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**Voiceless alveolar stop coarticulation in typically developing
5-year-olds and 13-year-olds**

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ABSTRACT

In this study, vowel-on-consonant lingual coarticulation at [t] closure offset was compared in 5-year-old children and 13-year-old adolescents. The study aimed to establish whether by the end of the closure children from the younger age group adjust the tongue shape to the following vowels to the same extent as adolescents. Ten 5-year-olds and ten 13-year-olds, all speakers of Scottish Standard English, produced [t]-vowel syllables with the vowels [i] and [a], in a carrier phrase. Measures of tongue shape based on midsagittal ultrasound imaging data were used to compare anticipatory coarticulation and within-speaker variability across groups. Both age groups changed the extent of tongue dorsum bunching in order to coarticulate the consonant with the following vowels. The 5-year-old children, unlike the adolescents, did not consistently modify the bunching location within the tongue curve to accommodate the tongue shape to that of the upcoming vowel. Token-to-token variability was significantly greater in the younger age group. The results suggest that vowel-on-[t] coarticulatory patterns produced by typically developing children are affected by the development of motor control, with articulatory constraints on the tongue limiting the extent of lingual coarticulation in 5-year-old children. The findings on typical coarticulation development are relevant for clinical practice, and they highlight the need for more detailed descriptions of how phonetic characteristics of speech sounds affect coarticulation throughout childhood.

Keywords: lingual articulation, coarticulation, child, adolescent, ultrasound

INTRODUCTION

The development of lingual coarticulation in alveolar stops produced by typically developing children has been addressed in a number of studies (e.g., Sussman et al., 1992; Goodell & Studdert-Kennedy, 1993; Sussman et al., 1999; Noiray et al., 2013; Rubertus et al., 2015; Zharkova et al., 2015b). Alveolar consonants in children's productions have generally been demonstrated to undergo smaller vowel-related coarticulatory effects than labial and velar consonants, thus yielding consonant-specific patterns similar to those observed in adults (cf. Sussman et al., 1991). However, despite the broadly adult-like relationship across consonant places of articulation in children, certain immaturities have been observed in children's productions. Sussman et al. (1999), in an acoustic study focussed on a typically developing child aged between two and three years old, described alveolar consonant coarticulation as presenting a special challenge for young children. The challenge, according to Sussman and his colleagues, is due to the nature of alveolar consonant production. During coarticulating an alveolar stop with the following vowels, the speakers need to find a balance between "articulatory effort" and "coarticulatory overlap" (p. 1094), i.e., between the requirement to produce a closure at the alveolar ridge and the demand on the tongue to adjust to the upcoming vowel target.

A number of previous studies of vowel-on-consonant coarticulation in children have used locus equations, which quantify coarticulation in consonant-vowel sequences by comparing F2 values at the vowel onset and at mid-vowel (for cross-linguistic findings from locus equations studies on adult speech, see Sussman et al., 1991; 1993). Originally designed for acoustic data, locus equations were adapted by Iskarous et al. (2010) for use with articulatory data on tongue movements. Sussman et al. (1992), in an acoustic locus equation study of coarticulation in typically developing American English children aged between three and five years old, found an adult-like relationship between voiced alveolar and non-alveolar

consonant coarticulation, with the alveolar stop coarticulated less than labial and velar stops. Similar findings for voiceless stops were reported in a study of 4-to-5-year-old Canadian French speaking children by Noiray et al. (2013), who, in addition to acoustic locus equations, used articulatory locus equations, based on horizontal changes of the highest point of the tongue. Smaller coarticulation for the alveolar stop than for non-alveolar stops has also been found in German speaking 5-year-old children, in an ultrasound study by Rubertus et al. (2015). Noiray et al. (2013) interpreted their results by referring to Iskarous et al. (2010), who showed that locus equations are directly related to an articulator synergy between the tongue body and the tongue tip. In a study of adult productions, using locus equations derived from acoustic, electromagnetic articulography and X-ray microbeam data, Iskarous et al. (2010) concluded that locus equations capture “the advancement of the tongue back to help the tongue tip” (p. 2029) during alveolar consonant production. Thus, alveolar consonants have a reduced potential for vowel-related coarticulation, compared with labials, which in many languages have no specific constraint on the tongue (e.g., Sussman et al., 1993; Recasens et al., 1997), and with velars, which can have substantial adjustment of the tongue in the horizontal plane, to accommodate to the vowel influence (e.g., Fowler & Brancazio, 2000; Recasens & Espinosa, 2009; Frisch & Wodzinski, 2016). Noiray et al. (2013) concluded that children by 4-5-years old have learned the articulator synergy between the tip and back of the tongue.

Tongue body advancement for alveolar consonants, referred to by the articulator synergy described by Iskarous et al. (2010), in adult speech coexists with additional adjustments in the tongue root area, to accommodate the consonant tongue shape and position to the following vowel (see Recasens & Rodríguez, 2016). For example, in adult speech, coarticulation of [t] with the contrasting vowels [i] versus [a] largely manifests itself through a difference in the tongue root and dorsum position at the middle of the consonant closure,

with a noticeably advanced root and raised dorsum in the context of [i], compared with the context of [a] (e.g., Zharkova & Hewlett, 2009), affecting the overall tongue shape (see also Zharkova, 2016). The differences in the alveolar consonant tongue shape conditioned by the adjacent vowel target reflect the “coarticulatory overlap” part of the challenge described by Sussman et al. (1999). Therefore in order to accurately describe the development of coarticulation in alveolar consonants, measurements of coarticulation need to be able to quantify these vowel-dependent differences. The relevant tongue shape changes due to the tongue root and dorsum displacement cannot be directly captured by a measure used for quantifying articulatory locus equations, as it is based on the position of one point on the tongue, rather than the shape of the tongue. Using measures of tongue shape that quantify the extent of tongue bunching and the relative location of the bunching within the tongue curve, noticeable differences for [t] across [a] versus [i] vowel contexts have been reported for adults and adolescents with typical speech (e.g., Zharkova, 2013b; Zharkova et al., 2015a). If children had adult-like coarticulation, we would expect to observe similar-to-adult patterns of tongue shape across vowel contexts. In reality, though, certain age-related differences have been found. In a recent ultrasound study using tongue shape measures, a similar extent of coarticulation at [t] mid-closure through raising the tongue dorsum was reported in ten 5-year-old children and ten 13-year-old adolescents (Zharkova et al., 2015b). However, the adolescents also had tongue shape changes reflecting progressive advancement versus retraction of the tongue towards the vowel, while 5-year-olds did not demonstrate this pattern. This age-related difference was ascribed to developmental immaturities of lingual motor control in the 5-year-olds.

In the present study, vowel-on-[t] coarticulation in 5-year-old typically developing children was further analysed using ultrasound imaging data on tongue shape. The same dataset was used as that analysed in Zharkova et al. (2015b), consisting of productions by 5-

year-old children and 13-year-old adolescents. The study aimed to establish whether vowel-related differences similar to those in adolescents appear in 5-year-olds later into the alveolar stop, namely by the end of the consonant closure. Closure offset was chosen because after this time point there is no contact of the active articulator, i.e., the tongue tip/blade, with the alveolar ridge. After the closure release, without the need for the active articulator to contact the hard palate, there are no competing demands of “articulatory effort” and “coarticulatory overlap” (Sussman et al., 1999) on the tongue any more, with the sole task now consisting in reaching the vowel target. Therefore accommodating the consonant tongue shape to the vowel before the release of the closure is conceivably a more demanding task than after the release, due to those competing demands of consonant accuracy versus coarticulatory accommodation. Finding developmental immaturities at the end of the [t] closure, similar to those reported by Zharkova et al. (2015b) at mid-closure, would suggest that children may be constrained by the competing demands, focussing on the consonant production at the cost of coarticulating the consonant with the following vowels. On the opposite, if by [t] release children behaved in a similar way to adolescents, it could be interpreted to mean that 5-year-old children can achieve the balance in these competing demands by the end of the alveolar closure.

The study also addressed the question of within-speaker variability, focussing on token-to-token differences in the tongue shape of the alveolar stop. Previous studies of lingual articulation in children have reported increased token-to-token variability in absolute tongue position in children than in adults (e.g., Zharkova et al., 2011; 2012). Differences in variability between child and adolescent speakers have previously been reported in studies of lip and jaw movements (Smith & Zelaznik, 2004; Sadagopan & Smith, 2008), and regarded as evidence that younger children have less developed articulatory control. In this study,

more token-to-token variability in tongue shape was expected in the younger age group than in the adolescent group.

METHOD

Participants, stimuli and data collection

Two age groups took part in the study, with ten children speaking Scottish Standard English in each age group. The participants in the younger group were aged between 5;5 [years;months] and 5;11, with the mean age of 5;8. The adolescent participants were aged between 13;0 and 13;11, with the mean age of 13;5. There were five and six girls in the younger and older age group, respectively. The target consonant was presented in consonant-vowel syllables with the contrasting vowels [a] and [i], embedded in the carrier phrase “It’s a ..., Pam”. The stimuli in orthographic form were presented to the participants on the computer screen, accompanied by pictures (the syllable [ta] was presented as the name of an imaginary creature). The 13-year-old participants read the sentences, and most of the 5-year-olds repeated the sentences after their parents or carers.

Ultrasound tongue movement data, synchronised with acoustic data, were collected using Articulate Assistant Advanced software (Articulate Instruments, 2012). The frame rate for the ultrasound data was 100 Hz, and the acoustic signal was recorded at 22050 Hz. The participants were seated together with the experimenter in the sound-treated studio, while the ultrasound scanner and the associated computer were located in an adjacent room. In all recordings, the ultrasound transducer was hand-held by the experimenter. Each participant was video recorded *en face* and in profile during the data collection session. The video data were used to help with selecting the tokens for inclusion in quantitative analyses.

Data analysis

In order to select consonant tokens for the analyses of tongue shape, the same process was followed as that used in Zharkova et al. (2015a). Video recordings of the participants were qualitatively examined, to ensure that the transducer was relatively stable during the target syllable, and that the midsagittal tongue image was flanked by the shadow of the hyoid bone on the left and the shadow of the chin on the right. Five repetitions of each target consonant-vowel syllable were included for each participant. The end of [t] closure was annotated for every token, identified in the acoustic signal as the onset of the stop burst. At this time point, tongue curves were automatically traced for every token in Articulate Assistant Advanced software, with manual correction. Then *xy* coordinates of each tongue curve were exported from the software as plain text files, and these files were used in subsequent analyses for calculating tongue shape indices.

The quantitative indices used in the study have previously been shown to produce reliable results for ultrasound data recorded without head stabilisation (Zharkova et al., 2015a). Dorsum Excursion Index (DEI; Zharkova, 2013a) quantified the extent of tongue bunching in a given curve, while LOC_{a-i} index (Zharkova et al., 2015a) quantified the location of bunching along the tongue curve. Both indices have higher values for [t] in the context of [i] than in the context of [a] in typical adults and adolescents (Zharkova, 2013b; Zharkova et al., 2015a). These two indices were used in Zharkova et al. (2015b) for analysing coarticulation at [t] mid-closure for the same dataset. Choosing DEI and LOC_{a-i} for the present study, over other measures of tongue shape suitable for quantifying coarticulation (e.g., Bressmann et al., 2005; Aubin & Ménard, 2006), ensured comparability of the results with the previous findings on 13- and 5-year-olds published by Zharkova et al. (2015b).

The indices of tongue shape were calculated for each token in R (R Development Core Team, 2013), using the scripts written by the author. Figure 1 illustrates the calculations of

the indices, using example [t] tongue curves from an adolescent participant. Both indices are ratios of straight lines, therefore no additional normalisation across participants or age groups is required for within-group or across-group comparisons. A straight line plotted between the ends of the tongue curve (line n in Figure 1) is involved in computing both indices. For DEI, line n constitutes the denominator in the formula, while the numerator is line d , which is a straight line plotted from mid- n to the tongue curve. For LOC_{a-i} , line n is involved in the calculations indirectly, as the index is a ratio of the straight line f (a perpendicular from one third of line n to the tongue curve) to line b (a perpendicular from two thirds of n to the tongue curve).

Insert figure 1 about here

Comparing tongue shape index values in the context of the vowel [a] to those in the context of the vowel [i], separately for each index, was used to determine if there was a significant coarticulatory effect. Linear mixed models (LMMs) were used for these comparisons. LMMs were carried out in R (R Development Core Team, 2013), with speaker as a random effect. A significant difference between index values across the two vowel contexts was taken as evidence of a significant coarticulatory effect. Following Zharkova (2016), the value of F in the analysis of variance table had to be greater than 7.20 in order for the result to be deemed significant at the 0.05 level, and greater than 8.49 for the result to be significant at the 0.01 level. In the event that a significant effect was observed in both age groups, an LMM was run including both vowel and age group as factors, with a significant interaction between the two factors indicating a difference in the magnitude of the coarticulatory effect across age groups. Token-to-token variability in tongue shape was measured by calculating Coefficient of Variation values (i.e., the standard deviation divided

by the mean) on the two indices of tongue shape, separately for each speaker and vowel context. Coefficient of Variation values were compared across age groups.

RESULTS

Figure 2 shows tongue curves for five repetitions of the consonant at the closure offset, produced by a speaker from each age group. In the panel illustrating adolescent productions, there is a noticeable difference in tongue shape between [t] in the two vowel contexts. Specifically, the tongue curves in the context of [i] are more bunched than in the context of [a], and the bunching in the front vowel context is clearly towards the front of the tongue, due to the predorsum advancement in anticipation of [i]. The tongue contours for the 5-year-old appear more scattered, within vowel context, than for the adolescent. Absolute positions of individual tongue curves, however, cannot be used to draw inferences regarding vowel effects on [t] production, since the recordings were carried out without head-to-transducer stabilisation. Instead, when focussing on the *shape* of individual tongue curves, without reference to absolute coordinates, it appears that there is a vowel-related difference for the 5-year-old. Specifically, the extent of tongue bunching is larger in the context of [i] than in the context of [a], similarly to the pattern observed for the 13-year-old. The relative location of bunching within the tongue curve does not seem to differ across the two vowel contexts for the 5-year-old child.

Insert figure 2 about here

Values of DEI and LOC_{a-i} in the two age groups are presented in Figure 3. In the figure, DEI appears to have a noticeable difference across vowel contexts for both age groups, probably reflecting the earlier visual observation about a difference in the extent of tongue

bunching. LOC_{a-i} , however, does not show a noticeable difference across vowel contexts for the younger age group, while for the adolescents the two vowel contexts seem to be differentiated on this measure as well as on DEI.

Insert figure 3 about here

Table 1 presents group mean and standard deviation values of the tongue shape indices. The results of the LMMs on DEI and LOC_{a-i} are reported in Table 2, and they confirm visual observations from Figure 3. While for DEI, there was a significant vowel effect on the consonant for both age groups, the effect for LOC_{a-i} was only observed for the adolescents. A separate LMM model on DEI, including both vowel and age group as factors, was carried out to establish whether there was a significant difference across age groups in the magnitude of the observed coarticulatory effect. The results of this model are also presented in the table. These results do not show a significant interaction of the two factors, therefore we can conclude that there was no age-related difference in the magnitude of effect on DEI.

Insert table 1 about here

Insert table 2 about here

Mean Coefficient of Variation values on DEI were 0.08 for the adolescents, and 0.15 for the 5-year-olds. On LOC_{a-i} , mean Coefficient of Variation values were 0.09 and 0.14 for the 13-year-old and 5-year-old group, respectively. The results of LMMs on within-speaker variability, presented in Table 2, show that on both indices, the 5-year-old group was more variable than the adolescent group. There were no differences in variability across vowels,

and no significant interaction of vowel and age group, suggesting that similar patterns in both age groups were observed across the two vowel contexts.

DISCUSSION

In this study, measures of tongue shape were applied to compare vowel-on-consonant coarticulation at [t] closure offset in Scottish English speaking 5-year-old children and 13-year-old adolescents. The study aimed to establish whether by the end of the alveolar consonant closure 5-year-olds are able to adjust the tongue shape to the following vowels to the same extent as adolescents. The results showed that both age groups changed the extent of tongue dorsum bunching in order to coarticulate the alveolar stop with the following vowels. However, unlike the adolescents, the 5-year-old children did not consistently modify the bunching location within the tongue curve to accommodate the tongue shape to that of the upcoming vowel. The study extended the findings on mid-[t] from Zharkova et al. (2015b), showing that developmental immaturities in 5-year-olds' productions of [t] affect the consonant until the release of the stop closure.

These results suggest that coarticulating alveolar consonants with adjacent vowels presents a challenge for children until at least the age of five years old. It appears that the balance that children need to achieve in coarticulating alveolar stops (Sussman et al., 1999) is still not fully reached by this age, and that the 5-year-olds from this study focussed on “articulatory effort” to achieve perceptual accuracy of [t], at the expense of coarticulating the consonant with the following vowels. This was demonstrated through the lack of coarticulation by the younger children on LOC_{a-i} , a measure that captures vowel-conditioned difference in the relative location of the most excursed part of the tongue. For [t] in the context of [i] versus in the context of [a], a difference in LOC_{a-i} reflects a contrast between the advanced versus retracted tongue position in anticipation of the following vowel,

respectively. The lack of this difference in the 5-year-olds suggests that for these children the goal of producing [t] target overrode the goal of adjusting [t] to following vowel, limiting the extent of vowel-on-[t] lingual coarticulation. Because the measurement was taken at the consonant closure offset, we can conclude that our 5-year-old children, even by the end of the tongue tip-to-palate contact for [t], did not have the vowel-related modifications of tongue shape that LOC_{a-i} registered for the adolescents.

The study provided additional information to that reported in locus equation studies of coarticulation in children (e.g., Sussman et al., 1992; Sussman et al., 1999; Noiray et al., 2013; Rubertus et al., 2015). Specifically, ultrasound tongue shape data were used, including information on the root of the tongue. This information has not been reported in locus equation studies, because for electromagnetic articulography data, the point of measurement is located as far back as the speaker can tolerate, so typically further forward than the tongue root; and for ultrasound data, the measurement point is located on the highest point of the tongue, also missing the tongue root. While, as described in previous works, by the age of five years old children may have learned the synergy that consists in advancing the tongue body in order to assist the tongue tip in making [t] closure (Noiray et al., 2013), the present study has demonstrated vowel-related changes in [t] tongue shape in 5-year-olds.

Furthermore, certain subtle adjustments in tongue shape in anticipation of the following vowels, found in adolescents, were not present in the 5-year-olds. There is a possibility that the age-dependent difference found in the present study could be related to the ongoing development of the coordinated control of the tongue and the jaw. Tongue movement patterns in alveolar stop production have been previously shown to be non-adult-like even in 7-year-old children (Nittrouer, 1993), unlike jaw movement patterns, which, in the same study, were inferred from the acoustic data to be similar to those in adults by the age of seven years old. Protracted development of the coordination between the tongue and the jaw was also

mentioned by Reidy (2015) as a possible reason for reported immaturities in alveolar fricative coarticulation in children aged between two and five years old.

The findings from this study indicate that tongue movements for the alveolar stop production were less consistent in the 5-year-old children than in the 13-year-old adolescents, resulting in more token-to-token variability in tongue shape. These results on the reduction in variability with increasing age agree with previous findings on speech variability in children (e.g., Sharkey & Folkins, 1985; Nitttrouer, 1993; Smith & Goffman, 1998; Lee et al., 1999; Green et al., 2000; Munson, 2004; Nijland et al., 2002; Smith & Zelaznik, 2004; Sadagopan & Smith, 2008; Terband et al., 2009). In future work, it would be useful to include children who are older than five years old, in order to establish the time course of the reduction in tongue shape variability with increasing age.

The finding of age-related differences in coarticulation adds to existing information from a growing number of studies showing that the development of coarticulation patterns in children may depend on the speech segment (Katz & Bharadwaj, 2001; Zharkova et al., 2011, 2012; Reidy, 2015). For example, the alveolar fricative [s] has been shown to exhibit non-adult-like coarticulatory patterns in children until nine years old (Zharkova et al., 2012; Reidy, 2015). For adult speech, a substantial number of studies have shown that articulatory requirements for the consonant affect the extent of coarticulation that neighbouring segments exert on the consonant (e.g., Recasens et al., 1997; Recasens & Espinosa, 2009; Recasens & Rodríguez, 2016). Specifically, constraints on the tongue involved in producing alveolar consonants render them more resistant to coarticulatory effects from neighbouring vowels than labial consonants in adult productions (e.g., Recasens et al., 1997). Similar cross-consonant patterns have been observed in typically developing 13-year-old adolescents (Zharkova et al., 2015a). Very little is known on how phonetic characteristics of speech sounds affect coarticulation throughout childhood. Such information has important

implications for clinical practice, particularly regarding the question of how protracted the development of coarticulation is in typical child speech. As shown by the results from the present study, articulatory constraints on the tongue limit the extent of lingual coarticulation in typically developing 5-year-old children, compared with adolescents. Ongoing work is focussed on establishing the precise course of acquisition of segment-specific coarticulation patterns during childhood, and the reasons for any age-related differences.

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DECLARATION OF INTEREST

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FIGURE CAPTIONS

Figure 1. Tongue contours at [t] closure offset in the two vowel contexts, from the productions by a 13-year-old participant (the context of [a] is in the left panel, and the context of [i] in the right panel). The values of the two tongue shape indices are printed in each panel.

Figure 2. Tongue curves at [t] closure offset for a representative speaker from each age group: solid lines for the context of [a]; dotted lines for the context of [i].

Figure 3. Tongue shape index values in the two age groups; DEI in the left panel, LOC_{a-i} in the right panel. White bars represent the context of [a], and shaded bars represent the context of [i].

Figure 1

Figure 2

Figure 3