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An ultrasound study of the development of lingual coarticulation during childhood

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Abstract

Background/Aims. There is growing evidence that coarticulation development is protracted and segment-specific, and yet very little information is available on the changes in the extent of coarticulation across different phonemes throughout childhood. This study describes lingual coarticulatory patterns in six age groups of Scottish English speaking children between three and thirteen years old.

Methods. Vowel-on-consonant anticipatory coarticulation was analysed using ultrasound imaging data on tongue shape from four consonants that differ in the degree of constraint, i.e., the extent of articulatory demand, on the tongue.

Results. Consonant-specific age-related patterns are reported, with consonants that have more demands on the tongue reaching adolescent-like levels of coarticulation in older age groups. Within-speaker variability in tongue shape decreases with increasing age.

Conclusion. Reduced coarticulation in the youngest age group may be due to insufficient tongue differentiation. Immature patterns for lingual consonants in 5-to-11-year-olds are explained by the goal of producing the consonant target overriding the goal of coarticulating the consonant with the following vowel.

Introduction

Coarticulation in children has been studied for several decades, using different methodologies. In particular, lingual coarticulation has been demonstrated to be present since at least the age of two years old (Goodell & Studdert-Kennedy 1993). And yet, the development of lingual coarticulation has been shown to be protracted, with certain non-adult-like patterns observed in children up to twelve years old (e.g., Zharkova et al., 2014). A growing number of studies have also shown that coarticulation development is segment-specific (Katz and Bharadwaj 2001; Zharkova et al., 2012, 2014; Reidy, 2015). There is, however, very little information on the developmental course of segment-specific lingual coarticulatory patterns throughout childhood (see, e.g., Rubertus et al., 2015; Zharkova, 2017). This study aims to provide such information, using ultrasound imaging data on lingual coarticulation in four different consonants, produced by several groups of Scottish English speaking children between the ages of three and thirteen years old.

Two influential theories of coarticulation development, both formulated in the 1980s, compete with each other in relation to the nature of the units of speech production in children, and, consequently, on whether the extent of coarticulation increases or decreases during childhood. The theoretical view proposed by Kent (1983) is that children start with the segment as a unit of production, and that the skill of overlapping adjacent segments develops later. It follows that the amount of coarticulation between neighbouring segments should increase with increasing age, and Kent (1983) provided acoustic data from adults and children, supporting this idea. On the other hand, Nittrouer et al. (1989) claim that motor planning of speech in young children is carried out at the syllabic level. This idea is based on the observed reduction with age of the extent of anticipatory vowel-on-consonant coarticulation within a consonant-vowel (CV) syllable. The amount of within-syllable coarticulation, according to this approach, is larger in children than in adults. Both these theories are compatible with the premise that children's productions are limited by their general motor abilities, which undergo continuous development during childhood. Such protracted maturation of speech motor abilities, in particular, has been demonstrated in a number of acoustic and articulatory studies (e.g., Smith and Goffman, 1998; Walsh and Smith, 2002; Koenig et al., 2008; Zharkova et al., 2011, 2012, 2014; Romeo et al., 2013). For the children in their first two years of life, the dependence of speech production on developing motor skills has been formulated in terms of language-specific "opportunities and challenges" (Vihman, 2010: 279), which enhance or inhibit, respectively, the likelihood of children's phonetic realisations corresponding to adult targets (see also Vihman, 2014). In this paper we will argue that neither of the two main theories of coarticulation development can fully account for the actual production patterns, because the development of coarticulation during childhood is subject to the challenge of articulatory demands on the tongue for the target speech sound.

Segment-specific coarticulation

Segment-specific patterns of coarticulation have been relatively well described for adult speech. They have often been explained by referring to the concept of coarticulation resistance, "a uniform control principle upon whose information the speech encoding mechanism continuously draws" (Bladon & Al-Bamerni 1976, p. 149). The idea that phonetic properties of speech sounds matter in their interactions with neighbouring sounds is central to the Degree of Articulatory Constraint (DAC) model of lingual coarticulation (Recasens et al., 1997), which has been used in the literature to account for coarticulatory patterns in adult speech across languages. The model postulates that the extent of coarticulation in a given speech sound conditioned by neighbouring sounds reduces with increasing constraint on the tongue for the target sound. According to the DAC model, labial consonants, which have no constraint on tongue position in many languages, experience more influence from neighbouring vowels in CV syllables than alveolar and alveolopalatal consonants (e.g., Recasens, 1985; Recasens et al., 1997; Recasens and Espinosa, 2009). During the production of lingual consonants, the tongue is constrained due to closure or constriction requirements, and therefore has less freedom to adapt to the vocalic influence (e.g., Recasens et al., 1997; Recasens, 2002). The alveolar fricative /s/ has been shown to be more resistant to coarticulation than /t/, due to additional constraints on the lateral margins of the tongue required for producing sustained frication, thus increasing its potential to resist the vocalic influence, compared with the alveolar stop (Stone et al., 1992; Recasens et al., 1997; Recasens & Rodríguez, 2016). Postalveolar consonants, such as the English /ʃ/, which has a requirement that the tongue predorsum is raised, may be less affected by neighbouring sounds than alveolars. For example, /ʃ/ has been shown in a number of languages to resist to the influence from neighbouring sounds, experiencing less lingual coarticulation than /s/ in adult speech (Tabain 2001; Recasens & Espinosa 2009; Niebuhr and Meunier 2011; Niebuhr et al. 2011; Pouplier et al., 2011; Recasens & Rodríguez, 2016; see also Pouplier & Hoole, 2016). The DAC model has been developed for adult speech, and testing the model for child speech has yet to be carried out. Age-related segment-specific differences in coarticulation, increasingly reported in the literature (e.g., Sussman et al., 1999; Katz & Bharadwaj, 2001; Zharkova et al., 2012, 2014, 2015b; Reidy, 2015; Noiray et al., 2017; Rubertus & Noiray, 2017), provide evidence that does not support either of the two theoretical models of coarticulation development described above, since the extent of coarticulation can increase or decrease with age depending on the speech sound and/or on the specific gestures involved in coarticulating the sound. In this study, vowel-on-consonant coarticulation in CV syllables was documented throughout childhood, using consonants which differ in their DAC properties: /p/, /t/, /s/ and /ʃ/.

In previous studies, segment-specific patterns of coarticulation have been observed already in very young children. For 22-month-olds and 32-month-olds, an acoustic study of vowel-on-consonant coarticulation including the consonants /b/, /d/ and /g/, and the vowels /a/ and /i/, reported differences across stop consonant places of articulation, with evidence of reduced vowel effects on the alveolar stop (Goodell and Studdert-Kennedy, 1993). Adult-like segment-specific coarticulatory patterns for stop consonants have been demonstrated across languages for children aged 3-4 years old, in a number of studies (e.g., Sussman et al., 1992; Noiray et al., 2013; Rubertus et al., 2015). These studies used locus equations, which assess the extent of tongue advancement at the end of the consonant, specifically at the time point where any aspiration ends, i.e., the following vowel's voicing onset, and compare it to the extent of tongue advancement at the middle of the following vowel (Rubertus et al., 2015, included mid-consonant as well as the consonant offset, with the same results). Using F2 measurements and/or articulatory information from ultrasound tongue imaging, locus equation studies have shown that by the offset of the consonant the articulatory characteristics of the following vowel are anticipated in labial and velar stops more than in alveolar stops. Interestingly, changes in the extent of coarticulation during the first three years of age and into the fourth year were demonstrated in an acoustic study by Sussman et al. (1999) to be non-uniform across stop places of articulation. The observed changes in one child's alveolar stop coarticulation from more-than-adult to less-than-adult during the first three years of life were explained by Sussman et al. (1999) by reference to a trade-off between "articulatory effort" needed for attaining the stop closure and "coarticulatory overlap" in contrasting vowel contexts, a balance that may be hard to achieve for young children due to developmental immaturities in lingual motor control.

Further developmental differences concerning tongue control for alveolar stop coarticulation were recently demonstrated in 5-year-old children, in an ultrasound study by Zharkova et al. (2015b). In that study, 5-year-old children and 13-year-old adolescents had a similar amount of tongue shape adaptation at mid-closure to the vowels /a/ or /i/ for the bilabial stop /p/, but the alveolar stop /t/ patterned differently in the two age groups. Specifically, 5-year-olds, like the adolescents, adjusted the tongue to the upcoming vowel by raising the tongue dorsum, but unlike the adolescents, the younger children did not have additional modifications of the front and back of the tongue in anticipation of the vowel. This was interpreted to mean that 5-year-olds have less mature control of the tongue than adolescents. Protracted maturation of tongue control has also been suggested to account for vowel-on-fricative coarticulation development patterns. A recent acoustic study by Reidy (2015), which involved 2-5-year-old children and adults, reported a non-uniform direction of age-related differences in the magnitude of vocalic coarticulatory effects on the sibilants /s/ and /ʃ/. Specifically, the effect of vowel frontness (i.e., the difference in spectral characteristics of the consonant depending on whether the conditioning vowels were front or back) decreased developmentally, and the effect of vowel height (i.e., the conditioning vowels being high versus non-high) increased with age. Reidy ascribed the latter finding to the maturation of articulator control involved in coordinating different articulators, namely the tongue and the jaw (see also Nittrouer, 1993, for a similar suggestion regarding the acquisition of stop consonants). Alveolar fricatives have been shown to have immature coarticulatory patterns in 3-year-olds (Katz et al., 1991), as well as in older children (Nittrouer et al., 1989; 1996; Katz and Bharadwaj, 2001), up to the age of nine years old (Zharkova et al., 2011, 2012). Perhaps due to methodological differences, these studies provide a somewhat contradictory picture of the nature of the developmental process, with both smaller- and greater-than-adult spatial coarticulation reported for children (note that similar-to-adult patterns of fricative coarticulation in children have also been found: e.g., Katz et al., 1991; Katz and Bharadwaj, 2001; Munson, 2004). By 10-12-years old, however, /s/ appears to have reached an adult-like extent of spatial and temporal lingual coarticulation, as reported in an ultrasound study by Zharkova et al. (2014). On the other hand, the postalveolar fricative /ʃ/, in the same study, was demonstrated to still have age-related differences, specifically in temporal coarticulatory patterns, with the coarticulation onset in the preadolescent child group observed later in the consonant than in the adult group. For 13-year-old adolescents from Zharkova et al. (2015a), the postalveolar fricative was found to have segment-specific coarticulatory patterns similar to those previously reported for adult speech, with less evidence of coarticulation than alveolar consonants /t/ and /s/. In particular, the alveolars had vowel-related changes on a measure of the extent of tongue bunching, as well as on a measure of the relative location of bunching along the tongue curve, while /ʃ/ only exhibited tongue shape adjustment to the upcoming vowels on the former measure.

Tongue differentiation

It has been claimed in a number of studies that immature coarticulation patterns may be due to the lack of tongue differentiation in children (e.g., Gibbon, 1999; Gick et al., 2008; Zharkova et al., 2012), i.e., to their inability to differentiate between parts of the tongue and therefore to produce contrasting tongue shapes. Articulatory studies using electropalatography have described patterns of tongue-to-palate contact for lingual consonants, when contact is registered over most of the artificial palate. These patterns, referred to as “undifferentiated lingual gestures” (Gibbon, 1999), suggest simultaneous involvement of the tongue tip/blade and the tongue body in the articulation. Undifferentiated gestures observed for target alveolar consonants produced by children have been interpreted to mean that “the basic control mechanism that allows the tongue apex, lateral margins and tongue body systems to operate relatively independently is not yet developed” (Gibbon, 2003: 261). One of the aims of the present study was to establish whether an increase in tongue differentiation with increasing age would be observed in ultrasound data on tongue movements. As ultrasound does not register tongue-to-palate contact, changes in tongue *shape* over time were used to infer the extent of differentiating between parts of the tongue. Tongue differentiation was assessed in this study independently of coarticulation. While coarticulation was measured by comparing tongue curves at mid-consonant across two vowel contexts, differentiation was quantified by comparing tongue curves within a consonant token, at two different time points.

The ability to differentiate between the tip/blade of the tongue and the rest of the midsagittal part of the tongue is required when producing a consonant-vowel syllable consisting of an alveolar consonant and a high front vowel. Specifically, the speaker needs to be able to separately control the tip/blade of the tongue, which is making the constriction for the consonant, and the rest of the tongue, which is involved in achieving the raised and advanced position required for the following vowel gesture. In consonant-/i/ syllables, substantial midsagittal tongue shape adjustments have been documented for adults and for preadolescent children in fricative consonants, with gradual changes towards the vowel tongue shape (Zharkova, 2016). Particularly, between mid-/s/ and the consonant offset, there was a noticeable change on a measure reflecting progressive raising and advancement of the tongue predorsum towards the high front vowel (cf. nearly no midsagittal tongue movement during /s/ before the low vowel /a/, reported in the same study). In the present paper, a change in consonant tongue shape over time before the vowel /i/ was taken as an indication of the ability to differentiate between parts of the tongue. Differentiation was quantified by comparing tongue curves for /t/ in the context of /i/, within token, at the middle versus the end of the closure. The alveolar stop was chosen because of its short duration, creating a challenge for adjusting the tongue shape towards the vowel between the middle and the end of the closure.

If patterns of reduced coarticulation in lingual consonants produced by younger children were observed, we would be able to explain those patterns by one of two alternative scenarios. In one scenario, if the younger children did not show tongue differentiation, then the lack of coarticulation would likely be due to motor constraints related to independently controlling different parts of the tongue. In the other scenario, if there was a lack of coarticulation while the children did show tongue differentiation, it would suggest that insufficient coarticulation may have occurred not because of inability to adjust the consonant to the vowel, but rather because the priority for the children was to produce the consonant itself in a perceptually appropriate way.

Variability

Variability in speech is potentially a measure of oral motor control, and reduction in within-speaker variability on different parameters has been shown to happen during childhood. Previous studies have demonstrated developmental decreases in variability in durational and spectral measures (e.g., Kent and Forner, 1980; Nittrouer 1993; Lee et al., 1999; Nijland et al., 2002; Nittrouer et al. 2005), labial and mandibular articulation (e.g., Sharkey and Folkins, 1985; Smith and Goffman, 1998; Walsh and Smith, 2002), as well as lingual articulation (e.g., Zharkova et al., 2011, 2012; Barbier et al., 2015; Yip et al., 2015). This study for the first time described age-related changes in variability of tongue shape over repetitions of the same speech segment, between three and thirteen years old.

Predictions for the current study

For the consonants targeted in this study, based on the DAC model premises, if we assumed children behaved exactly like adults, the predictions would be that all child age groups will have the same coarticulation patterns, with /p/ coarticulated more than lingual consonants, and the postalveolar being most resistant to coarticulation. However, given previously reported developmental findings, segment-specific coarticulatory patterns may be expected to differ across age groups. The study used a dataset consisting of productions by children between 3 and 13 years old, with six tightly spaced age groups, and two year intervals between successive groups. This made it possible to trace the development of coarticulation throughout childhood, in order to better understand the nature of any age-related changes in consonant-specific patterns. Some comparisons of the four consonants across the two vowel contexts produced by 13-year-old adolescents from this dataset have been reported in Zharkova et al. (2015a), described above. Zharkova et al. (2015b), who compared 13-year-olds' and 5-year-olds' productions, also used this dataset, although they only reported the data on /p/ and /t/. The current study extends the analyses to all age groups and consonants; several earlier reported within-group comparisons will be included here for completeness, accompanied by specific references in the relevant tables and in the text.

In this study, based on the literature reviewed above, lingual coarticulation is expected to be observed for /p/ in all groups of children. A similar relationship between the consonants across age groups, namely more coarticulation in /p/ than in the lingual consonants, is predicted. For /t/, a vowel effect on a measure capturing the extent of tongue bunching is predicted for the 7-, 9- and 11-year-olds, based on the results for 5-year-olds from Zharkova et al. (2015b). The effect on a measure of the relative location of tongue bunching for /t/, not observed in Zharkova et al. (2015b) for 5-year-old children, in this study is expected to emerge in one of the older groups between 7 and 11 years old. Vowel-related coarticulation for the alveolar fricative is predicted to be observed in older age groups than for the alveolar stop, due to the challenges associated with additional articulatory constraints required for producing sustained frication (cf. Zharkova et al., 2012). Additional constraints on /ʃ/, i.e., predorsum raising, are expected to result in less adjustment between tongue front and back, compared with /t/ and /s/, across age groups. Tongue differentiation is predicted to increase with increasing age, and in at least some of the younger age groups the lack of differentiation is expected to accompany immature coarticulation patterns. Variability in tongue shape across repetitions is expected to decrease with increasing age.

The hypotheses for the study are as follows.

1. There will be more vowel-related influence on the bilabial stop than on each of the lingual consonants in every age group, because of the lack of constraint on the tongue for the bilabial stop.
2. For the lingual consonants, age-related differences will be observed, with most protracted development of coarticulatory patterns for /ʃ/, and more for /s/ than for /t/, since the extent of constraint on the tongue for a given consonant is expected to differentially affect coarticulation across age groups.
3. The ability to differentiate between contrasting tongue positions will increase with increasing age, as part of the general progress in motor development.
4. Within-speaker variability in tongue shape over repetitions of the same segment will decrease with increasing age, indicating age-related maturation in controlling the tongue.

2. Method

Participants and experimental stimuli

The participants were 60 typically developing children speaking Scottish Standard English, without parent-reported speech or hearing disorders, ten speakers in each of the following age groups: 3-year-olds; 5-year-olds; 7-year-olds; 9-year-olds; 11-year-olds; 13-year-olds. The details on the six age groups are presented in table 1. The stimuli used in the study were CV syllables with the consonants /p, t, s, ʃ/ and the vowels /a, i/, produced in the carrier phrase "It's a ..., Pam" ("Pam" was the name of a toy penguin, which was introduced to the children at the beginning of the session). The stimuli consisted of real words /pi/ ("pea"), /ti/ ("tea"), /si/ ("sea"), /ʃi/ ("she"), and /ʃa/ ("shah"), as well as the following nonsense words, which were presented to the participants as names of imaginary creatures: /pa/ ("Pa"), /ta/ ("Tah"), /sa/ ("Sah")[1]. The phonological structure of the target CV syllables was selected to provide minimal pairs for analysing vowel-on-consonant coarticulation for each of the four consonants, and to make it easier to compare the results with those from previous studies (e.g., Sussman et al., 1992; Nittrouer et al., 1996; Zharkova et al., 2012; Noiray et al., 2013; Reidy, 2015). The two vowels were chosen to provide sufficiently contrasting lingual articulations, while avoiding a confounding factor of lip rounding.

<table 1 about here>

Data collection

Synchronised midsagittal ultrasound tongue movement and acoustic data were collected in a sound-treated studio, and the equipment producing noise (i.e., the ultrasound scanner and the computer recording the data) was located in an adjacent room. An Ultrasonix Sonix RP scanner was used for ultrasound data collection, and the synchronisation of ultrasound and acoustic data was performed through Articulate Assistant Advanced (AAA) software (Articulate Instruments Ltd, 2012). Ultrasound data were recorded at the rate of 100 Hz, and the acoustic signal was sampled at 22050 Hz, using a lavalier microphone. Experimental stimuli were presented to the participants in the orthographic form (see above), as well as in the form of pictures (images for the three nonsense words were created to have no resemblance to any existing animate or inanimate objects). All participants were familiarised with the target pictures, and it was ensured that the child could clearly see the information presented on the screen. Before the recording began, the experimenter produced the carrier phrase several times, as part of the familiarisation procedure, to ensure that the speakers followed the same model with respect to prosody and speech rate. All participants were prompted to produce five repetitions of each target CV syllable. The prompts were presented in random order. The tokens of a consonant from a given child were included in quantitative analyses of tongue shape only if the child produced at least three repetitions of the target consonant in each vowel context.

Participants were seated opposite the computer screen on a chair, with the exception of nine 3-year-olds and two 5-year-olds, who sat on their carer's lap. Due to the large overall age range of the participants in this study, there were some further differences in the recording procedure across age groups, aimed to facilitate the data collection by using the

[1] In order to establish whether including a combination of real words and nonsense words, as well as any differences in frequency, might have affected the consistency of tongue shape across repetitions of the target consonants (see, e.g., Beckman & Edwards, 2000; Edwards et al., 2004), an investigative sensitivity analysis was carried out on the Coefficient of Variation. First, nonsense words were compared with real words, using linear mixed models with Speaker and CV Type as random effects, and there was no significant difference in variability of articulatory indices depending on whether the syllable was a real word or a nonsense word. The next step involved analysing only five real words, taking frequency into account, using information on word occurrences in the CHILDES Parental Corpus (MacWhinney, 2000; Li & Shirai, 2000). Results from linear mixed models comparing variability across word types (with Speaker as a random intercept), did not support the hypothesis that lower frequency words would have increased variability in tongue shape. Finally, the Coefficient of Variation was compared across the three nonsense words (also with Speaker as a random intercept), and there was no significant difference in variability across CV types.

most age-appropriate set-up for each age group. The older participants read the sentences, while the younger children (3-year-olds and most 5-year-olds) repeated the sentences after their carers. The carers of the younger speakers were instructed to read the entire sentence for the children to repeat[2]. For the youngest participants, the recording procedure was presented as a game, which involved teaching a toy penguin to say new words. The penguin was a passive listener in the game, while the child had to focus on the sentences to produce. The child was informed at the onset of the experiment that the new words, which Pam the penguin had to learn, would appear on the screen, and the child would need to repeat each sentence after the carer.

In the recordings of the age groups between 7 and 13 years old, the ultrasound transducer was stabilised in relation to the head, by means of a headset (Articulate Instruments Ltd, 2008). In total, out of the maximum of 400 tokens per age group, all 400 tokens were used in quantitative analyses for 7-, 11- and 13-year-old groups. For the 9-year-old group, 398 tokens were used, as one 9-year-old participant produced only three tokens of /s/ in the context of /a/.

The recordings of the two youngest age groups did not involve the headset, as it would have been too uncomfortable for the children due to its weight. For 3- and 5-year-olds, the ultrasound transducer was instead hand-held by the experimenter (see other ultrasound studies of young children's speech using hand-held recordings: e.g., Song et al., 2013; Lin & Demuth, 2015; Magloughlin, 2016). It was possible to use the same measures in this study for quantifying tongue shape in both stabilised and hand-held ultrasound data, because the measures have previously been shown to produce the same results for these two types of data (Zharkova et al., 2015a). All participants whose data were collected without head stabilisation were simultaneously video recorded in two planes, as shown in figure 1. The video data were used to guide the selection of tokens for further analyses (see the next subsection).

<figure 1 about here>

Selection of tokens recorded from the two youngest groups of speakers

As the study focussed on how contrasting vowel contexts affect the realisation of different consonants, only perceptually correct productions of the target consonant phonemes, as judged by the experimenter, were included in quantitative analyses. One 3-year-old participant did not have an audible contrast between the two sibilant fricatives, consistently producing both /s/ and /ʃ/ as a voiceless glottal fricative, so all fricative tokens by this child were excluded from quantitative analyses. Despite the fact that all other 3-to-5-year-old children produced perceptible contrasts between the four target consonants, further exclusions related to the nature of fricative production were made for three children. Two 3-year-old participants consistently produced an interdental /s/, as confirmed by the video recording of the face. All /s/ tokens produced by these two children were excluded from the analyses, because the visible tongue tip protrusion could have affected the overall tongue shape, thus confounding the results. One five-year-old girl realised most /ʃ/ tokens as somewhat palatalised, likely due to the fact that her lower centre incisors were missing. In order to avoid a possible confounding effect from any compensatory lingual articulations on tongue shape variability, it was decided to exclude from quantitative analyses all fricative tokens produced by this child. Finally, two children from the 3-year-old group did not produce the beginning

[2] Within the recording software, every presentation of the new stimulus is followed by saving the ultrasound video, which takes a comparable amount of time to the duration of the video. In the event, in order to keep the young children's attention focussed on the task, the carers of all 3-year-olds and one 5-year-old produced the stimulus several consecutive times for the child to repeat at each presentation of the new stimulus, thus reducing the number of separate individual recordings, and consequently the waiting time between recordings.

of the carrier phrase (i.e., “It’s a”), therefore stop tokens from these two children had to be excluded from quantitative analyses of tongue shape, as it would have been impossible to identify the onset of the stop closure, necessary for establishing mid-closure.

Video recordings of the two youngest groups were qualitatively examined in order to establish whether the tokens were suitable for quantitative analyses of tongue shape (see Zharkova et al., 2017, on the methodological challenges of analysing ultrasound data recorded without head stabilisation). In the tokens that were included, the ultrasound transducer was relatively stable under the chin during the target syllable, with the tongue curve flanked by the shadows of the chin and of the hyoid bone (see an example in Fig. 1). For the 5-year-olds, five tokens of /p/ produced by four different children did not satisfy these criteria. Thus, after applying all exclusion criteria, for the 5-year-old group the total of 375 tokens were included in quantitative analyses (48 tokens of /pa/, 47 tokens of /pi/, 45 tokens of each of the four CVs with fricatives, and 50 tokens of each of the CVs with /t/). For the 3-year-old group, the total of 240 tokens were included, and their details are as follows: 31 tokens of /pa/ and 30 tokens of /pi/ produced by seven different children; 28 tokens of /ta/ and 35 tokens of /ti/ (seven different children); 24 tokens of /sa/ and 25 tokens of /si/ (five different speakers); 33 tokens of /ʃa/ and 34 tokens of /ʃi/ (seven different speakers).

Annotations and tongue curve tracing

The middle of the consonant (for the stops, the middle of the closure) was annotated for every token. Mid-consonant was located automatically within AAA software, using manual annotations of the consonant duration. The consonant onset was located at the end of the periodic waveform for the vowel, which coincided with the closure onset and the onset of the frication noise for stops and fricatives, respectively. Across age groups, 22% of tokens were realised with preaspiration (ranging from 11% to 35% per age group). Between 6 and 10 children per group produced preaspirated tokens, and lingual consonants accounted for 97% of those tokens. The preaspirated interval, if it were present, was not included in the consonant duration. In such tokens, the consonant onset was located at the beginning of the closure for the stops, and, for the fricatives, at the abrupt increase of the frication noise. The offset of the closure for the stop consonants was located at the onset of the stop burst, and the offset for the fricatives was at the end of the frication noise.

Tongue curves at mid-consonant were automatically traced for every token in AAA, with some manual correction. In order to analyse tongue differentiation, tongue curves were additionally traced at the offset of the stop closure for all tokens of /t/ from /ti/. Then *xy* coordinates of the resulting tongue curves were used to calculate indices of tongue shape. Technical details on the procedure of exporting tongue curve coordinates from AAA are available in Zharkova et al. (2014).

Quantitative indices for analysing tongue shape

Tongue shape indices were calculated in R (R Development Core Team, 2013), using the scripts written by the author. The calculations of the two indices are illustrated in Fig. 2.

<figure 2 about here>

An index called $LOC_{a\text{-}i}$ (Zharkova et al., 2015a) quantified the location of bunching along the tongue curve. This index has been reported to have higher values in the context of /i/ than in the context of /a/ for /p/, /t/ and /s/ in typically developing adolescents (Zharkova et al., 2015a). In the left panel of Fig. 2, $LOC_{a\text{-}i}$ is a ratio of the straight line *f* (a perpendicular from one third of line *n*, starting from the front, to the tongue curve) to line *b* (a perpendicular from two thirds of line *n* to the tongue curve).

Curvature Degree, an index introduced by Aubin and Ménard (2006), was used to quantify the extent of tongue bunching. Curvature Degree has been shown by Zharkova et al. (2015a) to produce higher values in the context of /i/ than in the context of /a/ for /t/, /s/ and /ʃ/ produced by adolescents. This index was not used for analysing data from the bilabial consonant, as Zharkova et al. (2015a) showed that the index can produce different results for vowel-on-/p/ coarticulation depending on whether the participant's head is stabilised in relation to the transducer. In the right panel of Fig. 2, Curvature Degree is a ratio of the line CD (a perpendicular from the point on the tongue curve furthest away from AB, the straight line between two ends of the tongue curve) to the line AB. Curvature Degree was preferred in this study to another measure of tongue bunching, Dorsum Excursion Index, used in some of our previous studies (e.g., Zharkova et al., 2015b; Zharkova 2016), because the latter measure was shown in Zharkova et al. (2015a) to be affected by head-to-transducer stabilisation in the case of /ʃ/, while Curvature Degree had similar results for /ʃ/ across the two stabilisation conditions.

For our /a/-/i/ vowel context comparisons, the two indices represented different aspects of the contrasting vowel articulations that were expected to have an effect on the consonants. The /i/-like articulation involves advancing and raising the tongue blade, predorsum and dorsum, in conjunction with advancing the tongue root. The /a/-like articulation, by contrast, involves lowering the tongue front and dorsum, and retracting the root. In these articulations, $LOC_{a\text{-}i}$ captures the difference between the two vowels that consists in the relative positioning of the tongue front and the tongue back, while Curvature Degree captures the difference in lowering versus raising of the dorsum and predorsum. Both indices are ratios, so they could be compared across speaker groups without the need for normalisation.

Measuring coarticulation, tongue differentiation, and variability

$LOC_{a\text{-}i}$ and Curvature Degree were calculated for each token included in the quantitative analyses. Index values at mid-consonant across the two vowel contexts were used to assess whether a significant coarticulatory effect was present, and if so, to quantify the magnitude of effect. In order for an effect to be deemed present for a given age group and consonant, there had to be a significant difference between index values across the two vowel contexts. The magnitude of any significant effects was calculated by taking a ratio of the index value in the context of /i/ to that in the context of /a/. A higher ratio signified a greater effect magnitude, i.e., a larger difference between tongue shapes for a given consonant across the contrasting vowel contexts. To measure tongue differentiation, $LOC_{a\text{-}i}$ values were calculated for each token of /t/ from /ti/ at the end of the closure, and then compared with those from the middle of the closure. $LOC_{a\text{-}i}$ was chosen to quantify tongue differentiation because this measure has been previously shown to capture the raising and advancement of the tongue predorsum towards /i/ during the consonant articulated with the tip/blade of the tongue (Zharkova 2016). Variability was measured by calculating Coefficient of Variation values on the two indices of tongue shape at mid-consonant, separately for each speaker, and including only the Coefficient of Variation values based on five repetitions of a given target, the total of 211 and 218 observations in the contexts of /a/ and /i/, respectively.

Statistical analyses

Linear mixed models (LMMs) were carried out in R (R Development Core Team, 2013), with speaker modelled using both random slopes and intercepts, for all analyses except where explicitly specified. Determining the denominator degrees of freedom for the LMMs (see Baayen, 2008) was based on the approach described in Reubold et al. (2010). For the analyses of the presence of effect and of differentiation, the denominator degrees of freedom were set at 40, and LMM results were taken as significant at the 0.01 level if the value of F in the analysis of variance table (upper one-tailed) was greater than 7.31. To assess the presence of effect, LMMs were fitted within age group and separately for each consonant, for LOC_{a-i} and Curvature Degree. The ratios representing magnitude of any coarticulatory effects were compared within age group across consonants, to establish any consonant-specific patterns for each group of children; only random intercepts were used in these LMMs, because there was one ratio value per speaker per consonant. For the LMMs on the magnitude of coarticulatory effects, estimates of the numbers of degrees of freedom in the denominator were obtained using $df = n - k - 1$, where n represents the number of observations, and k represents the number of degrees of freedom (Reubold et al., 2010; see also Baayen, 2008). In the comparisons of the magnitude of any effect across age groups, it was not possible to use speaker as a random effect, because mean values per speaker were used in the analyses, so ANOVAs were carried out on the ratios, rather than LMMs. For analysing tongue differentiation, comparisons were carried out within age group, across the two time points of /t/ from /ti/. Finally, to compare token-to-token variability in tongue shape across age groups, LMMs were run on the Coefficient of Variation for LOC_{a-i} and for Curvature Degree, with speaker as a random intercept, separately for each vowel context, with the data from the different consonants pooled together (for the 5-to-13-year-olds, the data from all ten speakers per age group were represented in both models for at least two CV targets, while for the 3-year-old group, the data including between one and four different CVs were used for eight speakers in the model for the context of /a/, and for nine speakers in the model for the context of /i/). In the analyses of variability across age groups, a conservative value of 60 was selected for the denominator degrees of freedom, with LMM results taken as significant at the 0.01 level if the value of F in the analysis of variance table was greater than 3.34. For a more detailed comparison of the magnitude of any significant coarticulatory effects, as well as variability, across age groups, Tukey *post-hoc* tests were run in R, using *multcomp* package (Hothorn et al., 2008).

Results

Figures 3 – 6 show tongue contours at mid-consonant in a representative speaker from each age group, for each of the four consonants in turn. Tongue contours within the same consonant and vowel context in the children from the youngest two groups are more spread in absolute position than in the children from the other age groups, because of the nature of the recordings without head stabilisation. As the focus of the quantitative analyses in this paper is on the shape of each individual curve, rather than on variability in absolute position of the tongue curves, the following description of the figures also concentrates on within-curve tongue shapes. In all age groups, including the two youngest groups of children, visual observation makes it possible to see certain differences in the consonant tongue shape conditioned by the two vowel contexts. For example, for /p/ represented in figure 3, the difference in the relative location, along the tongue curve, of the most bunched part tongue across the two vowel contexts is visible, with more bunching towards the front of the tongue in the context of /i/, and towards the back of the tongue in the context of /a/. All lingual consonants have smaller differences in tongue shape than the bilabial stop, across age groups. For /t/ in figure 4, more tongue bunching appears to be present in the context of /i/ than in the context of /a/ in all age groups. A similar vowel-related difference seems to exist for /s/ (figure 5), although it appears to grow more prominent with increasing age. For /ʃ/ (figure 6), there are quite small differences in tongue shape across vowel contexts, with the children aged seven years old and above having a somewhat advanced tongue root in the context of /i/, compared with the context of /a/.

<figure 3 about here>

<figure 4 about here>
<figure 5 about here>
<figure 6 about here>

Presence of effect

Table 2 shows LOC_{a-i} values for each consonant in each vowel context, for every age group. The table also has the results of LMMs that established whether each age group had a significant coarticulatory effect on each consonant. The only consonant that had a significant effect in every age group was the bilabial stop. For the alveolar stop, the effect was present in the 9-year-old group and older, but not in three youngest groups. For the alveolar fricative, the effect was only observed in the oldest age group. The postalveolar fricative did not show a significant vowel-related effect on LOC_{a-i} in any age group. These results provide some support for the first two hypotheses on cross-consonantal differences, i.e., that the bilabial stop will be more affected by the vowels than the lingual consonants, and that coarticulatory patterns will be most protracted for /ʃ/, and more for /s/ than for /t/.

<table 2 about here>

In table 3, results of the analyses on Curvature Degree are presented for /t/, /s/ and /ʃ/ for every age group. The coarticulatory effect on /t/ was significant in every age group, as opposed to LOC_{a-i}, which showed no effect for 3-to-7-year-olds. For /s/, there was no significant effect in the youngest age group, while for /ʃ/, no significant effect was observed in the two youngest groups. The fact that a significant effect was observed in progressively older age groups for /t/, /s/ and /ʃ/, in this sequence, provides support for the hypothesis that the lingual consonants with more constraint on the tongue would show a more protracted development of vowel-on-consonant coarticulation.

<table 3 about here>

Magnitude of effect

Results on the magnitude of significant coarticulatory effects are presented in table 4. When comparing the magnitude of effect across two different consonants, the number of degrees of freedom in the denominator was estimated at 17 (based on the comparison with the smallest number of observations, /t/ versus /s/ in 5-year-olds), and the result was deemed significant if the value of F in the analysis of variance table was greater than 8.40, at the 0.01 level; for a comparison of the magnitude of effect across three different consonants, the number of degrees of freedom in the denominator was estimated at 27, and the result was taken as significant with the F value greater than 5.49, also at the 0.01 level.

<table 4 about here>

For the 9-year-old group and the 11-year-old group, both of which had a significant coarticulatory effect on /p/ as well as on /t/, as measured by LOC_{a-i}, the magnitude of this effect was significantly greater for /p/ than for /t/ (9-year-olds: $F = 11.64$; 11-year-olds: $F = 14.61$). For the 13-year-old group, which, on LOC_{a-i}, had a significant coarticulatory effect on /p/, /t/ and /s/, the magnitude of effect was significantly different across consonants ($F = 15.13$), with /p/ being different from both /t/ and /s/ at the 0.001 level (note that the results of this LMM for the 13-year-olds were originally reported in Zharkova et al., 2015a). These results, in addition to the fact that in the three younger groups /p/ was the only consonant showing a significant vowel-related coarticulatory effect through LOC_{a-i}, support the hypothesis that, due to the lack of constraints on the tongue, /p/ will undergo more coarticulation in all age groups than each of the lingual consonants. The importance of tongue constraints will be discussed below in relation not only to coarticulatory patterns, but also to the order of acquisition of consonants during early years of phonological development.

For Curvature Degree, in those cases where a coarticulatory effect was observed within the same age group on more than one lingual consonant, there were no significant differences in the magnitude of effect across the consonants in any age group except the 9-year-olds (5-year-olds: $F = 2.75$; 7-year-olds: $F = 2.93$; 9-year-olds: $F = 6.83$; 11-year-olds: $F = 3.20$; 13-year-olds: $F = 3.36$ (the results for the 13-year-olds were, as above, originally reported in Zharkova et al., 2015a)). In those age groups which had a significant coarticulatory effect for all lingual consonants, the magnitude of effect was greater for the two alveolar consonants than for the postalveolar fricative, although this difference only reached significance in the 9-year-old group ($p < 0.01$ for both /t/-/ʃ/ and /s/-/ʃ/ *post-hoc* comparisons).

Across-group comparisons on LOC_{a-i} were performed through carrying out ANOVAs for /p/ and /t/. A significant effect on LOC_{a-i} for /s/ was only observed in the oldest age group, so no across-group comparisons were possible. For both stops, the results were not significant (/p/: $F = 0.32$; /t/: $F = 0.08$), suggesting that there was no difference in the magnitude of coarticulatory effect across age groups. For Curvature Degree, across-group ANOVA results were significant for /t/ ($F = 3.60$, $p < 0.01$). *Post-hoc* tests showed significant differences between 3-year-olds and 13-year-olds ($p < 0.01$), 3-year-olds and 9-year-olds ($p < 0.05$), 3-year-olds and 7-year-olds ($p < 0.05$), and a marginally significant difference between 3-year-olds and 5-year-olds ($p = 0.06$). Across-group comparisons for /s/ and /ʃ/ on Curvature Degree did not produce significant results ($F = 0.87$ and $F = 1.55$, respectively).

Tongue differentiation

Table 5 presents the results of LMMs analysing tongue differentiation. The table shows that 3-year-old children were the only age group that did not have a significant difference on LOC_{a-i} between tongue shapes at the middle versus the end of /t/ closure. This result supports Hypothesis 3, which predicts an increase in tongue differentiation with increasing age.

<table 5 about here>

Variability

Results on within-speaker variability in tongue shape are reported for each age group in table 6. The general pattern of reducing Coefficient of Variation values with increasing age was observed.

<table 6 about here>

LMM results of the comparison of Coefficient of Variation on LOC_{a-i} yielded a significant difference across age groups both in the context of /a/ ($F = 10.16$) and in the context of /i/ ($F = 7.54$). *Post-hoc* tests in the context of /a/ showed significant differences at the 0.001 level between 3-year-olds and each age group starting from the age of seven years old. Also, 5-year-olds were significantly different from 13-year-olds ($p < 0.001$), and from 11- and 9-year-olds ($p < 0.05$ in both cases); the difference between 5-year-olds and 7-year-olds was marginally significant ($p = 0.06$). In the context of /i/, significant results of the *post-hoc* tests were as follows: 3-year-olds versus 13- and 11-year-olds ($p < 0.001$ in both cases);

3-year-olds versus 7-year-olds, and 5-year-olds versus 13-year-olds ($p < 0.01$ in both comparisons); 9-year-olds versus 13-year-olds ($p < 0.05$); also, the difference between 3-year-olds and 9-year-olds was marginally significant ($p = 0.05$).

For Curvature Degree, variability was also significantly different across age groups in both vowel contexts (the context of /a/: $F = 11.84$; the context of /i/: $F = 8.68$). *Post-hoc* comparisons produced significant results in the context of /a/ for the comparison between 13-year-olds and 7-year-olds ($p < 0.05$), as well as for each age group starting from the age of seven years old versus each of the two youngest age groups: $p < 0.05$ for the comparisons of 7-year-olds with 5- and 3-year-olds, and $p < 0.001$ for all other significant results. In the context of /i/, the following post-hoc test results were significant: 3-year-olds versus 7- and 9-year-olds (in both cases, $p < 0.05$); each of the two youngest groups versus each of the two oldest groups ($p < 0.001$, except the comparison of 5-year-olds versus 11-year-olds, which was signigicant at the 0.01 level).

Discussion

This study focussed on coarticulation, tongue differentiation and tongue shape variability in six child age groups between three and thirteen years old. The results provided support for all hypotheses, showing that lingual coarticulation develops during childhood in a segment-specific fashion, conditioned by the maturation of motor abilities and by the articulatory challenges presented by the speech segments. Below, the findings will be discussed in relation to each hypothesis.

The labial stop was clearly different in coarticulatory patterns from the lingual consonants, across age groups, so Hypothesis 1 was supported. As shown in tables 2 and 4, the effect on /p/ was observed for LOC_{a-i} for all age groups, with no significant difference in the magnitude of effect across age groups. For the lingual consonants, the extent of influence from the contrasting vowels on the consonant tongue shape, as measured by LOC_{a-i}, was either not statistically significant, or the magnitude of any effect was significantly smaller than for the bilabial. These results suggest that constraints on the tongue related to the consonant production affect lingual coarticulation already in young children. The results from Scottish English speaking children in this study agree with previous findings on coarticulation in children speaking American English (Sussman et al., 1992; Goodell & Studdert-Kennedy, 1993; Sussman et al., 1999), Canadian French (Noiray et al., 2013), and German (Rubertus et al., 2015), showing that this aspect of the development of coarticulation is present across languages, as well as across varieties of the same language.

The nature of age-related differences in coarticulation across the three lingual consonants provided support for Hypothesis 2. For lingual consonants, adjusting tongue dorsum/predorsum height for coarticulation (captured by Curvature Degree) was used already by three-year-old children, while further shape changes reflecting progressive tongue advancement versus retraction in anticipation of the different vowels (represented by LOC_{a-i}) was only employed by older children, starting from the age of nine years old. The development of these strategies of tongue shape adjustment for lingual coarticulation has been demonstrated in this study to be segment-specific. The coarticulatory patterns as measured by LOC_{a-i} had some age-related differences in the predicted direction. For /t/, a significant effect on LOC_{a-i} emerged in the 9-year-old group, while for /s/, only 13-year-olds had a significant vowel effect on LOC_{a-i}. As expected, the most protracted development of coarticulatory patterns was reported for /ʃ/. On Curvature Degree, a measure that showed a significant coarticulatory effect for both alveolar consonants starting from at least the age of five years old, a significant effect for /ʃ/ was only observed starting from seven years old.

The cross-consonant age-related differences reported in this study cannot be accounted for by either of the two competing theories of coarticulation development postulating that the extent of coarticulation uniformly increases or decreases during childhood (Kent, 1983; Nittrouer et al., 1989). Instead, the study has demonstrated that coarticulation development is dependent on consonant properties. In those cases where more than one age group exhibited a significant effect for a given consonant on a given measure of tongue shape, four out of five across-group comparisons of magnitude of coarticulatory effects did not produce significant results. Specifically, there were no age-related differences in the magnitude of effect on /p/ and on /t/ for LOC_{a-i}, nor on /s/ and on /ʃ/ for Curvature Degree. These data also do not support the theoretical claims about unidirectional changes in coarticulation with increasing age. Nor, however, can the coarticulatory patterns observed in this study be fully explained by the existing "adult" version of the DAC model of coarticulation (Recasens et al., 1997). While the data on the bilabial stop versus the lingual consonants generally support the DAC model, the non-uniform patterns of segment-specific coarticulation in different age groups suggest that other, "child-specific", constraints have played a role in the observed patterns. Suggestions of possible constraints explaining the reported developmental differences are outlined and discussed below. Before proceeding to the details of specific constraints, it is worth noting that the order in which the children in this study progress towards more mature coarticulatory patterns is reminiscent of the order of acquisition of consonant phonemes during the first two years of phonological development (see Vihman, 2014, and references cited there), particularly regarding generally early acquired bilabial consonants, and relatively later acquired sibilant fricatives, which are often substituted by stops in children with typically developing speech (see also Smit, 1993). These parallels suggest that the limitations defined by articulatory requirements associated with individual segments apply to the children's productions both at the early stage of phonological development and in later pre-school and early school years, with the impact from different articulatory challenges gradually reducing with the maturation of speech motor abilities.

In the analyses of tongue differentiation, the results showed that the only group unable to differentiate between contrasting target tongue postures at mid-/t/ versus end of /t/ closure in the context of /i/ was the group of 3-year-olds. Thus, Hypothesis 3 received support from the data, in that tongue differentiation increased with increasing age. We take this lack of differentiation in tongue shape as an indicator that the level of speech motor development in our 3-year-old children was not as advanced as in older age groups. This could conceivably be a reason for the lack of lingual coarticulation across vowel contexts on LOC_{a-i} in the youngest age group. This interpretation agrees with the idea that the lack of tongue differentiation may be a stage in typical child speech development (cf. Gibbon, 1999; Gick et al., 2008). The results from older age groups suggest that protracted development of coarticulation in those age groups was not due to inability to differentiate between tongue tip/blade and dorsum/predorsum (as hypothesised by Zharkova et al., 2012, as a possible explanation for the lack of vowel-on-/s/ coarticulation in 6-9-year-old children that they found). An alternative explanation for immature coarticulatory patterns in all other age groups up to 11 years old is that the goal of reaching the target for the consonant is more important for the children than the goal of coarticulating the consonant with the adjacent vowels. In other words, the children are able to differentiate between parts of the tongue to accommodate vocalic influence on the consonant, but prefer to concentrate on articulating the consonant at the expense of adjusting the tongue to the contrasting vowels. The different immature coarticulatory patterns in 3-year-olds versus older children might in fact constitute two successive stages of lingual motor control maturation in typically speaking children, forming a developmental continuum (Fiona Gibbon, personal communication). A further finding from this study that singles out the youngest age group is that the 3-year-olds coarticulated the alveolar stop consonant on Curvature Degree *more* than the older groups of children, despite having reduced tongue differentiation and the absence of coarticulatory effects on the lingual consonants as measured by LOC_{a-i}. It is possible that the 3-year-olds raised the tongue dorsum in anticipation of the vowel /i/ already by mid-closure, which would have led to a greater vowel-conditioned difference in tongue shape that was captured using Curvature Degree. The overshoot in the magnitude of coarticulation on Curvature Degree observed for the 3-year-old group could have been a manifestation of the developmental process described by Sussman et al. (1999), which consists in fine-tuning of “the interaction of articulatory effort and coarticulatory overlap” (p. 1094) that is required for adult-like coarticulation of alveolar stops.

Token-to-token variability in tongue shape was shown to decrease with increasing age. These results support Hypothesis 4, and agree with previous studies (e.g., Kent and Forner, 1980; Sharkey and Folkins, 1985; Nittrouer, 1993; Smith and Goffman, 1998; Lee et al., 1999; Nijland et al., 2002; Walsh and Smith, 2002; Nittrouer et al., 2005; Zharkova et al., 2011, 2012). The results were statistically significant for both measures of tongue shape in both vowel contexts. The two youngest age groups were often different from most other age groups, as shown by the *post-hoc* tests. There was a possibility that these results were affected by the fact that only the two youngest groups were recorded without head-to-transducer stabilisation. In order to investigate this possibility, variability in the 3-year-olds and the 5-year-olds was compared with the variability data on the 13-year-old group also recorded without head stabilisation. The latter data were collected at the same time as the head-stabilised recordings of the adolescent group (for more information on these data, see Zharkova et al., 2015a). Comparisons of 13-year-old data without stabilisation with the data from the two youngest groups were carried out for each tongue shape index in each vowel context. All four LMMs produced a significant age-related difference. In the *post-hoc* tests, the adolescents were significantly less variable than each of the two child groups, except the tests for LOC_{a-i} in the context of /i/, where this difference reached significance only in the comparison of the youngest group with the adolescents. These findings suggest that the difference in variability between the two youngest groups and the other age groups is unlikely to have been influenced by the presence versus absence of head-to-transducer stabilisation. Another potential effect of the different stabilisation conditions on the articulatory measures could have been observed if variability due to hand-held transducer obscured any vowel-related coarticulation. However, this suggestion is not supported by the data, with the pattern of results for LOC_{a-i} showing that there was no significant coarticulation for lingual consonants even for older children, who did wear the stabilisation headset. We can also draw confidence in our results on variability from the fact that they converge with the findings from recent ultrasound studies of speech production in young Canadian French speaking children (Barbier et al., 2015) and Cantonese speaking children (Yip et al., 2015). Despite using different recording methodologies (the former study used optical tracking head correction without stabilising the head, while in the latter study the head was stabilised relative to the ultrasound transducer), both studies reported a substantial amount of token-to-token variability in 3-to-5-year-old children, compared with older speakers.

Applying the exclusion criteria to the younger groups of children resulted in a noticeable difference in the amount of analysed data between the 3-year-old group and the older groups, to a considerable extent due to immature fricative production in some of the children (cf. Smit, 1993). There is a possibility that the large variability in the youngest group was in part due to the smaller data size for that group. In order to investigate this possibility, the Coefficient of Variation values for the 3-year-old group were compared with those for the older groups with a comparable amount of data per group. Five speakers were selected at random from each of the age groups between 5 and 13 years old, and LMMs were run across age groups, for each vowel context and articulatory index. The results of all comparisons still yielded significant age-related differences between the 3-year-old group and all the other age groups starting from seven years old. These findings suggest that the difference in variability between the youngest speakers and older groups is quite robust. The choice of perceptually appropriate productions in this study had a clear methodological reason, as in order to be able to compare tongue adjustment during a consonant to the neighbouring vowel it was important that the consonant itself was the same across speakers and age groups. The data on phonological errors and phonetic distortions were not included for reasons of space, but they constitute an important source of information, which could usefully contribute to studying the development of motor control in children, and they will be investigated in our future research.

While this study did not address any effects on lingual coarticulation from prosody, word or morphological structure (cf. an ultrasound study by Song et al., 2013, exploring the influence of morphological structure on lingual coarticulation in 2-year-old children), the results raise interesting questions on how these factors might interact with the extent of articulatory constraint on the tongue for individual speech segments during childhood. For example, in this study the target CV syllable words were in a prominent position in the carrier phrase; the age-related pattern of results on coarticulation might have been different if the target words had been in a less prominent position (see, e.g., Beckman et al., 1992). Designing future experiments to include varying prosodic conditions for the target word would make it possible to investigate how segmental articulatory constraints may differentially affect coarticulation across age groups and prosodic conditions, given that prosodic abilities continually develop throughout childhood and adolescence (Filipe et al., 2017).

The study for the first time used ultrasound imaging for analysing speech data from a wide range of child ages, extending into adolescence (cf. Rubertus et al., 2015, who reported data from German speaking children aged 3, 4, 5 and 7 years old). One of the challenges in this task was ensuring the reliability of quantitative comparisons of tongue contours across age groups, which required recording the same stimuli from all children. In order to keep the data collection procedure maximally ecologically valid for all age groups, the elicitation procedures differed across groups, taking into account age-related psychological differences, as well as the challenges involved with collecting articulatory data from young children (see Zharkova et al., 2017). For recording sufficient numbers of repetitions from the youngest participants, the optimal procedure was found to be repeating after the child's carer. While different elicitation methods have been used in some previous studies of young children's speech production, including those using ultrasound (e.g., Song et al., 2013; Lin & Demuth, 2015; McAllister Byun et al., 2016), in the present study repeating after the carer was the most natural behaviour for young children involved in playing a game together with the carer. All CV syllable tokens by the 3- and 5-year-old participants included in across-group comparison were perceptually correct realisations, which ensured comparability with older children's productions. The fact that the 3-year-olds produced some of the tokens consecutively within a single stimulus presentation could have arguably led to increased coarticulation; however this was not the case, as on most combinations of articulatory index and consonant the 3-year-olds did not have more coarticulation than the other groups. Moreover, the 3-year-olds had similar cross-consonant (particularly labial stop versus alveolar stop) coarticulatory differences to other groups, and they patterned largely with the 5-year-old group on variability; both these findings agree with previous reports (e.g., Goodell & Studdert-Kennedy, 1993; Barbier et al., 2015). The difference across age groups in reading versus repeating the stimuli might have affected the results, with potentially more careful productions in read speech (e.g., Koopmans-van Beinum, 1991), which could have led to reduced coarticulation (cf. Krull, 1989). The results, however, present largely the opposite picture, namely that younger age groups did not demonstrate any evidence of coarticulation on several combinations of articulatory indices and consonant types where older age groups did. Another potential factor related to the elicitation methods is that the younger 7-year-olds, as potentially less fluent readers, might have displayed reduced coarticulation. During the recordings care was taken to elicit fluent productions from all children, particularly the younger 7-year-olds. Reassuringly, the 7-year-old children did not show any within-group differences in coarticulation when precise age in months was taken into account (see below).

Age distributions within group had some differences across groups of children, which is a potential limitation of the study. In the 3-year-old group, eight children were older than three years six months, and only two children were aged three years four months; we need to bear this information in mind when interpreting the results for the youngest age group. Also, age ranges were not the same across groups, with the range for the 7-year-old group larger than for all other groups. In order to investigate whether these differences could have led to any within-group differences in coarticulation, analyses on the presence of coarticulatory effect for each age group and each consonant were run including precise age in months as an additional factor. There were no significant effects of age in months or significant interactions with this factor, except two, which are described below. On $LOC_{a\text{-}i}$, there was a significant interaction between vowel and age in months for the 11-year-olds for /s/, with larger values for /a/ than for /i/ in the three youngest children, and the opposite pattern, showing evidence of vowel-related coarticulation, in the older children. Given that the LMM reported in Table 2 did not show a coarticulatory effect on /s/ in the 11-year-olds as a group on this measure, this pattern might illustrate a gradual change in controlling tongue dynamics in preadolescents. On Curvature Degree, there was a significant interaction between age in months and vowel for the 9-year-olds for /ʃ/, with the younger children demonstrating a more pronounced vowel-related difference than the older children. While this within-group difference needs to be interpreted with caution due to the fact that 9-year-olds as a group did not have significantly less coarticulation on /ʃ/ than 7-year-olds or more than 11-year-olds, this pattern might represent ongoing changes in motor control, related to the vocal tract maturation (cf. Zharkova et al., 2011; Romeo et al., 2013). It also needs to be acknowledged that this study reports production data up to early adolescence, but not for older adolescent and adult productions. Such information would usefully complement the data reported in this paper, as it has been demonstrated in a number of studies that speech motor development is protracted, with even 14- to 16-year-old adolescents showing differences from adults (e.g., Lee et al., 1999; Sadagopan & Smith, 2008; Romeo et al., 2013).

An advantage of ultrasound imaging is that the technique allows for relatively direct articulatory measurements when the acoustic signal provides only limited information, e.g., during stop closure; when formants cannot be measured, such as at mid-consonant for voiceless fricatives; or when spectral information would not be sufficient to determine the exact tongue shape behind the closure or constriction. This made it possible in the current study to analyse lingual coarticulation at mid-consonant across voiceless stop and fricative consonants. In the data analysed in the study, information on the tongue-palate constriction was not included, due to the nature of the recording procedure for the youngest participants. In previous developmental studies, such information has been inferred from the acoustic signal, which represents combined activity of different parts of the vocal tract (e.g., Nittrouer, 1993). Other articulators, including particularly the lips and the jaw, as well as the lateral margins of the tongue, would have contributed to the coarticulatory patterns reported in the study (cf. Reidy, 2015). Because of the inability of ultrasound tongue imaging to simultaneously show other vocal tract structures, and because the study focussed on midsagittal tongue images without tracking lip or jaw movements, conclusions on the observed coarticulatory patterns are necessarily limited to midsagittal tongue movements. Also, the study focussed on a single time point at mid-consonant, unlike some previous studies that have traced vowel-on-consonant coarticulation over time (e.g., Katz &

Bharadwaj, 2001; Goffman et al., 2008; Zharkova et al., 2014; Reidy, 2015). Detailed dynamic analyses that are currently ongoing will make it possible to investigate the development of coarticulation in the temporal domain during childhood and into adolescence, including any changes in the effects of prosody and grammar on lingual coarticulation.

The measures of tongue shape used in this work, which are independent of head-to-transducer stabilisation, were employed for the first time to study the development of lingual coarticulation throughout childhood. While the obvious advantage of such measures is that they can be used with very young children, their limitation is that they may not be as powerful as the measurements based on the whole tongue contour (see a discussion in Zharkova et al., 2017). This may have been the reason why the difference between consonant contours conditioned by contrasting vocalic environments was not captured for /ʃ/ by $LOC_{a\text{-}i}$ in any age group, and also for the lack of significant differences in the magnitude of effect on Curvature Degree across lingual consonants in most age groups. However the results produced by using a combination of these two measures of tongue shape and a selection of consonants provided a sufficient amount of information to draw a coherent picture of the development of lingual control from the age of three years old to early adolescence, that could be expanded in future studies.

Conclusion

The results of this study suggest that developmental shifts in the degree of coarticulation of individual speech sounds are affected by changes in articulatory constraints on the tongue with age. Specifically, the study showed that coarticulating lingual consonants with adjacent vowels, unlike coarticulating the labial consonant, presented some challenges for all age groups except the adolescents. The group of 3-year-old children was the only age group where immaturities in coarticulatory patterns could be explained by the lack of tongue differentiation. For the older age groups, the findings on reduced coarticulation suggest that the goal of producing an alveolar consonant target may override the goal of coarticulating the consonant with the following vowel. The adjustment of the tongue shape reflecting tongue advancement/retraction involved with coarticulating the alveolar fricative was protracted compared with the alveolar stop. This finding was interpreted to mean that the articulatory difficulty involved with producing a perceptually appropriate alveolar fricative may limit the extent of vowel-related coarticulation until the age of 11 years old. The use of contrasting degrees of the tongue dorsum/predorsum bunching for coarticulating /ʃ/ was shown to be not in place until seven years old, as opposed to /t/ and /s/, which demonstrated this pattern by the ages of three years old and five years old, respectively. Decreased tongue shape variability was observed with increasing age. The patterns of coarticulation development for the different consonants throughout childhood show some similarities to the findings from the literature on the order of acquisition of consonant phonemes by children. The consonants that are generally acquired later were demonstrated in this study to take longer to develop mature coarticulatory patterns, with those consonants that have more articulatory demands on the tongue showing the most protracted development of vowel-related coarticulation. The evidence of protracted development in controlling tongue movements by children with typical speech reported in this study has implications for clinical practice, with some fine adjustments of tongue shape not expected to be present in typically coarticulated speech sounds, depending on age and on the speech sound.

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Table 1.

Age group	Mean age [years;months] and SD	Min age – Max age [years;months]	Median age [years;months]	Gender distribution
3-year-old	Mean = 3;9 SD = 3 months	3;4 – 4;1	3;10	4 girls, 6 boys
5-year-old	Mean = 5;8 SD = 2 months	5;5 – 5;11	5;9	5 girls, 5 boys
7-year-old	Mean = 7;7 SD = 5 months	6;11 – 8;2	7;7	1 girl, 9 boys
9-year-old	Mean = 9;5 SD = 4 months	9;0 – 9;9	9;5	5 girls, 5 boys
11-year-old	Mean = 11;5 SD = 3 months	11;0 – 11;10	11;5	7 girls, 3 boys
13-year-old	Mean = 13;5 SD = 5 months	13;0 – 13;11	13;4	6 girls, 4 boys

Table 2.

	/p/		/t/		/s/		/ʃ/	
	/a/	/i/	/a/	/i/	/a/	/i/	/a/	/i/
3-year-old	1.03 *0.41*	1.42 *0.29*	1.05 *0.37*	1.26 *0.37*	0.95 *0.22*	1.09 *0.29*	1.50 *0.37*	1.55 *0.54*
	F = **16.16**		*F* = 1.25		*F* = 1.91		*F* = 0.24	
5-year-old	0.93 *0.23*	1.29 *0.24*	1.11 *0.25*	1.11 *0.18*	0.99 *0.33*	0.96 *0.21*	1.40 *0.37*	1.45 *0.40*
	F = **27.15** ^		*F* = 0.00 ^		*F* = 0.27		*F* = 0.49	
7-year-old	0.87 *0.14*	1.26 *0.29*	1.10 *0.25*	1.19 *0.23*	0.86 *0.19*	0.95 *0.19*	1.58 *0.40*	1.57 *0.38*
	F = **51.79**		*F* = 2.59		*F* = 4.15		*F* = 0.03	
9-year-old	0.90 *0.16*	1.38 *0.29*	1.11 *0.31*	1.31 *0.35*	0.86 *0.25*	0.99 *0.31*	1.55 *0.44*	1.65 *0.55*
	F = **42.96**		*F* = **17.72**		*F* = 3.08		*F* = 2.08	
11-year-old	0.81 *0.18*	1.19 *0.27*	0.96 *0.23*	1.11 *0.24*	0.84 *0.19*	0.89 *0.20*	1.65 *0.76*	1.61 *0.68*
	F = **54.90**		*F* = **11.97**		*F* = 1.13		*F* = 0.41	
13-year-old	0.86 *0.16*	1.29 *0.32*	1.00 *0.21*	1.19 *0.29*	0.83 *0.23*	1.00 *0.27*	1.43 *0.33*	1.43 *0.32*
	F = **28.05** ^		*F* = **9.37** ^		*F* = **19.90** ^		*F* = 0.01 ^	

Table 3.

	/t/		/s/		/ʃ/	
	/a/	/i/	/a/	/i/	/a/	/i/
3-year-old	0.22 *0.07*	0.35 *0.08*	0.24 *0.07*	0.30 *0.07*	0.30 *0.05*	0.33 *0.06*
	F = **31.52**		F = 4.83		F = 5.61	
5-year-old	0.24 *0.05*	0.31 *0.06*	0.22 *0.05*	0.26 *0.05*	0.28 *0.06*	0.29 *0.06*
	F = **15.39**		F = **18.13**		F = 5.00	
7-year-old	0.25 *0.05*	0.32 *0.05*	0.24 *0.07*	0.31 *0.06*	0.30 *0.05*	0.34 *0.07*
	F = **24.57**		F = **13.75**		F = **12.96**	
9-year-old	0.25 *0.07*	0.31 *0.06*	0.25 *0.06*	0.31 *0.06*	0.33 *0.04*	0.35 *0.05*
	F = **35.99**		F = **17.11**		F = **15.64**	
11-year-old	0.25 *0.07*	0.33 *0.07*	0.23 *0.06*	0.30 *0.07*	0.31 *0.07*	0.36 *0.06*
	F = **48.64**		F = **24.13**		F = **21.15**	
13-year-old	0.27 *0.04*	0.33 *0.03*	0.26 *0.05*	0.31 *0.04*	0.34 *0.06*	0.37 *0.07*
	F = **18.33** ^		F = **45.86** ^		F = **7.52** ^	

Table 4.

	LOC_{a-i}				Curvature Degree		
	/p/	/t/	/s/	/ʃ/	/t/	/s/	/ʃ/
3-year-old	1.51	N/S	N/S	N/S	1.68	N/S	N/S
5-year-old	1.42	N/S	N/S	N/S	1.33	1.19	N/S
7-year-old	1.45	N/S	N/S	N/S	1.29	1.30	1.14
9-year-old	1.56	1.19	N/S	N/S	1.26	1.25	1.07
11-year-old	1.48	1.17	N/S	N/S	1.36	1.32	1.15
13-year-old	1.51	1.19	1.21	N/S	1.22	1.19	1.09

Table 5.

Age group	LOC_{a-i} at end of closure	LOC_{a-i} at mid-closure	LMM results
3-year-old	Mean: 1.39; SD: 0.43	Mean: 1.26; SD: 0.37	F = 3.39
5-year-old	Mean: 1.20; SD: 0.24	Mean: 1.11; SD: 0.18	F = **7.85**
7-year-old	Mean: 1.33; SD: 0.28	Mean: 1.19; SD: 0.23	F = **10.30**
9-year-old	Mean: 1.58; SD: 0.47	Mean: 1.31; SD: 0.35	F = **26.84**
11-year-old	Mean: 1.24; SD: 0.26	Mean: 1.11; SD: 0.24	F = **18.62**
13-year-old	Mean: 1.33; SD: 0.32	Mean: 1.19; SD: 0.29	F = **12.05**

Table 6.

LOC_{a-i}								
	Context of /a/				Context of /i/			
	/p/	/t/	/s/	/ʃ/	/p/	/t/	/s/	/ʃ/
3-year-old	0.23	0.34	0.15	0.12	0.15	0.17	0.20	0.23
5-year-old	0.13	0.14	0.19	0.18	0.12	0.10	0.12	0.18
7-year-old	0.09	0.11	0.11	0.09	0.12	0.09	0.13	0.09
9-year-old	0.09	0.09	0.11	0.08	0.10	0.12	0.15	0.15
11-year-old	0.11	0.10	0.08	0.08	0.10	0.08	0.12	0.09
13-year-old	0.05	0.06	0.09	0.05	0.06	0.06	0.08	0.06
Curvature Degree								
	Context of /a/				Context of /i/			
	/p/	/t/	/s/	/ʃ/	/p/	/t/	/s/	/ʃ/
3-year-old	0.12	0.21	0.16	0.11	0.09	0.11	0.18	0.16
5-year-old	0.14	0.13	0.18	0.11	0.13	0.11	0.16	0.12
7-year-old	0.09	0.11	0.11	0.07	0.09	0.09	0.11	0.07
9-year-old	0.08	0.08	0.08	0.06	0.09	0.09	0.10	0.06
11-year-old	0.07	0.10	0.08	0.04	0.06	0.07	0.08	0.07
13-year-old	0.05	0.05	0.05	0.05	0.04	0.05	0.06	0.05

Table headings

Table 1. Detailed information on the participants.

Table 2. LOC_{a-i} values for each group (Standard Deviation in italics), and *F* values from LMMs. Significant results are in bold. The results of four LMMs for 13-year-olds from Zharkova et al. (2015a) and two LMMs for 5-year-olds from Zharkova et al. (2015b) are marked by a "^" sign.

Table 3. Curvature Degree values for each group (with Standard Deviation), and *F* values from LMMs. Significant results are in bold. The results of three LMMs for 13-year-olds from Zharkova et al. (2015a) are marked by a "^" sign.

Table 4. Mean group values for the magnitude of effect. "N/S" refers to those cases where in tables 2 and 3 there was no significant vocalic coarticulatory effect on the consonant.

Table 5. Mean LOC_{a-i} values and Standard Deviation values at the end of the stop closure for /t/ from /ti/; mean and Standard Deviation values at mid-closure, from table 2, are also provided here, for easier reference. *F* values from LMMs comparing LOC_{a-i} at mid-closure and at the end of the closure can be found in the last column. Significant results are in bold.

Table 6. Mean group values for the Coefficient of Variation on the two tongue shape indices.

Figure legends

Fig. 1. Left panel: still synchronised images of a participant from two video cameras during the recording, from the ultrasound recording software. Right panel: a midsagittal ultrasound tongue image recorded from a three-year-old participant. The front of the tongue is on the right in this figure and in all other figures in the paper. The acoustic shadows of the chin and of the hyoid bone are indicated by arrows.

Fig. 2. Example tongue curves from a 13-year-old participant, illustrating calculations of the two indices of tongue shape. Both panels show the same tokens of /s/ from /sa/ (solid curve) and /s/ from /si/ (dashed curve).

Fig. 3. Tongue curves for the bilabial stop produced by a representative speaker from each age group: solid lines for the context of /a/; dotted lines for the context of /i/. For each age group, data from the same speaker are provided for /p/ (this figure) and for the other three consonants (figures 4 – 6).

Fig. 4. Tongue curves for the alveolar stop produced by a representative speaker from each age group: solid lines for the context of /a/; dotted lines for the context of /i/.

Fig. 5. Tongue curves for the alveolar fricative produced by a representative speaker from each age group: solid lines for the context of /a/; dotted lines for the context of /i/.

Fig. 6. Tongue curves for the postalveolar fricative produced by a representative speaker from each age group: solid lines for the context of /a/; dotted lines for the context of /i/.

Figure 1

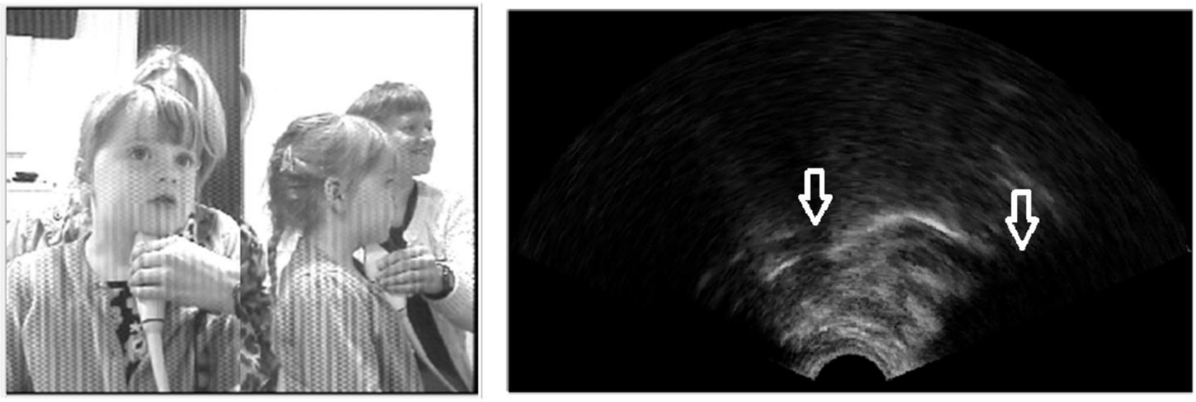

Figure 2

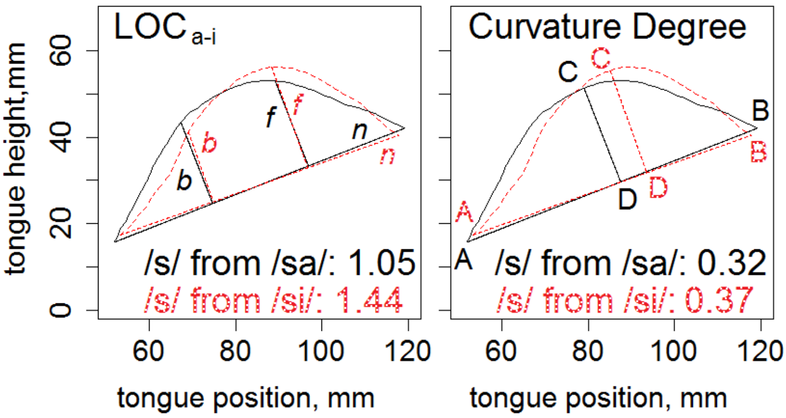

Figure 3

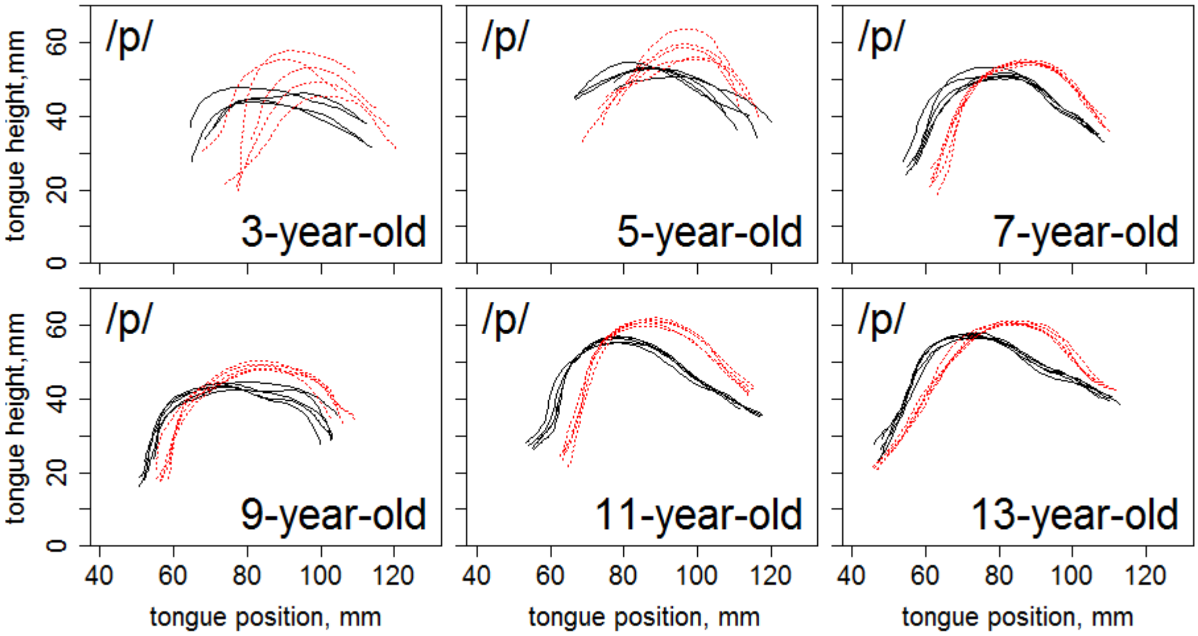

Figure 4

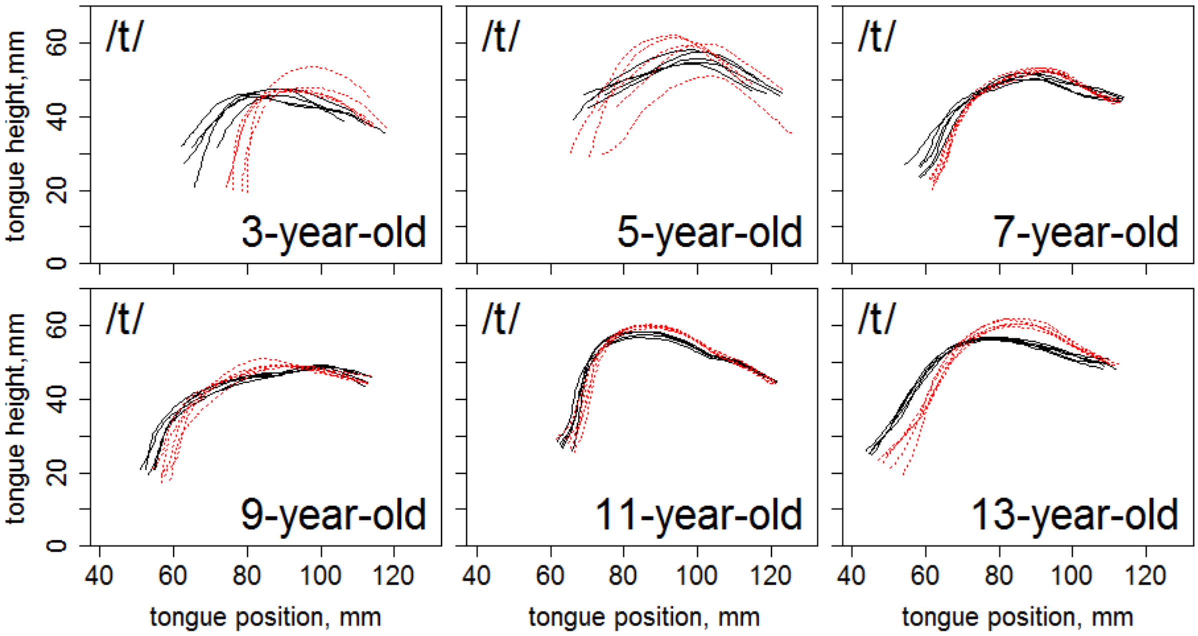

Figure 5

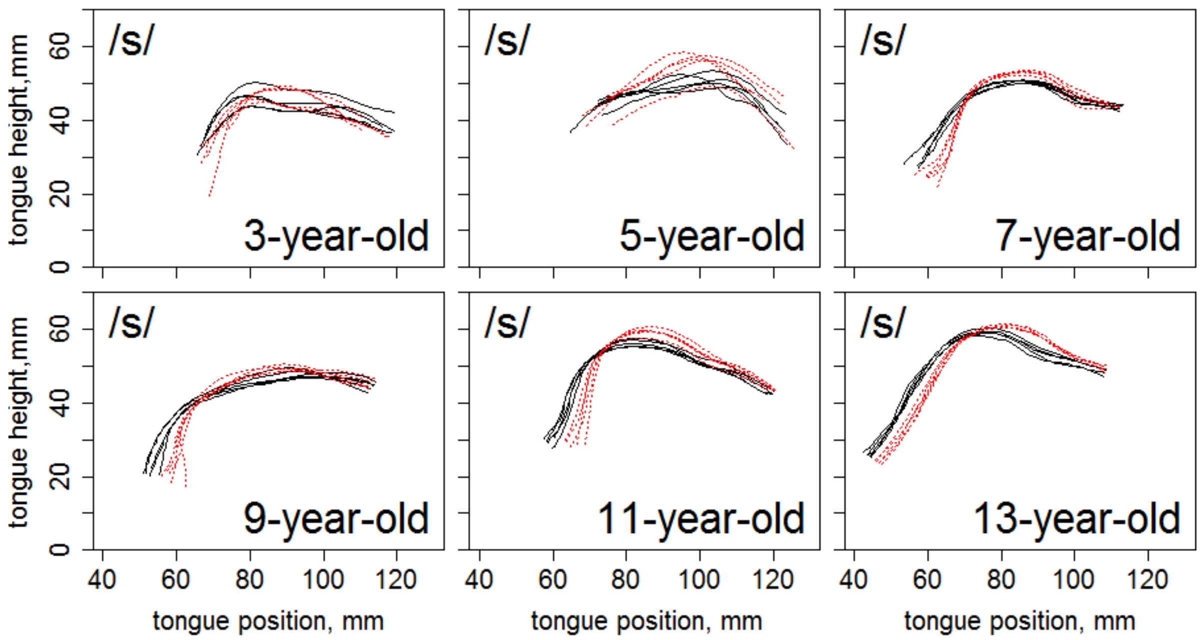

Figure 6