginning to downplay voicing-related durational adjustments. American English-speaking children, on the other hand, did not attenuate contextual voicing, perhaps because phonemic vowel length does not carry the same contrastive function in English as it does in Swedish.

Children must therefore learn to accommodate various vowel length effects according to language specific requirements. This raises many questions about how and when the interplay between phonemic vowel length and phonological context is learned. To investigate these issues, we turned to non-rhotic standard Australian English (AusE), where some vowels are phonemically distinguished primarily by length.

There are 12 stressed monophthongs in non-rhotic AusE (/iː/, /ɪ/, /eː/, /e/, /ɜː/, /æ/, /ɐː/, /ɐ/, /oː/, /ɔ/, /ʉː/, /ʊ/). The vowel symbols used in this paper are those adopted by Cox and Palethorpe (2007) in their illustration of AusE. In this paper we were interested in the pair of open vowels that exhibit a phonemic vowel length distinction. According to Cox (2012), the central open vowels /ɐː/ and /ɐ/ (as in "pass"[1] and "pus") have minimal spectral differences in the $F1/F2$ plane. In Cox's (2006) vowel study of 120 adolescent speakers of AusE (60 males and 60 females), the mean $F1$ and $F2$ values of /ɐː/ for male speakers were 757 and 1349 Hz and for /ɐ/ were 743 and 1386 Hz, respectively. The female speakers had mean $F1$ and $F2$ values for /ɐː/ of 955 and 1525 Hz and for /ɐ/ of 941 and 1553 Hz. While these values indicate that /ɐː/ and /ɐ/ showed minimal spectral difference, they were distinguishable from one another in terms of duration (282 ms for /ɐː/, 161 ms for /ɐ/). In spite of the minimal difference at the steady state of the vowels, it is possible that some spectral differences might persist in terms of the

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on-glide to and off-glide away from the steady state (Bernard, 1970). Watson and Harrington (1999) used a set of Gaussian classification experiments to establish the degree to which AusE vowels could be separated from each other. They compared a simple "target" model with a "dynamic" model of the vowel formant contour based on discrete cosine transform (DCT) coefficients. They found that both models performed equally well in differentiating monophthongs when durational data were included, suggesting that the formant on-glide and off-glide are not critical to the distinction of the long/short vowel pairs. An examination of Watson and Harrington's (1999) results shows that excluding duration from the input data greatly reduced the ability of both models to correctly classify /ɐː/ and /ɐ/. For instance, when duration was excluded from the DCT model, the classification scores for /ɐː/ dropped from 98.5% to 67.6% correct for females and 98.4% to 77.4% correct for males. For /ɐ/, classification scores dropped from 91.4% to 80% correct for females and 98.4% to 64.5% correct for males. In addition, Bernard (1967), who manipulated the steady state duration in two vowel identification experiments, further confirmed the primacy of vowel duration in signaling the distinction between the /ɐː/ - /ɐ/ pair.

This pair of vowels is therefore particularly interesting because it provides an ideal opportunity to investigate the acquisition of the phonemic vowel length contrast in various prosodic contexts in a language where phonemic vowel length is not systemic, as it is, for example, in Swedish or Japanese. We might then expect that learning to maintain the phonemic vowel length contrast for this pair of vowels in AusE would be even harder for children than in languages where phonemic vowel length contrasts play a systemic role in the vowel system.

In a recent study, Cox and Palethorpe (2011) showed that phonemic vowel length also interacted with the coda within the rhyme. In the context /hVd/ vs /hVːd/, AusE-speaking adults produced shorter closure duration in long vowel items (a trading relationship) compared to short vowel items. This raises additional questions about if and how learning the vowel length contrast might also be reflected in the duration of the coda, and whether this will interact with prosodic contexts.

In the adult literature, segmental duration has been reported to vary as a function of phonological/prosodic context (Klatt, 1975, 1976; Fletcher and McVeigh, 1993). Klatt (1976) examined many factors contributing to the durational structure of the sentence in American English. For instance, duration could be used as the primary cue to distinguish (1) long vs short vowels, (2) voiced vs voiceless fricatives, (3) voiced vs voiceless postvocalic consonants, (4) phrase-final vs non-final syllables, (5) stressed vs unstressed vowels, (6) the presence vs absence of focus/accent. In AusE, Fletcher and McVeigh (1993) examined the segmental durations of a male speaker from the SHLRC-ANDOSL database (Vonwiller *et al.*, 1995), confirming the durational contrast between the /ɐː/ - /ɐ/ vowel pair. In line with Klatt (1976), they also identified final lengthening and accentuation as factors contributing to segmental and syllable duration.

In light of these findings, we focus on two different extrinsic contexts (utterance position and focus accent) to examine how these interact with phonemic (intrinsic) vowel length in language acquisition. The positional effect involves utterance-final lengthening, where a syllable/word occurring at the boundary of an utterance is lengthened. This phenomenon has been widely reported in English (Lehiste, 1973; Oller, 1973; Klatt, 1975, 1976; Lehiste *et al.*, 1976; Cooper and Paccia-Cooper, 1980; Scott, 1982; Wightman *et al.*, 1992; Turk and Shattuck-Hufnagel, 2007) and other languages (Hebrew: Berkovits, 1993a,b, 1994; Dutch: Hofhuis *et al.*, 1995; Finnish: Nakai *et al.*, 2009; Nakai *et al.*, 2012). This type of lengthening appears to be progressive, affecting the segments within a syllable to different degrees (Turk and Shattuck-Hufnagel, 2007). The coda consonant immediately adjacent to the utterance boundary is lengthened the most, followed by the nucleus and then the onset consonant. In other words, the domain of utterance-final lengthening is the utterance-final syllable, and the direction of the lengthening is *leftward* from the right edge of the syllable adjacent to the utterance boundary (i.e., progressive lengthening). This positional effect has also been observed in children. Snow (1994) reports that American English-speaking children exhibit utterance-final lengthening by around 2 yrs of age (see also Yuen *et al.*, 2011), although it is still an open question whether children would also show *progressive* final lengthening like the adults.

The other type of lengthening involves accentual lengthening, where a syllable/word is lengthened when it contains a focus accent (Turk and Sawusch, 1997; Cambier-Langeveld and Turk, 1999; Turk and White, 1999; Turk and Shattuck-Hufnagel, 2000). Turk and Sawusch (1997) examined the effect of focus accent on segmental duration in American English-speaking adults and observed that lengthening took place within the accented syllable, and that the extent of the effect depended on the position of the segment within the syllable. For instance, the onset consonant /f/ of the accented syllable/word "*farm*" in "*bee farm*" is longer than the same segment in coda position of the accented syllable/word "*beef*" in "*beef arm*." Thus, the *onset* consonant of an accented syllable (e.g., *farm*) is lengthened more than the *coda* consonant of an accented syllable (e.g., *beef*). A further study by Turk and White (1999) reported that asymmetrical accentual lengthening of monosyllables also operated across word boundaries. For instance, the word "*Mark*" in a sentence like "*Bless Mark now*" tended to be longer when the focus accent fell on "*bless*" than when it appeared on "*now*." These findings suggest that accentual lengthening spreads *rightwards* from the beginning of the word under focus (i.e., regressive lengthening). It remains unclear whether children also exhibit regressive accentual lengthening.

In a recent study on the interaction of prosodic lengthening and vowel length contrasts in Northern Finnish, Nakai *et al.* (2009) showed a ceiling effect in which an allophonically half-long *final* vowel in a CVC<u>V</u> word was less influenced by utterance-final lengthening relative to the other vowels. The authors proposed a durational ceiling constraint which would provide a safeguard against perceptual confusion with phonemic long vowels in Northern Finnish. It is possible that a similar durational constraint might also operate in AusE across different extrinsic contexts in order to maintain the vowel length distinction.

Although the direction of utterance final lengthening is progressive whereas that of focus accent is regressive over a domain such as the syllable or rhyme, they converge on the nucleus where the vowel length contrast in AusE must be learned. Learners must process the input they hear from different prosodic contexts in order for these language-specific segmental and prosodic aspects of lengthening to be learned. Perhaps this is why some of the literature suggests that vowel *quality* distinctions are more easily learned, appearing before vowel *quantity* distinctions, at least in perception (Sato *et al.*, 2010). The goal of the present study was to examine the extent to which AusE-speaking 3-yr-olds can maintain phonemic vowel length contrasts under the prosodic conditions of utterance position and focus accent and compare this to adults' productions. This would shed light on the nature of the developmental processes involved in learning about the interaction between intrinsic vowel duration at the *segmental* level, and extrinsic duration at the higher, *prosodic* level of structure.

The main questions of this paper are thus the following: (1) Do children around 3 yrs of age distinguish phonemic (intrinsic) vowel duration in AusE (which has some phonemic vowel length contrasts but not systemic vowel length contrasts as in Japanese or Swedish), (2) have they learned about the interaction between phonemic vowel length and coda duration (the trading relationship) within the rhyme, (3) do they exhibit utterance-final lengthening and accentual lengthening, and (4) is utterance-final lengthening progressive and accentual lengthening regressive? To address these questions, we compared children's productions to those of adults.

II. METHOD

A. Task

We used an elicited imitation task to evaluate children's ability to maintain phonemic vowel length contrasts across prosodic contexts. This type of task circumvents the problem of young children's lack of reading ability, and facilitates the elicitation of controlled speech production data. The task is based on the assumption that children can only repeat what they process (Mattes, 1982). Elicited imitation along with acoustic analysis has been widely used to explore the nature of children's developing phonologies (see also Theodore *et al.*, 2012; Song *et al.*, 2012), allowing researchers to tap into the phonological representations that young children have access to when generating speech.

B. Participants

Twelve monolingual AusE-speaking children from the Sydney area (four male, eight female) participated in the study. Their ages ranged from 2.0 to 3.5 yrs (mean age of 2.9 yrs). According to their parents, they were healthy and typically developing with no speech and hearing problems. The short form of the MacArthur Communicative Development Inventories (CDI) 100-word checklist was used as a screening tool to ensure typical language development (Fenson *et al.*, 2000). The raw CDI scores ranged from 85 to 100 (mean of 95.08). Five other children participated but were not included in the analysis: Four did not reach the criterion of producing 80% of the test items, and one added a lateral /l/ to the onset consonant, resulting in a consonant cluster for most of the test items.

We also recruited ten monolingual AusE-speaking undergraduate students (three male, seven female) to serve as a baseline control against which the children's productions were compared. Their ages ranged from 20 to 32 yrs (mean age of 25.1 yrs).

C. Stimuli

Four C_1VC_2 novel word test items were constructed from the /ɐː/ and /ɐ/ pair of vowels that contrast in phonemic vowel length in AusE. Novel words were used because there were few minimal word pairs that were comparable in lexical frequency and that 3-yr-old children would know. To ensure easy segmentation and subsequent acoustic analysis, we used a plosive consonant for C_1 and a fricative consonant for C_2 to construct the novel words: /kɐːs/, /kɐs/, /gɐːs/, and /gɐs/. In this set the item /gɐs/ could be considered a proper name *Gus*, arguably a potential word. To check whether this item might be familiar to children, we ran ChildFreq (Bååth, 2010) using the CHILDES database to calculate the word frequency of the item, which were 2 out of a million for children at 36 months. Given the very low frequency of this item as a proper name in Australia, we considered all the test items to be novel and unfamiliar to the children under investigation.

The onset plosive is characterized by discontinuity in the acoustic signal in the form of closure and burst release. The vowel is characterized by continuous periodicity and resonances in the vocal tract. These acoustic properties were used to reliably identify C_1 (onset) and the vowel. Similarly, /s/ for C_2 was chosen because this fricative is voiceless and characterized by continuous aperiodic noise, thereby contrasting with the continuous periodicity of the vowel. To provide variety to the test items so that children would remain engaged throughout the task, we manipulated the voicing status of C_1. Voicing was balanced across the stimuli. These novel words were used as proper names to refer to a picture of a novel animal/toy in cartoon format.

The four novel words were embedded in a carrier sentence to create four test conditions on two dimensions: (1) Utterance position: Final vs medial, (2) focus accent: + vs − to generate 16 stimulus sentences, shown in Table I.

A female AusE-speaking adult recorded the stimuli in child-directed speech. These served as the auditory prompts. The AusE speaker was instructed to put focus accent on the test word in the accented condition, whereas the default focus accent fell on the verb in the unaccented condition. These auditory prompts were analyzed to check whether the target words were accented by examining fundamental frequency (*f*0) (Turk and Sawusch, 1997; Turk and White, 1999). *F*0 was automatically extracted over the target vowels

TABLE I. Sixteen stimuli in two positions (Final vs Medial) and two focus accent conditions [+ vs −].

Position	Focus accent [+]	Focus accent [−]
Final	There goes **Karrs**	Now goes Karrs
	Here comes **Garrs**	In comes Garrs
	There goes **Kus**	Now goes Kus
	Here comes **Gus**	In comes Gus
Medial	There **Karrs** goes	Now Karrs goes
	In **Garrs** comes	In Garrs comes
	There **Kus** goes	Now Kus goes
	Here **Gus** comes	In Gus comes

in Praat at seven equidistant time points, with pitch minimum set at 75 Hz and maximum at 600 Hz. We excluded *f*0 values at the first and the last time points in order to avoid intrinsic *f*0 perturbation from the onset and coda consonants. *F*0 values at time points overlapping with creak/glottalization could not be reliably estimated in Praat and were therefore not taken into consideration in calculating the average *f*0 value of the accented vowel. The *f*0 values, which were checked and corrected for any octave jump and halving, were then averaged. The average *f*0 of the accented vowels from the model speaker was 358 Hz, and that of the unaccented vowels was 156 Hz. In other words, there was a noticeable *f*0 difference of 202 Hz in the accent [+] condition. The same procedures were applied to the two experimental groups (adults vs children) to extract *f*0 values.

The average vowel and coda durations of the model speaker's productions are summarized in Table II. The auditory stimuli showed the following characteristics: (1) The long vowel (i.e., VV) was longer than the short vowel (i.e., V) in corresponding contexts, (2) the coda of the word containing the long vowel (i.e., coda_VV) was shorter than that of the word containing the short vowel (i.e., coda_V) in corresponding contexts, showing the expected vowel-coda trading relationship, (3) the vowel and the coda were longer in the utterance-final position than in the medial position, (4) the vowel and coda were generally longer with a focus accent than without, yet there was little difference between the coda duration across focus accent conditions. The 16 stimulus sentences were pseudo-randomized and embedded with the accompanying pictures of the novel items in a PowerPoint display for presentation.

TABLE II. Mean vowel and coda durations (in ms) of the AusE-speaking model's production as a function of position [Final vs Medial] and focus accent [+ vs −].

		Words with long vowels		Words with short vowels	
Position	Focus accent	VV	Coda /s/	V	Coda /s/
Final	[+]	423	267	220	276
	[−]	351	241	195	285
Medial	[+]	257	154	137	190
	[−]	209	124	160	127

D. Experimental procedure

Each participant was invited into a sound proof studio to participate in a "language game." This involved looking at the pictures on a computer display while repeating the pre-recorded auditory prompts presented via speakers (Altec BXR1220) placed on both sides of the Mac computer. A Behringer C2 microphone was placed directly in front of the participants to record their speech productions. Recordings were made at a sampling rate of 44.1 kHz through a pre-amplifier (Digidesign Mbox2) connected to a separate Mac computer running ProTools LE. Four practice trials were used to familiarize participants with the task before testing began. The parents were asked to complete the McArthur CDI vocabulary questionnaire, after the child participants completed the task. The entire procedure took approximately 20 min, often less for the adult participants. The analysis and findings for both are presented below.

E. Acoustic coding

A trained coder annotated the data using Praat (Boersma and Weenink, 2005). We used wideband spectrograms (with the duration of the analysis window set at 0.005 ms), waveforms, and auditory impressions to identify and demarcate the following acoustic events in the target words: (1) The beginning and the end of the vowel and (2) the beginning and the end of the fricative coda. We demarcated the vowel on the basis of *F*2. We used the end of *F*2 and the beginning of high-energy aperiodic noise to identify the beginning of the fricative coda. For the end of the fricative, we used the cessation of frication (high frequency aperiodic noise).

A total of 145 items were coded for the children. Eighteen tokens (12%) were randomly selected across all the conditions for reliability checking by a second trained coder. The average inter-coder difference was 2 ms for the vowels and 18 ms for the fricative coda across all the test conditions. The correlation between coder 1 and coder 2 was high, $r = 0.975$, $p < 0.001$. A total of 158 items were coded for the adults. Sixteen tokens from the adult data set (10%) were randomly selected for reliability checking. The average durational difference between the two coders was 6 ms for the vowels and 10 ms for the codas. The inter-coder correlation was again high, $r = 0.992$, $p < 0.001$. Analyses were based on annotated data from the first coder.

F. Predictions

Given previous findings for the acquisition of Swedish (Buder and Stoel-Gammon, 2002), we predicted that the AusE-speaking children and adults in this study would distinguish phonemically long and short vowels, as manifested in vowel duration and vowel ratio (i.e., VV/V). A vowel ratio greater than 1 would suggest that long vowels are longer than short vowels. The larger the vowel ratio, the greater the durational difference between the two vowels.

Cox and Palethorpe (2011) found that, for AusE-speaking adults, phonemic vowel length interacted with a vowel-coda trading relationship within the rhyme. The vowel-coda trading relationship was therefore expected for the adults in our study, with a short coda in the rhyme containing a long vowel, and vice versa. If the children showed a similar effect, this would indicate that they had already acquired subtle control of segmental duration within the rhyme. However, these effects might only be mastered later in life. The vowel-coda relationship would be reflected in coda duration and the coda ratio (i.e., coda_VV/coda_V). If children's short vowels co-occur with long codas, the coda ratio will be smaller than 1. However, if children's long vowels co-occur with long codas, the ratio will be greater than 1.

On the basis of findings from American English-speaking adults, we also expected progressive utterance-final lengthening in the AusE-speaking adults, with more coda lengthening in the target word immediately adjacent to the utterance boundary. In accordance with Snow (1994), we also expected that the children would lengthen both the vowel and coda in utterance-final position. They might also exhibit progressive lengthening patterns like those of the adults. If so, this would be reflected in the proportion of the vowel within the rhyme (i.e., vowel/rhyme). Without progressive lengthening, the vowel and coda would be lengthened in equal proportions (i.e., a constant factor) within the rhyme, and the vowel proportion measure would therefore stay the same.

We also anticipated accentual lengthening on the vowel for the adults, and possibly the children. Adults were predicted to attenuate accentual lengthening towards the coda (i.e., regressive lengthening). Children might do the same. Without regressive accentual lengthening, the vowel proportion would stay the same.

In light of the North Finnish data reported in Nakai *et al*. (2009), we hypothesized regulation in the use of extrinsic lengthening so that phonemic vowel length in AusE could be maintained, predicting a lengthening constraint on short vowels. This would be most likely to occur in those prosodic contexts where long and short vowels might overlap in their absolute intrinsic durations. Under this scenario, there would be a restriction on the degree of short vowel lengthening to minimize durational overlap with the lower limit of the long vowel. The long vowel, on the other hand, would not be subject to such a restriction. In other words, the short vowel would not be as freely lengthened as the long vowel, resulting in a reduction in the degree of lengthening. This disproportionate lengthening would then be reflected in a large VV/V vowel ratio in lengthening contexts.

III. RESULTS

A total of 160 items were possible for the 10 adults. One item was missing and one was mispronounced, resulting in 158 items for analysis. For the 12 children a total of 192 items were possible. Eighteen were excluded due to mispronunciation, clipping, or poor acoustic quality. Two children, who produced a total of 29 items, were further excluded from the analysis because they exhibited extreme values, suggesting exaggerated productions. These items were identified in SPSS as those that occurred outside ± 1.5 times the interquartile range. They were also disconnected from the overall distribution graphically in stem-and-leaf plots of the vowel and coda durations. These two speakers were aged 2.3 and 3.4 yrs. The auditory impression of their outliers showed some anomalous productions; for instance, a short vowel in the Acc[−] condition from one speaker was 3 times longer than that in the Acc[+] condition. In the other speaker, one coda was 3 times longer in the Acc[+] condition than in the Acc[−] condition. We therefore conducted two repeated measures analysis of variance (ANOVAs) on vowel and coda durations to compare the data set with and without the outliers. For both analyses, we observed the distinction of phonemic vowel length, the presence of accentual lengthening on the vowel, and the presence of utterance-final lengthening on the vowel and the coda. The statistical results were comparable between the two data sets, except for the effect of vowel on coda duration. Inclusion of the outliers might obscure this vowel effect.

Therefore, on the basis of the auditory impressions and the statistical comparisons, we considered it appropriate to exclude the identified outliers in the final analysis. Consequently, the final child data set included 145 items from 10 participants (mean age of 2.7 yrs).

To verify that the children actually produced focus accent on the test items, we measured the average $f0$ [standard deviation (SD)] of their test items, using the same procedures as for the model speaker. The $f0$ of the *accented* vowels was 352 Hz (52) and that of the *unaccented* vowels was 248 Hz (42), resulting in a difference of 104 Hz. A paired sample t-test showed significantly higher $f0$ for the accented vowels than for the unaccented counterparts with $t\,(9) = 3.919$, $p = 0.004$ (two-tailed). This is consistent with the adults who also exhibited an average $f0$ of 273 Hz (99) for the accented vowels and 159 Hz (45) for the unaccented vowels, with $t\,(9) = 5.593$, $p < 0.0001$ (two-tailed).

Overall lengthening patterns between adults and children are graphically represented in Figs. 1–3. As above, we

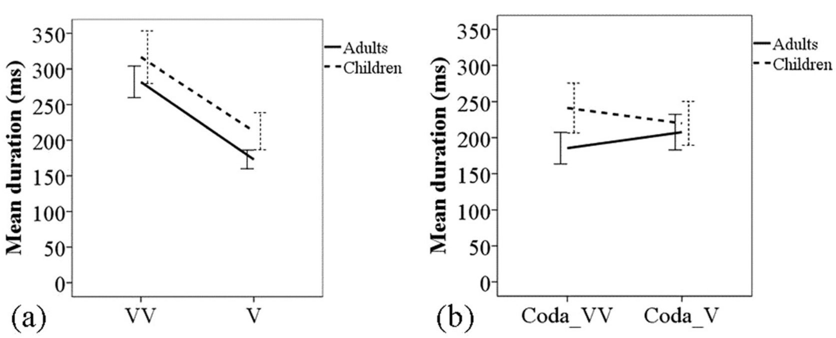

FIG. 1. (a) Average duration of long and short vowels (in ms) for adults and children with CI (confidence interval) at 95%, (b) average duration of coda co-occurring with long and short vowels (in ms) for adults and children with CI at 95%.

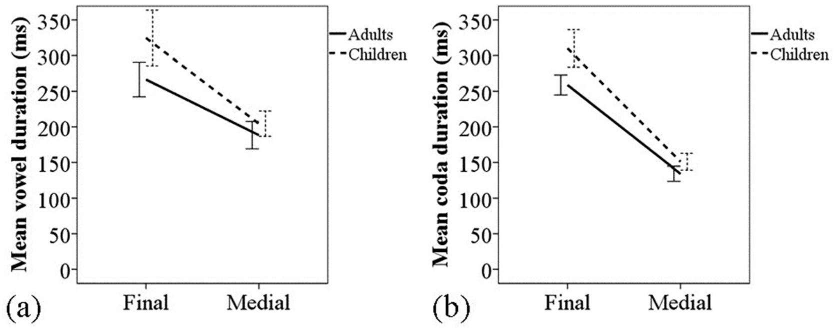

FIG. 2. (a) Average vowel duration (in ms) in utterance-final vs medial position for adults and children with CI at 95%, (b) average coda duration (in ms) in utterance-final vs medial position for adults and children with CI at 95%.

represent long and short vowels as VV and V, respectively. The coda following the long vowel is denoted as coda_VV, and that following the short vowel as coda_V. Both adults and children distinguished the long and short vowels as shown in Fig. 1(a). However, the two groups diverged in coda duration, as illustrated in Fig. 1(b). Both groups exhibited utterance-final lengthening in the vowel and coda, as shown in Figs. 2(a) and 2(b), respectively. Figure 3(a) shows accentual lengthening on the vowel for both groups; whereas the two groups differed in accent-related coda lengthening, as shown in Fig. 3(b).

Repeated measures ANOVAs were conducted using the absolute vowel and coda durations as dependent variables to examine the vowel length distinction, vowel-coda interaction, presence of utterance-final lengthening, and accentual lengthening in the child and adult groups. Using the proportion of the vowel within the rhyme (i.e., vowel/rhyme) as a dependent variable, we evaluated whether utterance-final lengthening is progressive and accentual lengthening regressive. Using the vowel ratio (i.e., VV/V) as a dependent variable, we also tested the possibility of a short-vowel lengthening constraint. In addition, we calculated the coda ratios (i.e., coda_VV/coda_V) to capture any vowel-coda interaction.

Table III summarizes the vowel and coda durations, and Table IV the vowel proportion, vowel ratio, and coda ratio for both groups.

We used repeated measures ANOVAs with three within-subject independent factors of position, focus accent, and vowel. Group was the between-subject factor. As the vowel and coda ratios were subsumed under the factor vowel, we only employed two within-subject independent factors of position and focus accent in analyzing these ratios. Details of the statistical results for vowel duration, coda duration, and vowel proportion are summarized in Table V, and results for vowel and coda ratios are given in Table VI. An alpha level of 0.05 was used for all statistical tests. For clarity, we only report significant effects and interactions with p values equal to or less than 0.05 in the text below.

A. Vowel duration

A repeated measures ANOVA was run to evaluate the presence of a vowel length distinction, utterance-final lengthening, and accentual lengthening in the adult and child data. There was a main effect of group, with overall longer duration in children (265 ms) than the adults (227 ms) [see Fig. 1(a)]. There were main effects for vowel, position, and focus accent, but these did not interact with group [see Figs. 1(a), 2(a), and 3(a)]. Overall, the long vowel was 299 ms and the short vowel 193 ms. The average duration of the vowel in utterance-final position was 296 ms, relative to 196 ms in medial position. The accented vowel averaged 266 ms and the unaccented counterpart 227 ms. As predicted, both groups distinguished the long and short vowels, exhibiting utterance-final lengthening and accentual lengthening.

Since we also observed higher $f0$ on accented vowels in both adults and children, it might be the case that it takes a longer time to realize higher pitch (Xu and Sun, 2002). To explore this possibility, a Pearson product-moment correlation coefficient was computed to assess the relationship between $f0$ and accented vowel durations for adults and children separately. There was a trend toward a correlation between the two variables ($r = 0.623$, $n = 10$, $p = 0.054$) for the adults. However, there was no correlation between the two variables for the children ($r = -0.367$, $n = 10$, $p = 0.297$). In other words, children did not appear to systematically associate higher pitch with longer duration.

There were three significant interactions: (1) Position-by-focus accent, (2) focus accent-by-vowel, and (3) vowel-

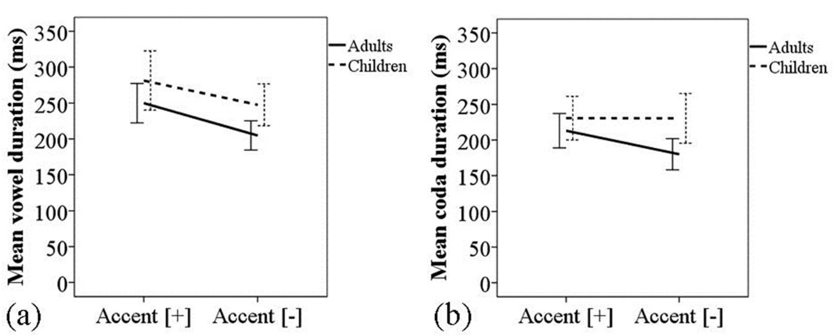

FIG. 3. (a) Average vowel duration (in ms) in accent [+] vs [−] condition for adults and children with CI at 95%, (b) average coda duration (in ms) in accent [+] vs [−] condition for adults and children with CI at 95%.

TABLE III. Mean vowel and coda durations (in ms) with SD as a function of position [Final vs Medial] and focus accent [+ vs −] in adults and children.

		Adults				Children			
		Words with long vowels		Words with short vowels		Words with long vowels		Words with short vowels	
Position	Focus accent	VV	Coda /s/	V	Coda /s/	VV	Coda /s/	V	Coda /s/
Final	[+]	364 (43)	251 (35)	224 (24)	298 (56)	441 (112)	320 (64)	264 (111)	298 (67)
	[−]	289 (51)	242 (33)	190 (18)	245 (25)	355 (88)	341 (101)	239 (62)	282 (92)
Medial	[+]	269 (37)	139 (31)	144 (18)	165 (34)	254 (37)	151 (22)	167 (38)	154 (56)
	[−]	207 (30)	110 (16)	134 (15)	123 (20)	216 (37)	153 (24)	181 (64)	146 (39)

by-position. Apart from (3), they did not interact with group. The first interaction was due to more accentual lengthening in the final than the medial position (a difference of 55 vs 24 ms). The second interaction reflected that an accented short vowel was not lengthened as much as an accented long vowel (a difference of 65 ms in the accented long vowels vs 14 ms for the accented short vowels). The third interaction indicated that both groups lengthened the long vowels more than the short vowels in final position (89 vs 68 ms), with this lengthening exaggerated in the children's productions (163 vs 78 ms).

B. Coda duration

A repeated measures ANOVA was used to evaluate the presence of coda length effects, including the presence of utterance-final lengthening and accentual lengthening in the adult and child data. There was a significant group effect, with children showing overall longer coda duration than adults (231 vs 197 ms). There were also main effects of position and focus accent [see Figs. 2(b) and 3(b)]. The utterance-final codas were on average 142 ms longer than the medial counterparts (285 vs 143 ms). The accented codas were 17 ms longer than the unaccented counterparts (222 vs 205 ms). The effect of focus accent also interacted with the group. As expected, both groups realized utterance-final lengthening on the coda. However, while adults manifested accentual lengthening on the coda, children did not, as illustrated in Fig. 3(b).

There was also a significant interaction between vowel and group, indicating that the two groups diverged in the vowel-coda interaction [see Fig. 1(b)]. Among the adults, the coda_VV duration was 185 ms, and the coda_V duration 208 ms. That is, a long vowel is paired with a short coda and vice versa, consistent with the *vowel-coda trading* relationship reported in Cox and Palethorpe (2011). Contrary to the adult pattern, the children had longer coda_VV duration (241 ms) and shorter coda_V duration (220 ms). They thus showed a *vowel-coda matching* relationship. There was also a significant interaction between focus accent and vowel, with more accentual lengthening on coda_V compared to coda_VV (a difference of 30 vs 3 ms).

To summarize so far, the findings confirmed a vowel length distinction, presence of utterance-final lengthening, and accentual lengthening on the vowel for both the adults and children. With regard to coda duration, there were similarities and differences between the two groups. While both groups realized final lengthening on the coda, they diverged in how vowels modulated coda lengthening. This resulted in the two groups differing in the vowel-coda interaction, with a vowel-coda trading relationship in adults, and a vowel-coda matching relationship in children.

C. Vowel proportion (vowel/rhyme)

This ratio metric was used to address the question of whether utterance-final lengthening is progressive and accentual lengthening regressive (i.e., whether the degree of lengthening on the vowel and the coda is disproportionate). If utterance-final lengthening is progressive with more lengthening on the coda than the vowel, the prediction was that the vowel proportion of the rhyme would decrease in utterance final position. If accentual lengthening is regressive and lengthens the vowel more than the coda, the vowel proportion would increase in the focus accent [+] condition.

Main effects of position and vowel were found. As predicted, the overall vowel proportion decreased (from 0.573 in medial position to 0.502 in final position), indicating progressive utterance-final lengthening. This did not interact with group. As anticipated, long vowels showed a large vowel proportion (0.593) and short vowels a small vowel

TABLE IV. Mean vowel ratio, coda ratio and vowel proportion (i.e., vowel/rhyme) with SD as a function of position [Final vs Medial] and focus accent [+ vs −] in adults and children.

		Adults				Children			
		Vowel proportion				Vowel proportion			
Position	Focus accent	VV	V	Vowel ratio	Coda ratio	VV	V	Vowel ratio	Coda ratio
Final	[+]	0.59 (0.04)	0.43 (0.06)	1.64 (0.19)	0.86 (0.13)	0.58 (0.09)	0.46 (0.1)	1.98 (1.12)	1.11 (0.31)
	[−]	0.54 (0.05)	0.44 (0.04)	1.53 (0.27)	0.99 (0.09)	0.51 (0.1)	0.47 (0.08)	1.53 (0.37)	1.29 (0.5)
Medial	[+]	0.66 (0.04)	0.47 (0.06)	1.88 (0.28)	0.85 (0.11)	0.63 (0.04)	0.53 (0.11)	1.59 (0.37)	1.14 (0.59)
	[−]	0.65 (0.06)	0.52 (0.04)	1.55 (0.21)	0.91 (0.13)	0.58 (0.05)	0.55 (0.13)	1.29 (0.41)	1.12 (0.37)

TABLE V. Statistical results from repeated measures ANOVA with group [adults vs children] as a between-subject factor, position [Final vs Medial], focus accent [+ vs −] and vowel [long vs short] as within-subject factors, with vowel duration, coda duration, and vowel proportion (vowel/rhyme) as dependent variables. The first number in each cell indicates the F value, the second number represents the p value, with $df = 1, 18$. * shows statistical significance with the alpha value of 0.05.

	Dependent variables		
Factors	Vowel	Coda	Vowel proportion
Group (G)	5.292, *0.034**	7.135, *0.016**	0.007, 0.935
Position (P)	88.343, *<0.0001**	128.187, *<0.0001**	33.496, *<0.0001**
G × P	3.964, 0.062	1.896, 0.185	0.065, 0.802
Focus Accent (A)	32.486, *<0.0001**	5.32, *0.033**	0.914, 0.352
G × A	0.672, 0.423	5.099, *0.037**	0.894, 0.357
Vowel (V)	114.957, *<0.0001**	0.009, 0.925	96.207, *<0.0001**
G × V	0.066, 0.8	19.27, *<0.0001**	9.67, *0.006**
P × A	10.913, *0.004**	0.237, 0.633	4.674, *0.044**
G × P × A	1.8, 0.196	0.002, 0.964	1.395, 0.253
A × V	23.42, *0.0001**	6.06, *0.024**	11.297, *0.003**
G × A × V	0.264, 0.614	0.052, 0.822	0.031, 0.861
P × V	13.977, *0.002**	1.475, 0.24	0.076, 0.787
G × P × V	5.041, *0.038**	2.699, 0.118	0.864, 0.365
P × A × V	0.001, 0.979	2.45, 0.135	0.003, 0.954
G × P × A × V	0.177, 0.679	0.007, 0.935	0.163, 0.691

proportion (0.482), in line with the vowel length distinction. This vowel effect also interacted with group, with wider separation between long and short vowels for the adults (0.611 vs 0.466), than for the children (0.575 vs 0.499).

Contrary to our prediction, there was no main effect of focus accent (0.54 in the accent [+] vs 0.53 in the accent [−] conditions), suggesting no regressive accentual lengthening for either the children or adults. Given the observations of accentual lengthening on vowels for both the children and the adults in absolute terms, this reflects stable proportionate lengthening of the vowel and the coda within the rhyme.

Two significant interactions were also observed: (1) Position-by-accent, and (2) vowel-by-accent. While in the first interaction the vowel proportion increased from 0.49 without focus accent to 0.514 with focus accent utterance-finally, there was no change utterance medially (0.576 vs 0.571). That is, there was a tendency not to lengthen accented vowels in medial position. In the second interaction, the vowel proportion increased from 0.572 to 0.614 for the accented long vowels, whereas it decreased from 0.493 to 0.472 for the accented short vowels. This implies the expected lengthening constraint on accented short vowels.

TABLE VI. Statistical results from repeated measures ANOVAs with group [adults vs children] as a between-subject factor, position [Final vs Medial], focus accent [+ vs −] as within-subject factors, using vowel ratio (i.e., VV/V) and coda ratio (coda_VV/coda_V) as dependent variables. The first number in each cell indicates the F value and the second number represents the p value, with $df = 1, 18$. * shows statistical significance with the alpha value of 0.05.

	Dependent variables	
Factors	Vowel ratio	Coda ratio
Group (G)	0.133, 0.72	20.686, *<0.0001**
Position (P)	1.524, 0.233	0.455, 0.508
G × P	8.801, *0.008**	0.028, 0.868
Focus accent (A)	9.223, *0.007**	1.259, 0.277
G × A	0.616, 0.443	0.015, 0.904
P × A	0.028, 0.87	0.858, 0.366
G × P × A	0.736, 0.402	0.223, 0.642

D. Vowel ratio (VV/V)

We used this ratio metric to evaluate whether short vowels are subject to a lengthening constraint in utterance-final position and the accent [+] condition. We hypothesized that the vowel ratio would increase under such constraint. The vowel ratio also reflects a vowel length distinction if the value is greater than 1. The higher the ratio, the larger the distinction will be.

A repeated measures ANOVA was conducted with position, accent, and group as factors. There was a main effect of accent, with a ratio of 1.47 in accent [−] and 1.77 in accent [+] conditions. The effect did not interact with group. As predicted, both groups showed a lengthening constraint on accented short vowels. Accentual lengthening was applied to VV and V disproportionately, with less lengthening on V than VV.

There was also a position-by-group interaction. Recall that the lengthening constraint on short vowels leads to a large vowel ratio in final position. While children *increased* the ratio from 1.44 in medial position to 1.75 in final position in the predicted direction, the adults *decreased* it from 1.71 to 1.58. Thus, as hypothesized, the children did not lengthen V as much as VV in final position. Contrary to our prediction, however, the adults did not constrain lengthening on the short vowel in the corresponding location. They appeared to constrain lengthening on the long vowel instead. This might be related to the vowel-coda trading relationship in the adults. When coda_V is lengthened in the final position, it is consistent with the short vowel-long coda pattern. On the other hand, lengthening the coda_VV in the corresponding position runs the risk of compromising the long vowel-short coda pattern. The divergence between children and adults provides additional evidence that the children might not yet have acquired the vowel-coda trading relationship.

E. Coda ratio (coda_VV/coda_V)

We expected a vowel-coda trading relationship in adults, and possibly late mastery of the relationship in children. Recall that the coda ratio (i.e., coda_VV/coda_V) should be smaller than 1 in a vowel-coda trading relationship. When the ratio is greater than 1, coda_VV is longer than coda_V. In this scenario a long vowel goes with a long coda, i.e., a vowel-coda matching relationship.

There was a significant effect of Group, with an overall coda ratio of 1.17 for the children, but 0.9 for the adults. Consistent with the coda-duration findings, the children showed a *vowel-coda matching* relationship, whereas the adults showed a *vowel-coda trading* relationship. No other effects were observed, suggesting that utterance position and focus accent did not alter these vowel-coda patterns.

IV. DISCUSSION

This paper examined three questions: (1) Whether monolingual AusE-speaking 3-yr-olds could produce and maintain a phonemic vowel length distinction in two prosodic contexts (utterance position and focus accent) in the same way as adults, (2) whether children would produce utterance-final and accentual lengthening as adults do, and (3) whether children would show an adult-like interaction between vowel and coda durations within the rhyme.

Overall, the findings confirmed that the children maintained the phonemic vowel length contrast at both the segmental level (i.e., vowel duration and vowel ratio) and within the rhyme (i.e., vowel/rhyme proportion), just like the adults. Both groups also showed lengthening under conditions of both utterance-final position and focus accent. In these contexts, the children also showed a short vowel lengthening constraint, providing further support for the position that AusE children have a phonemic vowel length distinction by the age of 3.

The result for utterance-final lengthening is consistent with findings across many languages (English: Lehiste, 1973; Oller, 1973; Klatt, 1975, 1976; Lehiste *et al.*, 1976; Cooper and Paccia-Cooper, 1980; Scott, 1982; Turk and Shattuck-Hufnagel, 2007; Dutch: Hofhuis *et al.*, 1995: Hebrew: Berkovits, 1993a,b). Like the adults, children showed a larger amount of lengthening in the coda than in the vowel, providing evidence for the progressive nature and leftward spread of utterance-final lengthening.

In terms of accentual lengthening, there were similarities and differences between the two groups. Both the children and adults realized accentual lengthening on the vowel. Since both also showed evidence of a short vowel lengthening constraint, this means that the effect of accentual lengthening was driven primarily by the items containing long vowels. There was also a larger amount of lengthening in the vowel than in the coda for both groups, providing further support for the nucleus as the locus of accentual lengthening.

However, there was also a difference between the two groups. The adult data showed statistically significant accentual lengthening on both the vowel and coda, suggesting that the domain of lengthening went beyond the segment to include the entire rhyme. In contrast, the child data only showed a significant accentual lengthening on the vowel.

There are two possible inter-related reasons for the lack of *coda* lengthening in the focus accent condition for the children. First, the amount of utterance-final lengthening was generally larger than the amount of accentual lengthening for the children, for the adults, and also for the model speaker who served as the auditory prompt. For example, the prompt had a difference of 118 ms in the coda as a function of utterance position, but a difference of 28 ms in the coda as a function of focus accent. It is therefore possible that the durational difference of the coda as a function of focus accent was not salient enough for the children to detect.

The second possibility relates to the absence of *f*0 cue in codas, relative to its presence in vowels. For example, the auditory prompt in this experiment contained an *f*0 difference of 202 Hz on the vowel as a function of focus accent. But the *f*0 cue was absent in the voiceless fricative coda of the target word. Perhaps *f*0 excursion on the vowels helps children to attend to the nucleus and therefore highlights its associated duration. Without a concomitant *f*0 cue in the voiceless coda, the durational information may not be salient enough for children. As a result, the children might have failed to show a significant accentual lengthening on the voiceless fricative coda in this experiment. This could be tested in a future production experiment in which the /s/ coda consonant is replaced with a nasal. In this scenario, the *f*0 cue as well as the durational cue could be realized across the nasal coda ensuring salience. We would then expect accentual lengthening on both the vowel and the nasal coda in children's productions.

Alternatively, perhaps children do not understand that the focus accent forms are actually focused. Given that there was no discourse context in this experiment, which is typically required for focus to be felicitous, perhaps the children in this study are not treating these forms as focused. However, the findings that the children in this study did realize both higher *f*0 and lengthening on the accented vowels make this a less likely explanation for the children's lack of lengthening in the coda. This is an issue to be addressed in a modified experimental design, testing children's perception and production sensitivities to the acoustic correlates of focus that are more clearly motivated by the context.

Alternatively, it is possible that accentual lengthening on children's codas was not observed due to a lack of statistical power, given the small number of items in the analysis.

Children and adults diverged on how the vowel-coda interaction was realized. The vowel-coda interaction suggests that the two segments within the syllable rhyme are not independent of one another, providing support for the rhyme as the domain for encoding vowel length. Adults showed an inverse relation (i.e., long vowels occurred with short codas), in line with the reported vowel-coda trading relationship (Cox and Palethorpe, 2011). This means that the rhyme functions as a unit with respect to temporal organization. Support for this position can be found in the adult vowel ratio analysis where the vowel coda trading relationship appears to override the short vowel lengthening constraint. In contrast, the children showed a *matching* relationship (i.e., long vowels occurred with long codas). This suggests that 3-yr-olds have not yet acquired the fine-grained adult-like temporal organization within the rhyme. Note also that Cox and Palethorpe's (2011) observations regarding the trading relationship also held for long/tense vowels and diphthongs (i.e., bimoraic vowels more generally). It would therefore be interesting in future research to explore this issue across a range of long vowel types.

The findings presented here raise many questions about when children become sensitive to segmental/prosodic interactions. It will be interesting in future work to compare the acquisition of vowel length cross-linguistically to examine languages with varying types of vowel length contrasts. For example, long-short vowel contrasts in Finnish are apparently acquired relatively early, being well-established by 3 yrs of age (Saaristo-Helin *et al.*, 2011; Kunnari and Savinainen-Makkonen, 2007). As Finnish adults exhibit complex interactions between vowel length and utterance-final lengthening (Nakai *et al.*, 2009), such complexity may present a challenge to Finnish-speaking children learning how to integrate this information into their own speech productions.

V. CONCLUSION

This study examined how children learning AusE maintain phonemic vowel length contrasts as a function of prosodic context. The results showed that 3-yr-olds can preserve phonemic vowel length under conditions of both utterance-final lengthening and accentual lengthening. In utterance-final position there was also evidence of progressive lengthening, where the segment immediately adjacent to the phrasal boundary is lengthened the most, with lengthening attenuating leftward. However, these children are still in the process of learning about accentual lengthening, as reflected in the diverse effects of focus accent on the duration of both the vowels and coda consonants within the syllable rhyme. In other words, 3-yr-olds learning AusE can control intrinsic vowel duration independent of extrinsic utterance-final and accentual lengthening. Learning phonemic vowel length, however, did not preclude children from producing utterance-final and accentual lengthening. This is somewhat different from the findings in Buder and Stoel-Gammon (2002) for Swedish-speaking children who attenuated extrinsic vowel duration effects during the acquisition of phonemic vowel length. Perhaps this might be related to whether vowel length contrasts are systemic, as in Swedish, or not, as in AusE. The difference between the two studies also lies in the choice of extrinsic contexts. While Buder and Stoel-Gammon (2002) examined the post-vocalic voicing context, the present study investigated utterance-final position and focus accent at a prosodic level. Despite these differences, both studies showed that children learn to adjust the extrinsic context to preserve phonemic vowel length.

Most intriguing was the finding of vowel-coda interactions within the rhyme. The child data in the present study showed a *matching* vowel-coda relationship, with increased coda duration in the long vowel conditions, and shorter coda durations in the short vowel conditions. This goes counter to the *vowel-coda trading relationship* found for the adults in this study and in Cox and Palethorpe (2011). It thus appears that 3-yr-old AusE-speaking children have yet to fine-tune the temporal organization within the syllable rhyme.

The present findings therefore shed light on some of the challenges children face in learning to maintain phonemic vowel length contrasts within both words and utterances. This requires fine-grained attention to the language-specific temporal organization of segments within the rhyme. As this temporal organization also varies in different prosodic contexts, the learner must also be attentive to the relationship between segments and their temporal structure at different levels of prosodic structure. AusE only exhibits phonemic vowel length contrasts for a small number of vowel pairs, and yet 3-yr-olds already show acute sensitivity to many of the adult-like cues to vowel length adjustments across prosodic contexts. We hypothesize that children learning languages where phonemic vowel length contrasts are more robust (e.g., Swedish, Finnish, Japanese, Arabic, etc.) may also demonstrate this sensitivity by the age of 3, if not before. It is hoped that the results presented here will provide a framework for exploring these issues more fully, contributing to our understanding of how and when children acquire more adult-like means of encoding the phonetic details of phonemic contrasts across different prosodic contexts.

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[1]The long vowel form /ɐː/ results from a range of historical processes including the loss of non-prevocalic "r" as in "farther" and "arms" but also from contextual backing and lengthening as occurred in words like "father" and "alms" (Beal, 1999). The orthographic pairs "farther/father" and "arms/alms" are homophonous in non-rhotic AusE. The possibility was raised that the long vowel form might arise from replacing the rhotic segment that is not realizable in a non-rhotic dialect. However, the homophone father is also realized as a long vowel even though it contains no historical r in the first syllable.

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