The development of motor synergies in children: Ultrasound and acoustic measurements

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The present study focuses on differences in lingual coarticulation between French children and adults. The specific question pursued is whether 4–5 year old children have already acquired a synergy observed in adults in which the tongue back helps the tip in the formation of alveolar consonants. Locus equations, estimated from acoustic and ultrasound imaging data were used to compare coarticulation degree between adults and children and further investigate differences in motor synergy between the front and back parts of the tongue. Results show similar slope and intercept patterns for adults and children in both the acoustic and articulatory domains, with an effect of place of articulation in both groups between alveolar and non-alveolar consonants. These results suggest that 4–5 year old children (1) have learned the motor synergy investigated and (2) have developed a pattern of coarticulatory resistance depending on a consonant place of articulation. Also, results show that acoustic locus equations can be used to gauge the presence of motor synergies in children.
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I. INTRODUCTION

Coarticulation is generally defined as the articulatory overlapping of a sound on another one. Beyond this basic definition, describing the nature of this process; i.e., whether it is a crucial *motor control* for speaking a language or the *"on-line" consequence* of the interactions among articulators, has remained an object of longstanding controversy (see Hardcastle and Hewlett, 1999).

In this study, we consider coarticulation to be a complex mechanism, involving multiple articulators (e.g., the tongue, the lips) whose actions are finely coordinated in the space of the vocal tract, as well as over time to produce intelligible and fluent speech. It involves functional articulatory synergies whose crucial function is to permit efficient and stable language-specific coordination among muscles and articulators to achieve speech tasks. From a developmental point of view, a main goal for the child is therefore to develop these functional synergies and reduce the number of possible articulatory coordinations to the ones that are the most consistently produced by adults in a given language (Smith and Zelaznik, 2004). Indeed, although children's articulations of phonemes may be perceptually intelligible very early in age, their articulatory strategies differ from adults' because of immature speech motor control. In addition, differences in the anatomy of their vocal tract between children and adults, children may require to adapt their articulations in order to achieve an acoustic target that is comparable to adults and intelligible to others.

A main question in this study regarded, therefore, whether 4–5 year old children have acquired one particular synergy: The use of the back of the tongue to assist the tip in the formation of alveolar closures in CV (consonant-vowel) syllables. Both the jaw and the tongue back might assist the tongue tip to make contact with the palate. Adults consistently use the tongue back to push the tip forward (e.g., Iskarous *et al.*, 2010; Sussman *et al.*, 1999), whether or not they also use the jaw, but it is unknown whether young children do the same, as at 4–5 years of age, they may lack fine control over the functional subparts of the tongue.

To achieve our goal, we transposed measures of Locus equation (LE), commonly employed in acoustics to the articulatory domain. LE was used as a metric to investigate whether 4–5 year old children differentiate the tongue tip and tongue body to achieve adult-like patterns of CV coarticulation according to consonantal contexts, i.e., large coproduction between the vowel and labial or velar consonants, but lesser coarticulation in the alveolar context (Sussman *et al.*, 1999) as a result of a motor synergy between the tongue back and the tongue tip for achieving the main constriction at the alveolar ridge.

To our knowledge, no study investigating coarticulatory patterning in preschoolers has ever provided any direct account from the tongue [(Zharkova *et al.*, 2012, 2008) but in school-aged children from 6 to 9 years of age]. Unlike other muscle systems in the human body, the tongue is a muscular hydrostat—like octopus tentacles or

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elephant trunks—that does not rely on a distinct skeletal system (Kier and Smith, 1985; Stone *et al.*, 1992) but can produce a large variety of movements and complex shapes. In a developmental (and clinical) perspective, it is important to study the maturation trajectory of the tongue as it is central to the production of all vowels and most consonants, and therefore it is a crucial articulator to be controlled for coarticulation.

A. Development of coarticulation in CV syllables

In children, the development of spatial and temporal organization of speech actions, that is, of articulatory gestures, is poorly understood because its investigation has mostly been limited to measures of the acoustic output or phonetic transcriptions (e.g., Goodell and Studdert-Kennedy, 1993; Lee *et al.*, 1999; Munson, 2004; Nittrouer *et al.*, 1996; Sussman *et al.*, 1999) that give only incomplete evidence of the underlying articulations. Although acoustic measurements of the speech signal provide important insight into the ontogeny of coarticulation, the lack of corresponding information from articulation itself limits theoretical conclusions about (1) the maturation of the speech motor system (Zharkova *et al.*, 2011) and (2) the convergence of coarticulatory strategies on adults' patterns (Noiray *et al.*, 2009; Noiray *et al.*, 2011).

There is general agreement that in the first years of life, children's vowel productions exhibit high variability in acoustics, which suggests that they also vary in their articulatory strategies to match the perceived targets of adults (Lee *et al.*, 1999; Ménard *et al.*, 2007; Macleod *et al.*, 2011). The development of articulatory skills required for fluency varies a lot both across children and within a child, with spurts and plateaus, (cf. Kent, 2004). Regarding consonants, children's production accuracy differs depending on whether they are produced in isolated forms or within words (with differences in accuracy depending on word position; Canadian French: Macleod *et al.*, 2011; English: Macleod *et al.*, 2001; Stemberger and Bernhardt, 2002). Results from previous studies (de Boer 2000; Goldstein and Fowler, 2003; Goldstein, 2003; for consonant clusters) suggest coarticulation of phonemes distinguished by motion from two distinct articulators (e.g., lip motion for /b/ and tongue motion for /i/ in "beep") would be mastered earlier in typically developing children than those requiring contrastive actions from a single articulator (e.g., successive tongue motions for /t/ and /æ/ in "tack"). In the latter case, young children may be expected to show more spatiotemporal overlap between C's and V's than adults because of an immature control over the functional subparts of their tongue. However, such a hypothesis has not yet been empirically demonstrated in young children with articulatory data partly because of methodological constraints associated with child studies.

B. LE as a measure of lingual synergy

1. LE measures in adults

LE have been identified as relational invariants for consonants (Sussman *et al.*, 1991), as a measure of the degree of coarticulation between consonants and vowels (Krull, 1987), and as a measure of the coarticulation resistance of consonants (Fowler, 1994). LE are linear regressions calculated between F2 at the beginning of a CV transition and F2 at the acoustic midpoint of the vowel for a given consonant produced in the context of a variety of vowels (Lindblom, 1963; Nearey and Shammass, 1987). The regression equation parameters (slope, intercept) provide insight into the magnitude of coarticulation depending on the consonant's place of articulation. A steep slope of 1.0 is evidence for a high degree of coarticulation between C and V, because it means that for every 1 Hz change in the vowel midpoint, there is a corresponding 1 Hz change in the CV transition onset. On the other hand, a low slope indicates that the consonant's F2 shows a smaller change for each 1 Hz change in the vowel, an indicator of a smaller degree of coarticulation. The intercept value indicates the value for F2 at the consonant release for a zero F2 value at the midpoint of the subsequent vowel. Empirical work has shown that the magnitude of the slope characterizing CV coarticulation differs according to consonant place of articulation (e.g., Krull, 1987; Nearey and Shammass, 1987; Sussman *et al.*, 1998); it is larger in labial context than in the velar and especially the alveolar contexts. The difference between alveolars (e.g., /t, d/) and non-alveolars (e.g., /k, p/) is consistent across all studies, whereas labials and velars often have similar slopes. Intercept magnitudes are negatively related to slopes, with labial intercepts smallest and alveolars largest. Using articulatory and acoustic data, Iskarous *et al.* (2010) showed that the reason that alveolars have a lower slope and higher intercept than non-alveolars is the particular way in which the tongue back interacts with the main constrictor for the consonant. Specifically, alveolars have a low slope, because the tongue back is pushed forward to assist the tip and that prevents it from assisting in the constriction for the following vowel (Manuel and Stevens, 1995). This means that coarticulatory overlap is limited, and, correspondingly, coarticulation resistance is high. The high intercept is a direct indication that the tongue back is more advanced in the vocal tract for the alveolars than for other consonants. Iskarous *et al.* argued that the synergy involving the tongue back for the achievement of alveolars is the basis for the difference in slopes, and is the basic reason why alveolars have a lower degree of coarticulation and a higher coarticulation resistance. Note, depending on the nature of the vowel, the synergy between the tongue body and tongue tip may be facilitated. For instance, in /ti/, the front position of tongue body is required both for the alveolar and the high front vowel. However, as regression slopes are computed across a range of vowels, they reflect general patterns of coarticulation for places of articulation.

Contrary to adults, children may first mainly use the jaw synergy to assist the tongue tip in making constrictions before starting to use the tongue back to move the tip as the jaw requires fewer muscles for its motion and may therefore be easier to control. This would be measureable using LE, because, if the tongue back is not occupied by helping the tip for the alveolar constriction, it could start to coarticulate earlier with a following vowel, raising the slope for the alveolar to the level where there may not be a difference between alveolars and non-alveolars (e.g., bilabials and velars) in coarticulation degree (or in locus equation slope). The children we examine are 4–5 year olds. This age group does still show many differences with adults in measures of their speech (Macleod *et al.*, 2001; Sadagopan and Smith, 2008), and our interest is in establishing whether these differences extend to this motor synergy.

2. LE measures in infants and children

So far, several studies have reported LE measures of infants/children's speech productions (Gibson and Ohde, 2007 and from 17 to 22 months; Goodell and Studdert-Kennedy, 1993 at 22 to 32 months; Sussman *et al.*, 1996 at 12 and 21 months, Sussman *et al.*, 1999 from 7 to 40 months; Sussman *et al.*, 1992 at 3–5 year olds) to characterize children's modifications of articulatory controls with age. The main results of these studies are: (1) High variability in infants' coarticulatory patterns, (2) gradual distinctions in stop place of articulation with lexical development, and (3) a general trend toward greatest coarticulation magnitude in the labial context (illustrated by having the steepest slopes), intermediate in the velar contexts, and lowest in the alveolar context.

However, results are contradictory across studies, showing either more coarticulation in children than adults (Nittrouer and Whalen, 1989; Nittrouer *et al.*, 1996; Studdert-Kennedy, 1987) or less (Green *et al.*, 2002; Kent, 1983) or finally no substantial difference (Sereno *et al.*, 1987; Katz *et al.*, 1991) between the groups. These differences are compounded by the fact that it is difficult to measure formants from children's speech due to their high F0 and consequent wide separation between harmonics. Developmental studies using standard LE measures provide only a partial explanation for the maturation of articulatory coordination, because analyses are conducted on the acoustic outputs of the articulatory mechanisms responsible for coarticulation rather than on the articulatory actions themselves. In one of the most important studies, Sussman *et al.* (1999) observes a decrease in the slope for alveolar consonants, as children develop, and attributes that decrease in slope to the development of separate control for the tip and dorsum. We believe that this would be quite an important result if confirmed by articulatory measures and it is one of the motivations of our ultrasound data analysis. This type of articulatory examination has been lacking in typically developing children. Moreover, normative data would be valuable for diagnosis and development of treatment strategies of speech and/or language disorders [e.g., detection and treatment of early stuttering disorders that manifest as differences in formant transitions in CV syllables (e.g., Cheng *et al.*, 2007; Subramanian *et al.*, 2003)].

In this work we use non-invasive ultrasound imaging, together with acoustic measures, to establish whether the coarticulatory difference involving alveolar /t/ and non-alveolars /p, k/ is present in 4–5 year old children. Although this relation has been demonstrated recently in adults (Iskarous *et al.*, 2010), it has not yet been evidenced in preschool children with direct measures of tongue motion. This work, therefore, aims at providing new insight on the control of a crucial articulator for language acquisition.

Based on the literature, we predict children's coarticulatory patterns as young as 4 and 5 years old to differ from adults. Variability in both F2 and horizontal position of the tongue body between the consonant and the vowel (indicated by correlation coefficients) are expected to be higher in children than in adults. We expect the lowest correlation coefficients to be observed for both measures in alveolar context as a consequence of immature speech motor control (Noiray *et al.*, 2010; Terband *et al.*, 2009; Walsh *et al.*; 2006). Also, we expect children to exhibit higher slopes in alveolar context than adults, as they may not have mastered fine control over the lingual subparts to achieve articulatory synergies as in adults. If this prediction is verified, it will bring articulatory evidence that children display greater coarticulation degree than adults in alveolar context.

II. METHOD

A. Subjects and stimulus material

Six Canadian French children aged 4 and 5 years old were recruited in Montreal among monolingual French families. Their coarticulatory strategies were compared with those of five adults (mean age: 25) who have achieved a mature speech motor system and full knowledge of the phonological system of their language. Prior to the recording, a hearing screening, as well as a phonological assessment (Chevrie-Muller and Plaza, 2001), was administered for each participant. The study was approved by an IRB (Institutional Review Board), and consent was obtained from the parents of the children, and the non-invasive methods used were explained to the children before the experiment.

The task consisted in the production of /V_1CV_2/ sequences with the consonant C corresponding to the bilabial stop /p/, alveolar /t/ and velar /k/ and vowel V to the high front /i/, low /a/ and high back /u/. The three cardinal vowels allowed for testing diverging tongue positions. In addition to the alveolar stop /t/ that is the target consonant under investigation in this study, the bilabial and velar provided examples of stops that either do not require any active motion from the tongue (e.g., bilabial stops) or in the case of /k/, implies motion from the tongue but with contextual adaptability in the tongue positioning as observed in adults [i.e., the amount of movement from the tongue body varies with the surrounding vowel (e.g., Lofqvist, 1999; Mooshammer *et al.*, 1995)]. Sequences were embedded in short carrier sentences: "c'est VCV ça." Ten to twelve repetitions of each VCV sequence were collected in random order for each participant, young children included (with an average of 30–36 sequences for each consonant type: Labial, alveolar, velar). A total of 90–108 utterances recorded per participant.

B. Experimental procedure

Because of the young population targeted in this study, children's recordings were conducted at school, whereas adults were recorded in a sound booth (at the *Laboratoire de Phonétique*, UQAM). Individual recordings consisted in a single 20 min session during which preliminary screenings and data were collected. Recordings were preceded by a familiarization period with the experimenter, the task, target sequences, and ultrasound setup. Note that the duration of familiarization phase was longer for children to stimulate interest in performing the task and to ensure comfort with the experimenter and setup.

During the recording, tongue data were collected via ultrasound imaging. This technique has become an appealing tool to be used in the developmental field, because it is a non-invasive and uncomplicated method for collecting lingual data of high quality with very young children. Ultrasound imaging has been used in clinical studies with school-aged children as a tool for speech therapy and on-line feedback (e.g., Adler-Bock *et al.*, 2007) and recently for tracking the development of vowel control in children (Ménard and Noiray, 2011).

Also, ultrasound imaging provides a continuous view of the tongue surface, which is more convenient to measure the position of the highest point on the tongue during vowels and consonants production than points tracking [e.g., with electromagnetic mid-sagittal articulography (Perkell *et al.*, 1992) or x-ray microbeam (Westbury, 1994)].

Subjects were recorded with an ultrasound system (Sonosite 180 Plus, sr: 30 Hz) with an 84° probe and audio system (unidirectional microphone Sure). Participants were seated comfortably in a chair and the ultrasound probe was held under the chin with a stand similar to microphone stands. Although head stabilizing devices are usually used to hold the head stable during the experiment (e.g., Zharkova *et al.*, 2011), it is not possible to use them with very young subjects. Even so, for the children, as for adults, the ultrasound probe was held below the chin via a stand to prevent horizontal and lateral motion from the probe. As a consequence, the probe follows jaw movement and the resulting ultrasound images are in jaw-based coordinates. However, it is important to mention that this method also presents some constraints [i.e., the probe provides an indirect estimate of the vertical jaw motion as the elasticity of the tongue's floor is likely to trigger variable distance between the probe and the jaw (Noiray *et al.*, 2008)].

In a recent study designed to test various articulatory parameters to characterize ultrasound data, Ménard *et al.* (2012) confirmed that in such a setup, the horizontal position of the highest point of the tongue is a reliable measurement point, which is robust independently of vertical probe movement. An experimenter monitored the experiment to insure participants would remain in the same position throughout the recording and would not remove their chin from the probe. In the present study, both ultrasound and speech sound signals were simultaneously recorded on a mini-DV Panasonic AG-DVC 30 camera, in NTSC format.

Two types of LE measures were taken: On the acoustic speech signal and on the lingual data. For each participant and target V_1CV_2 sequence, a phonetic transcription of the acoustic speech signal was conducted (via Boersma and Weenink, 1996). Acoustic measures of F2 were automatically extracted using Linear Predictive Coding formant estimation at the consonant–vowel transition [the first glottal pulse of the vowel onset (T1)] and 25 ms window centered at the midpoint of the

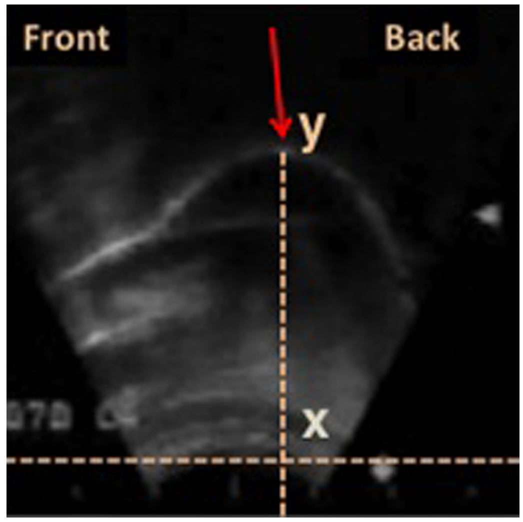

FIG. 1. (Color online) Midsagittal tongue contour collected via ultrasound imaging technique. The *y*-coordinate represents the highest point on the tongue surface and the *x*-coordinate shows its horizontal position. The front part of the oral cavity is on the left-hand side of the ultrasound image.

vowel (T2). The number of poles varied from 10 to 14, and a 14 ms Hamming window and pre-emphasis were applied before formant extraction. Because obtaining measurements of formants in child speech is more complex and can lead to more formant detection errors than in adult speech, the automatic formant extraction was compared for each vowel with spectral slices from a fast Fourier transform with a hamming window. Complete details on the method can be found in Ménard *et al.* (2008). For each participant, LE regression fits were generated between F2 calculated at two points in time, i.e., at T1 (C release) and at T2 (the acoustic midpoint of V_2).

The adaptation of LE to the articulatory domain was conducted on the lingual data simultaneously recorded with the acoustic speech signal via the video camera. Relevant tongue images were extracted from ultrasound movies with Adobe Premiere Pro. These corresponded to the consonant closure and T2 as identified in the acoustic analysis. Tongue surface contours were then extracted using a semi-automatic system (EdgeTrak; Li *et al.*, 2005) and sampled at 100 points. The horizontal x coordinate corresponding to the highest point y on the tongue body was used to determine the position of the constriction on the front/back dimension for both C and V (cf. Fig. 1). We refer to this point as TBx.

III. RESULTS

Locus equation analyses have been done in two ways (Sussman *et al.*, 1991). In the first method, all the data from a group of subjects for a given consonant are pooled and a regression line is estimated from the pooled data. In the second method, the regression line is estimated separately for each subject, and then regression coefficients and statistics are compared across subjects. The first method has the advantage of providing more reliable statistics than if a regression is estimated for each subject separately, because more data are available through the pooling. However it is possible that a regression across a group shows a relation between two variables that is not characteristic of individuals

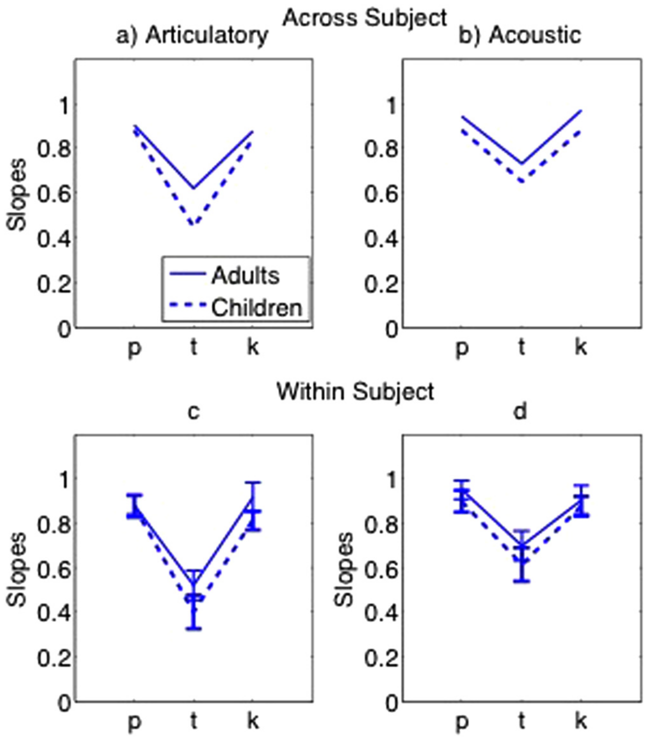

FIG. 2. (Color online) Slopes for LE measure performed in the articulatory domain [panels (a) and (c)] and acoustic domains [panels (b) and (d)] for the adults (solid lines) and children (dashed lines) in /p/, /t/, /k/ contexts. Panels (a) and (b) show the slopes lines estimated on the data pooled amongst adults (solid line) or children (dashed line). Panels (c) and (d) present the slopes derived from individual data as well as the SD values.

or subgroups (Raudenbush and Bryk, 2002). We performed both types of analyses in this work. After presenting the data from both methods, we present a statistical analysis of the difference between children's and adults' regressions using a mixed effects general linear model.

Figure 2 compares the slopes for the adults and children based on the articulatory and acoustic data. Figures 2(a) and 2(b) show the slopes of regression lines estimated using the first method, from data pooled amongst adults (solid line) or children (dashed line). The expected difference between alveolar and non-alveolar consonants can be seen in both the adults' and children's data: The slope for /t/ is lower than the slope for /p/ and /k/ for both groups. This is true of the slopes derived from the articulatory data in Fig. 2(a) and the slopes derived from the acoustic data in Fig. 2(b). The lower panels show the mean and standard errors of the slopes for adults and children, where the regressions were estimated for each subject separately and the mean and standard errors are calculated across the 5 adults and 6 children. The statistics for individual subjects are presented in Tables I and II. The patterns within individuals closely resemble those in the figures. Specifically, the low slope for alveolars is true for individuals, and not an artifact of data pooling. The difference between adults and children that can be seen by comparing the standard errors will be discussed later in this section, when the statistical analysis is presented.

Figure 3 presents the intercepts. The upper panels show the intercepts derived from pooled data, whereas the lower panels show the intercepts derived from individual data. Both analyses show that /t/ has a higher intercept than /p/ and /k/, in both the acoustic analyses (as in Gibson and Ohde, 2007) and the articulatory analyses, for both adults and children. The asymmetry between /p/ and /k/ is present in the acoustic analysis across subjects, and in those within subjects, but it is less obvious in the articulatory analysis across subjects. These differences, however, are smaller than the difference between the alveolar and non-alveolar places of articulation, which is the main focus of this research.

Figures 2 and 3 show that children at 4–5 years have basically the same patterns as the adults, but there are some small differences. The significance of the differences and the differences between groups in patterns of slopes and intercepts was examined by testing the hypothesis that there is no difference in patterns. Two mixed-effects general linear model tests were performed, one for the articulatory and the other for the acoustic data. A single value was entered for each subject and for each sequence produced. We used a conservative $p < 0.001$ level for significance. In the

TABLE I. Acoustic data.[a]

			/p/			/t/			/k/		
Group	Age	P	S	Int. (Hz)	R^2	S	Int. (Hz)	R^2	S	Int. (Hz)	R^2
Adults	25	1	0.85	230.77	0.98	0.74	590.25	0.8	0.98	231.86	0.86
		2	0.93	27.51	0.92	0.57	744.48	0.7	0.77	499.17	0.88
		3	0.95	42.35	0.99	0.84	265.5	0.98	1.00	22.75	0.98
		6	0.95	49.85	0.99	0.68	689.5	.96	0.91	217.2	0.93
		7	0.96	57.36	0.96	0.68	560.12	0.83	1.00	92.26	0.96
	Mean		0.93	81.56	0.97	0.7	569.97	0.85	0.93	212.65	0.94
Children	5	1	0.90	47.35	0.92	0.53	1279.5	0.87	.89	540.56	0.84
	4	2	0.90	225.57	0.96	0.64	987.88	0.86	0.88	540.6	0.84
	4	3	0.91	190.18	0.91	0.52	1070.4	0.88	0.85	560	0.91
	4	4	0.94	127.08	0.93	0.73	761.65	0.92	0.89	502.23	0.88
	5	5	0.94	218.59	0.94	0.76	766.16	0.94	0.87	426.6	0.94
	5	6	0.83	332.7	0.96	0.51	1344.9	0.77	0.94	291	0.96
	Mean		0.90	190.25	0.94	0.62	1035	0.87	0.89	476.83	0.90

[a]Locus data in the acoustic domain for both adults and children. Participant's age (Age), participant number (P), regression slopes (S), intercepts (Int.) in hertz, correlation coefficients (R^2) in labial /p/, alveolar /t/, and velar /k/ coarticulatory context. Correlation coefficients are significant at $p < 0.001$.

TABLE II. Articulatory data.[a]

Group	Age	P	/p/ S	/p/ Int. (mm)	/p/ R^2	/t/ S	/t/ Int. (mm)	/t/ R^2	/k/ S	/k/ Int. (mm)	/k/ R^2
Adults	25	1	0.72	2.52	0.88	0.38	5.8	ns.	0.7	2.84	0.63
		2	0.9	0.88	0.98	0.50	4.65	ns.	0.92	0.45	0.71
		3	0.9	0.94	0.94	0.70	2.7	0.78	1.00	−0.17	0.71
		6	0.98	0.19	0.97	0.53	4.38	.32	1.00	−0.74	0.83
		7	0.91	0.80	0.86	0.60	3.55	0.40	0.80	1.65	0.6
	Mean		0.88	1.07	0.93	0.54	4.25	0.5	.88	0.80	0.7
Children	5	1	0.9	0.86	0.81	0.45	5.62	0.42**	0.85	1.49	0.84
	4	2	0.98	0.16	0.82	0.32	6.85	ns	.95	0.61	0.84
	4	3	0.92	0.61	0.87	0.68	3.55	.45**	0.80	1.91	0.91
	4	4	0.96	0.61	0.91	0.42	6.23	ns	0.70	2.90	0.88
	5	5	0.84	1.45	0.80	0.11	8.75	ns	0.67	2.95	0.94
	5	6	0.78	2.11	0.60	0.40	6.45	0.3*	0.89	1.12	0.96
	Mean		0.9	0.97	0.80	0.40	6.24	0.39	.81	1.83	0.90

[a]Locus data in the articulatory domain for both adults and children. Participant's age (Age), participant number (*P*), regression slopes (*S*), intercepts (Int.) in millimeters, correlation coefficients (R^2) in labial /p/, alveolar /t/, and velar /k/ coarticulatory context. Correlation coefficients are significant at $p < 0.001$. ** indicates a value significant at $p < 0.05$; *indicates at $p < 0.2$. ns values that are not statistically significant.

articulatory model, the dependent variable was TBxC, i.e., TBx at the consonant closure. The independent variables were: (1) TBxV: TBx at the midpoint of the vowel (Continuous); (2) PofA: Place of Articulation (Levels: /p/, /t/, /k/); and (3) Generation (Levels: Adults and Children). Subject was the random effect. The main effect of PofA is the intercept of the LE regression line, as it indicates the value of TBxC when TBxV is controlled. The interaction effect between TBxV with Place of Articulation yields the slope of the regression lines, since it indicates how the effect of TBxV depends on PofA. The interactions between these two effects and Generation give the difference in patterns between the adults and children. The model tests for the acoustic slopes and intercepts had the same structure, except that the dependent variable was F2 at T1 (at C release) and the vowel measure was F2 at T2 (the acoustic midpoint of V_2). Significance was tested by using Monte Carlo Markov Chain simulations (Baayen, 2007; Quene and van den Bergh, 2008). The effects will be presented in terms of the magnitude of the effect, as contrasts between levels, and the confidence interval (CI) of the effect.

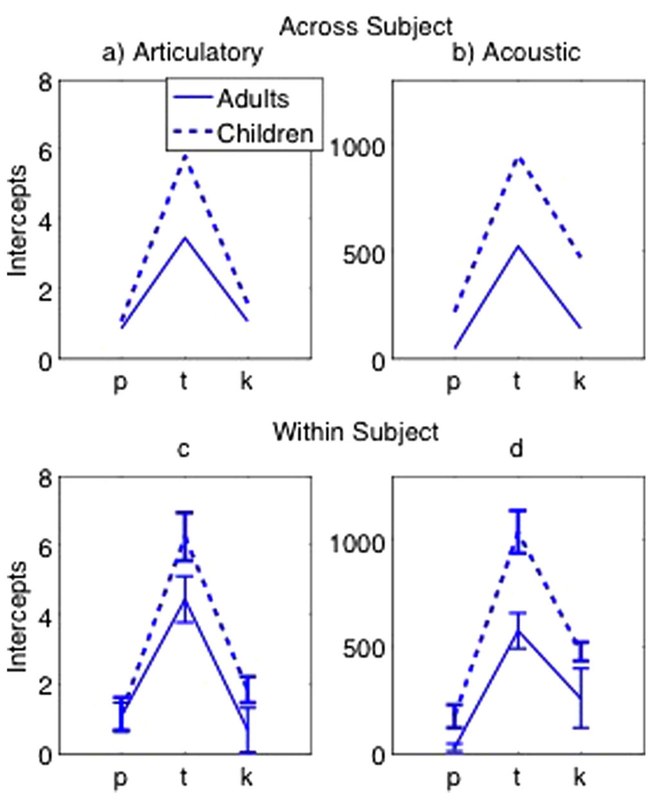

FIG. 3. (Color online) Intercepts for LE measure performed in the articulatory domain [panels (a) and (c)] and acoustic domains [panels (b) and (d)] for the adults (solid lines) and children (dashed lines) in /p/, /t/, /k/ contexts. Panels (a) and (b) show the slopes lines estimated on the data pooled amongst adults (solid line) or children (dashed line). Lower panels (c) and (d) present the intercepts derived from individual data.

Across adults and children, there was a significant effect of the interaction between PofA and TBxV, which expresses slope, as a difference in slope of 0.44 (CI [0.37, 0.54], $p < 0.001$) between /p/ and /t/, with /p/ having a higher slope. /k/ also showed significantly higher slope than /t/ by 0.39 (CI [0.29, 0.50], $p < 0.001$). But there was no significant difference between /p/ and /k/ in slope. There is also a non-significant tendency for the slope difference between /p/ and /t/ to be *larger* in children than in adults by 0.15 (CI [−0.007, 0.335]). The *p*-value for this non-significant effect is 0.07, a marginal effect. The effects for /p/ vs /k/ and /k/ vs /t/ showed no tendency to be different for adults vs children.

In the acoustic model, there was a significant difference in slope between /t/ and the other places, where the /t/ slope is lower than /p/ by 0.22 (CI [0.18, 0.28], $p < 0.001$), and lower than /k/ by 0.22 (CI [0.18, 0.27], $p < 0.001$). There was no tendency for these differences to depend on Generation.

To summarize, based on the statistical analysis, we conclude that the slope patterns are basically the same for adults and children, therefore the null hypothesis that the adults and children have the same slope pattern cannot be rejected.

For intercepts, across adults and children, /t/ showed a more advanced tongue than /p/ by 4.75 mm (CI [3.80, 5.69],

$p < 0.001$), and a more advanced tongue than /k/ by 4.23 mm (CI [3.25, 5.22], $p < 0.001$). But the intercept for /p/ and /k/ were not significantly different. There was a significant interaction between Generation and the intercept difference between /p/ and /t/, where the tongue back is more retracted for the /t/ in the adults than the children by 2.14 mm (CI [0.55, 3.71], $p < 0.01$). But we believe that this result is an artifact of a larger vocal tract for adults than for children. Such an artifact arises for the intercepts, but not for the slopes, because the slopes are in normalized units, whereas the intercepts are in millimeters. The acoustic study showed, across adults and children, that the intercept for /t/ was significantly higher than for /p/ by 733 Hz (CI [630, 834], $p < 0.001$) and for /k/ by 473 Hz (CI [364, 573], $p < 0.001$). The /k/ intercept is significantly higher than /p/ by 260 Hz (CI [149, 360], $p < 0.01$). There were also significant effects of Generation on intercepts derived from the acoustics. All of these effects show higher intercepts in the children than adults, in hertz, but all of them are likely to be artifacts due to the smaller vocal tract sizes for the children. To summarize, based on the statistical study, we conclude that the intercept patterns are basically the same for adults and children. Therefore, the null hypothesis that the adults and children have the same slope pattern cannot be rejected.

IV. DISCUSSION

This study aimed at investigating differences in coarticulation degree between 4 and 5 year old children and adults in CV syllables, employing ultrasound imaging of the tongue with acoustic measurements. To our knowledge, it is among the first studies providing a direct estimate of tongue motion in preschool children [cf. Zharkova *et al.* (2012, 2011, 2008) for children aged 6–9 years of age]. In light of the empirical work conducted over the past three decades, understanding the development of coarticulated speech from cross-study comparisons has indeed been quite challenging because of differences in stimuli material: For example, fricatives (Nittrouer and Whalen, 1989; Nittrouer, 1993, 1995; Munson, 2004), velar stops (Kent, 1983; Sereno *et al.*, 1987); the age span investigated (e.g., babbling period or first words, Sussman *et al.*, 1996; Sussman *et al.*, 1999; from 1 to 6 years of age with a gap between 2 and 6 years of age, Green *et al.*, 2002) or in method (acoustic measures: Goodell and Studdert-Kennedy, 1993; Katz *et al.*, 1991; Sereno *et al.*, 1987; or articulatory: Optotrak: Smith and Goffman, 1998; video: Green *et al.*, 2002; EMA: Cheng *et al.*, 2007; Katz and Bharadwaj, 2001; glossometry: Flege, 1983).

In this study, we transposed acoustic measures of LE to the articulatory domain to compare coarticulation degree. We further sought to examine whether at 4–5 years of age, children show articulatory synergy between the tongue tip and tongue body to achieve adult like patterns of coarticulation for /tV/ syllables with slopes in the descending order /p/ > /k/ > /t/. We predicted that children would exhibit (1) more variability in their coarticulation patterns across consonantal contexts than adults (lower R^2) and (2) greater coarticulation degree than adults in alveolar context (higher slopes) as a result of a global control of the tongue rather than a fine control over the functional subparts of the tongue to achieve adult like synergies.

Results show that (1) adults and children exhibited similar patterns of coarticulation magnitude according to stop place of articulation. This was demonstrated by the absence of significant differences in slopes and intercept patterns between the two groups, (2) within each Generation group, participants varied in the order of slope amplitude ($p \geq k > t$), which indicate that, contrary to a strictly fixed pattern of coarticulation amplitude in each age group, slight individual differences in slope order are possible within an age group (cf. Tables I and II).

This study aimed at providing a new type of data to foster understanding of how children develop articulatory coordination (or *synergy*) to achieve mature coarticulation patterns in their native language. Whether young children coarticulate more or less than their adult peers in the first years of their life has been a controversial subject. We believe the combination of LE measures on both the acoustic and articulatory productions of children provide elements allowing us to start addressing the debate. The main result of this study is indeed that the tongue back is used to advance the tongue tip in 4–5 year old children as in adults. This conclusion emerges from the results on slopes and intercepts of locus equations calculated in the articulatory and acoustic domains. Therefore by the age investigated, this synergy seems to have been learned.

This supports results from the acoustic LE literature, which have all converged toward a similar order of slopes [e.g., 0.62 for labial and 0.52 for alveolars in Gibson and Ohde (2007) vs 0.68 and 0.40, respectively (Sussman *et al.*, 1999) or ~0.80 and 0.40 in older children (Sussman *et al.*, 1992)]. Moreover this study has gone further in establishing the articulatory reason for the alveolar/non-alveolar asymmetry, linking the asymmetry to a synergy, in which the tongue back helps the tip for alveolars.

However, these data do *not* show that the velar is intermediate in slope between the labial and alveolar as found in some previous studies (Gibson and Ohde, 2007). However, note that this difference is not as frequently found as the asymmetry between alveolar and non-alveolar, and indeed several studies have reported data in which velars have the same slope value as labials (Lindblom, 1963; Sussman *et al.*, 1991; Sussman *et al.*, 1999).

Most studies using LE measures to assess coarticulation between C and V have exclusively relied on acoustic measures on infants or toddler's CV productions. However, Sussman *et al.* (1999) provides interesting suggestions about the underlying tongue behavior responsible for the slope patterns found in acoustics. In that study he followed the same child from age 7 to 40 months. In his measurement of alveolar slope, he found a steep slope for early measures that lowered toward the adult-like slopes by 12 months. He does estimate that the tongue must be fronted for the alveolars, based on the F2 values. But he conjectured that the early high slopes are due to a lack of differentiation of the tip and the dorsum, and that the lowering of the slope is due to the growing ability of the child to control the two parts of the tongue separately. Regarding the fall in slope, he says "We are suggesting that the child, perhaps by using heard adult forms as target sounds, has gained the ability to exercise independent motor control over the tongue body and tongue tip/blade during [dV] productions." The articulatory data we have presented show, rather, that the lowering of the slope indicates how the tongue back can be used to assist the tip, as observed in adults. That is, differentiation would lead to the possibility that the tip and tongue back could move independently, whereas what we suggest is that slope lowering is due to assistance, where the back moves the front, as if it were *not* independent of it. Indeed, we believe that the early steep slopes for /d/, if they are not due to the experimenters' difficulty of identifying the formants in young children's speech, suggest that the tongue body starts to move for the vowel during the formation of the /d/. Such a behavior observed in children but not in adults may reveal that they have not learned the synergy between the back and the front of the tongue.

One important observation of Sussman *et al.* (1999) that our study corroborates is that, even when children have learned an aspect of coarticulation, the resulting pattern may not be stable. We believe that the non-significant tendency we observe in this study for children to have a *larger* difference in slope between /t/ and /p/ than adults, based on articulatory measures, is in fact due to the immaturity of the pattern. A child's pattern may overshoot the adult's and oscillate, before it stabilizes. This supports the findings of Sussman *et al.* from their longitudinal study. A focus of further study is therefore to track individual development of the synergy longitudinally, as in the study of Sussman *et al.*, to determine the trajectory of maturation or lack of maturation in atypical speech. Such study should advance our understanding of how the development of speech motor control (together with those of the vocal tract) affects individual articulatory strategies for the production of distinct acoustic goals.

V. CONCLUSION

The results of the present study investigating children from 4 to 5 years old suggest that children aged 4 and 5 years old (1) have developed a pattern of coarticulatory resistance depending on consonant place of articulation; (2) they have a control of the different functional subparts of the tongue to achieve a proper /t/, and they use the back part of their tongue to produce these consonants; (3) the lower correlation coefficients (Table I and II) associated with children's regressions compared to adults' indicate more variability in coarticulatory patterns (e.g., for alveolar) that can be due to the immaturity of the speech motor system and organization of the articulatory gestures to produce distinct goals (e.g., an oral closure in the alveolar region for the alveolar stops). Other factors of variability such as anatomical growth of the vocal tract that could not be investigated in this study should also be carefully considered in future investigations.

Overall, the two LE analyses demonstrated that the relation found between C and V in acoustics is also observed in articulation both in adults and children, aged 4 and 5 years old. Results reaffirm (1) the significance of F2 as a robust indicator of tongue motion in the front/back dimension and (2) provide further details on coarticulatory resistance as a possible origin for variation in coarticulation magnitude.

Further studies testing more consonants, voiced and voiceless in various environments are needed to better understand how children learn to deal with the articulatory constraints underlying the coarticulation of various C's and V's and attune their control of the functional lingual subparts to the phonological regularities of their native languages.

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