Stop consonant voicing and intraoral pressure contours in women and children[a)]

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Previous authors have established that stop consonant voicing is more limited in young children than adults, and have ascribed this to immature vocal-tract pressure management. Physical development relevant to speech aerodynamics continues into adolescence, suggesting that consonant voicing development may also persist into the school-age years. This study explored the relationship between stop consonant voicing and intraoral pressure contours in women, 5 year olds, and 10 year olds. Productions of intervocalic /p b/ were recorded from eight speakers at each age. Measures were made of stop consonant voicing and δ, a measure designed to characterize the time course of intraoral pressure increase in stops, following Müller and Brown [*Speech and Language: Advances in Basic Research and Practice*, edited by N. Lass (Academic, Madison, 1980), Vol. **4**, pp. 318–389]. Age effects for stop consonant voicing and δ were not statistically significant, but correlations between δ and stop voicing were less often significant and sometimes reversed in the children, providing some evidence of immature aerodynamic control. The current data, as well as those of Müller and Brown, also show that the δ measure may yield some paradoxical values, indicating that more work is needed on methods of assessing time-varying characteristics of intraoral pressure.
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I. INTRODUCTION

A. Purpose

This paper investigates stop consonant voicing and intraoral pressure (P_{io}) trajectories in normal female and child speakers of American English. Although previous authors have speculated that developmental voicing patterns reflect limited aerodynamic control in children, no studies have directly compared voicing and pressure data from child speakers. Moreover, data on time-varying characteristics of P_{io} are very limited in adults as well as children.

The next section reviews the literature on stop consonant voicing and its relationship to P_{io}, focusing particularly on the work of Müller and Brown (1980). These authors introduced methods of assessing P_{io} trajectories and used aerodynamic modeling to explore how P_{io} signals might reflect underlying articulation. Many of their analysis methods have been adopted in the current work. The subsequent section reviews the developmental literature and considers reasons why one may expect differences in voicing and P_{io} control between children and adults.

B. Voicing of stop consonants and P_{io} control

In many languages, one class of stop consonants is produced with vocal-fold vibration during most or all of the closure. Such stops are typically called voiced, in contrast to voiceless stops, which have silent closures. When the vocal tract is closed for an oral stop, P_{io} builds up behind the occlusion. Since subglottal pressure (P_{sub}) does not vary greatly over the time scale of individual speech segments (Löfqvist, 1975; McGlone and Shipp, 1972; Netsell, 1969), this increase in P_{io} yields a reduced transglottal pressure (P_{trans}) differential. Diminishing P_{trans} can ultimately lead to cessation of voicing, even when the vocal folds are adducted. Voicing will persist during a consonantal closure (indeed, during any speech sound) only so long as P_{trans} remains above a threshold value (e.g., Ishizaka and Matsudaira, 1972; Lindqvist, 1972; Stevens, 1991; Titze, 1988).

Past work has documented several ways in which adult speakers increase supraglottal volumes during voiced stop closures, slowing the buildup of P_{io} and allowing phonation to last longer. Volume-expanding maneuvers may include lowering the larynx, elevating the soft palate, advancing the tongue root, depressing the tongue body, and/or expanding the cheeks or lateral pharyngeal walls (Bell-Berti, 1975; Kent and Moll, 1969; Perkell, 1969; Riordan, 1980; Svirsky *et al.*, 1997; Westbury, 1983). The degree to which tissues passively deform in response to P_{io} can also be altered: reducing the level of muscular contraction increases tissue compliance (Westbury, 1983). The specific methods of ex-

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panding supraglottal volume during a given stop closure appear to vary both within and across speakers (Bell-Berti, 1975; Westbury, 1983).

Müller and Brown (1980) conducted an influential study on P_{io} trajectories during stop closures and the underlying vocal-tract conditions. These authors collected intraoral pressure data during oral stops produced by five men, and evaluated the data both qualitatively and quantitatively. The qualitative analysis involved visually classifying each token by shape, primarily in an attempt to indicate whether pressure pulses showed a fast initial rise (convex tokens) or had more slowly rising trajectories (concave and linear tokens).[1] Schematic examples of concave and convex tokens are shown in Fig. 2 (Sec. II F). The results indicated that voiceless stops were more likely to have convex contours, whereas voiced stops more typically had linear or concave pressure signals. For the quantitative analysis, Müller and Brown calculated a δ measure as the difference between the slopes to average and peak pressures (Pa and Pk). Cases of $\delta > 0$ should be associated with a convex pressure contour; $\delta < 0$ would correspond to a concave contour, and $\delta = 0$ would indicate a linear contour, i.e., no slope change. These results showed higher δ values for voiceless consonants than voiced. In short, both the qualitative and quantitative analyses indicated that the initial P_{io} rise is slower in voiced stops than voiceless.

Müller and Brown (1980) next adapted the aerodynamic model of Rothenberg (1968) to investigate the articulatory conditions that could produce the slow-rising pressure traces observed in the men's voiced stops. The simulations showed that modeling relaxed (compliant) vocal-tract walls and adjusting the timing and magnitude of glottal opening affected the rate of P_{io} buildup somewhat, but did not produce concave trajectories. Only expanding supraglottal volumes resulted in concave P_{io} patterns. Westbury (1983), also working from Rothenberg's model, estimated that oral closures produced with tense vocal-tract walls would have voicing for only about 10 ms, whereas lax walls produced voicing for 80 ms or longer. Modeling active volume increases permitted voicing to continue "virtually indefinitely" for tense as well as lax wall characteristics (Westbury, 1983, p. 1333). Taken together, these studies imply that (a) stop consonant voicing is facilitated by supraglottal volume increases; (b) the effects of such volume changes may be evident in P_{io} trajectories; and (c) P_{io} contours can therefore provide insight into the degree to which speakers manage vocal tract pressures in service of maintaining stop consonant voicing.

The above-outlined experimental and modeling studies considered only adult speakers. As detailed in Sec. I C, there are several reasons to suspect that the results of this literature do not accurately characterize the speech production patterns of children.

C. Child–adult differences

Children differ from adults not only in absolute size, but also in the relative dimensions of their speech production systems and in aerodynamic quantities. Respiratory system variables such as lung volumes, capacities, and recoil pressures do not reach adult-like levels until adolescence (de Troyer *et al.*, 1978; Hoit *et al.*, 1990; Mansell *et al.*, 1977; Polgar and Weng, 1979). Laryngeal proportions in children are more similar to those of women than men; prior to puberty, sex differences in the larynx are minimal, but pubertal changes in males lead to disproportionate increases in vocal fold length and mass (Hirano *et al.*, 1983; Kahane, 1982). Differentiation of the laryngeal tissue layers continues into adolescence in both sexes, and growth of the vocal folds, both during childhood and at puberty in males, adds length mainly in the anterior, membranous region, which has lower stiffness characteristics than the posterior, cartilaginous region (Hirano *et al.*, 1983; Titze, 1989). As for the vocal tract, high laryngeal positions in early childhood yield shorter overall vocal tract lengths and particularly small pharyngeal cavities (Bosma, 1975; Crelin, 1987; Fitch and Giedd, 1999; Goldstein, 1980; Sasaki *et al.*, 1977; Vorperian *et al.*, 2005).

Given such differences in respiratory, laryngeal, and supralaryngeal systems, there is little reason to expect that the transglottal pressures needed to maintain vocal-fold vibration should be the same in children and adults, or that the mechanisms adults use to prolong stop consonant voicing would be equally effective for a child. Lucero and Koenig (2005) recently observed that scaling a laryngeal model down to a size appropriate for a 5 year old increased the phonation threshold pressure, as a result of less glottal tissue area absorbing the aerodynamic energy that fuels oscillation. Several past studies have found higher subglottal pressures in children compared to adults (Arkebauer *et al.*, 1967; Bernthal and Beukelman, 1978; Brown, 1979; Netsell *et al.*, 1994; Stathopoulos and Sapienza, 1993; Stathopoulos and Weismer, 1985; Subtelny *et al.*, 1966). Some researchers have pointed out that the increased resistance afforded by children's smaller airways will, all else being equal, lead to higher pressures (Stathopoulos and Sapienza, 1993; Stathopoulos and Weismer, 1985). Stathopolous and Weismer (1985) also proposed that children may simply select higher speaking intensities than adults. Whether higher pressures in children arise as a matter of anatomy or choice, they may be, to some extent, necessary in order to generate the requisite transglottal pressures for achieving phonation in a child-sized larynx (Lucero and Koenig, 2005).

Higher subglottal pressures notwithstanding, the developmental data suggest that young children do not produce many fully voiced (or prevoiced) stops. Early studies of voice onset time (VOT) by Preston and colleagues (Preston *et al.*, 1968; Preston and Port, 1969) indicated that toddlers from both English- and Arabic-speaking homes produced mainly voiceless unaspirated stops in syllable-initial position. In Arabic, the voicing contrast is between voiced and voiceless unaspirated stops (Yeni-Komshian *et al.*, 1977). In English, the contrast in utterance-initial, prestressed position is mainly between voiceless unaspirated /b d g/ and voiceless aspirated /p t k/; the "voiced" series may have optional closure voicing in this context for some speakers (e.g., Flege, 1982; Flege and Brown, 1982; Lisker and Abramson, 1964). Kewley-Port and Preston (1974), analyzing voicing acquisition in three young English-learning children, also found mostly voiceless unaspirated stops, and argued that this class of stops is, in effect, the easiest to produce because it requires neither volume-compensation movements to prolong closure voicing nor precise laryngeal-supralaryngeal timing to achieve aspiration. Zlatin and Koenigsknecht (1976), studying 2 and 6 year olds, and Barton and Macken (1980), studying 4 year olds, similarly noted a rarity of prevoiced stops in their data.

Stop consonant voicing patterns in noninitial positions provide further support for age-related differences. Smith (1979) found that 2- and 4-year-old English-learning children devoiced final /b d g/ both more extensively (as a percentage of closure duration) and frequently (as a percentage of the total number produced) than did adults. Allen (1985) observed that young children learning French (which contrasts voiced and voiceless unaspirated stops) tended to produce words beginning with /b d g/ in intervocalic rather than utterance-initial positions. The results of both of these studies are consistent with Westbury and Keating (1986), who used modeling to investigate how well aerodynamic considerations predicted cross-linguistic patterns of stop consonant voicing. The simulations showed that conditions for voicing were most favorable in intervocalic position, and least so in utterance-final position, where subglottal pressure often decreases (e.g., Atkinson, 1978; Gelfer *et al.*, 1983; Lieberman, 1967). Westbury and Keating concluded that "articulatory ease," defined as the likelihood of a stop being voiced in the absence of compensatory maneuvers, accounted for some, but not all, of the cross-linguistic data: Fully voiced stops do not appear to be particularly rare in languages, as the simulations suggested, but the contrast is often neutralized in final position, as predicted. The authors did note, however, that issues of "naturalness" or "case of production" might exert a greater influence on the speech of children than adults.

D. Research goals

Müller and Brown (1980) explicitly proposed that children's P_{io} trajectories might differ systematically from those of adults. Other authors (viz., Kewley-Port and Preston, 1974) have implicated P_{io} control in explaining developmental voicing data. Yet no studies have used time-varying measures to characterize P_{io} in children. Indeed, dynamic measures of speech aerodynamics are rare in adults as well. Finally, few studies, and none on children, have assessed the relationship between P_{io} and the actual degree of stop consonant voicing.

Thus, the purpose of this work was to determine whether children differ from women in their stop consonant voicing behavior and intraoral pressure characteristics as assessed using Müller and Brown's (1980) δ measure. Women were used as the comparison group because their laryngeal and vocal tract proportions are more similar to those of children than are men's. Anatomical and aerodynamic considerations lead to the prediction that children should produce less closure voicing than adults. Past empirical work has established this for children as old as 6 years of age (Zlatin and Koenigsknecht, 1976). Reduced differentiation of children's stops according to voicing would suggest less P_{io} differentiation as well. On the other hand, children may use articulatory maneuvers (e.g., more extreme laryngeal lowering, pharyngeal expansion, velar elevation, etc.) to achieve closure voicing patterns similar to those of adults.

II. METHODOLOGY

A. Speakers

Data were recorded from eight speakers in each of three groups: 4- to 5-year-old children (age range=4;2–5;11, μ=5;2), 9- to 10-year-old children (range=9;1–10;6, μ=9;9), and women (range=32;4–46;5, μ=39;5). For simplicity, the two child groups will henceforth be referred to as 5 year olds and 10 year olds. The children's age groups were chosen to include speakers (a) as young as possible given the requirements of the experimental task, and (b) as old as possible without introducing effects of puberty. The child groups each had four girls and four boys. The adult group was composed of mothers of child participants.

All children and women were normal, healthy, native monolingual speakers of American English from the New York City metropolitan region. None of the speakers had a strong regional accent. Children were required to have a normal birth and developmental history, and no speech or language intervention (current or past). The children also passed a hearing screening to establish binaural thresholds of 25 dB or less at 500, 1000, 2000, 4000, and 8000 Hz. The women had normal speech, language, and hearing by self-report, and speech characteristics within normal limits as judged informally by the first author. Parents filled out a questionnaire on their child's developmental milestones, including, for the older age group, questions about pubertal changes. None of the children included here evidenced onset of puberty. Finally, a short narrative or conversational sample was obtained from all children. These samples were analyzed to ensure that (a) any sound substitutions were developmentally appropriate for the child's age, and (b) the child's language development was within normal limits for his/her age. Adults and parents of child subjects provided informed consent for study participation, and all children provided assent.

In a short post-hoc study, two normal adult male native speakers of American English (unrelated to the children) were recorded using the same instrumentation and methods. Their data were analyzed to verify that small differences between the current methods and those of Müller and Brown (1980) did not systematically influence the results.

B. Instrumentation

Three signals were recorded from each participant: (a) acoustics, obtained using an AKG C420 head-mounted microphone hung around the speaker's neck; (b) oral airflow, collected using an undivided pneumotachograph (Glottal Enterprises) sized appropriately for the speaker; and (c) intraoral air pressure, obtained via a catheter-tip pressure transducer (Gaeltek CT/S). This device has a sensitivity of 5 μV/volt/mm Hg and a frequency response of 1 kHz. The sensor was screwed tightly within a piece of sterile medical tubing inserted through a hole in the airflow mask to rest inside the speaker's oral cavity during bilabial closure. The acoustic signal was used to verify that the speaker's utterances were perceptually accurate (see Sec. II D); all measures were made from the aerodynamic signals.

Data were collected using a PowerLab (4SP) connected to a laptop computer. Before recording began, all inputs were adjusted to yield adequate signal-to-noise levels. Acoustic signals were low-pass filtered at 10 kHz and sampled at 20 kHz. Acrodynamic signals were low-pass filtered at 5 kHz and sampled at 10 kHz. The signals and speakers were monitored throughout recording to ensure that the airflow mask was pressed tightly to the face, and that the pressure tube was not clogged with saliva. At the beginning or end of each recording session, pressure and flow calibration values were obtained using a water manometer for the pressure and a rotameter for the airflow.

The airflow recording methods used here differed from Müller and Brown (1980) in using a standard, unaltered pneumotachograph. Those authors, in contrast, adjusted their airflow mask to limit dead air space and avoid flows associated with lip and jaw movement. Specifically, they filled the area between the upper lip and nose with foam rubber and caulk, and affixed a sheet of dental dam material to the lower lip. These modifications were not implemented here partly because they were impractical for recording young children, and most studies on speech aerodynamics have used unaltered masks. Most important, perhaps, the signals obtained from the standard mask permitted reliable measurement of the two events necessary, namely oral closure and release. The relevance of this methodological difference for directly comparing this work to that of Müller and Brown is considered in Sec. III D.

C. Speaking task

Pictured stimuli were used to elicit multiple productions of the utterances "Poppa Popper" and "Poppa Bopper." (Poppa Popper had a bowl of popcorn, and a large P on his shirt; Poppa Bopper was "bopping" a large block, inscribed with a B, with a mallet). The stimuli were introduced to the speakers before recording took place. During recording, a picture was presented to the speaker, who then repeated the utterance five times. A research assistant presented the pictures and maintained the children's interest throughout the task. Each picture was presented five times during the recording session, in randomized order, resulting in approximately 25 productions per consonant.

D. Exclusion criteria

Tokens were discarded when (a) monitoring of the speaker or the airflow data suggested that an airflow leak may have occurred; (b) the target consonant was not perceptually accurate in voicing, place, and manner; (c) the flow signals for the target stop did not show abrupt changes associated with vocal-tract closure and release, suggesting lenition or spirantization, and/or if second derivative peaks defining closure or release could not be identified with certainty (described further in the next section); or (d) P_{io} did not return to near-baseline during the unstressed vowel preceding the target consonant, with "near-baseline" defined as 1 cm H_2O. Cases with nonbaseline pressures primarily occurred in a few 10 year olds who used faster speech rates. Most other exclusions in the children owed to airflow leaks (e.g., the child moved and mask seal was not maintained) or lenition. In total, 1017 pressure traces were analyzed (510 for /b/ and 507 for /p/); there were 282, 305, and 430 tokens for the 5 year olds, 10 year olds, and women, respectively. Subjects contributed an average of 21 tokens each of /p/ and /b/ to the data pool (range=10–31 tokens per consonant per speaker).

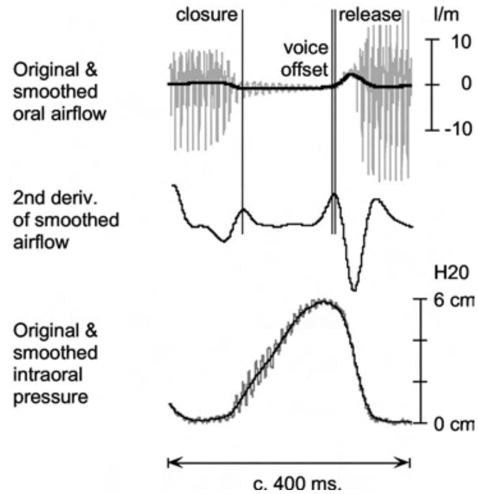

FIG. 1. Sample production of /əbɑ/ ("Poppa Bopper") showing events used for measurement. Top panel: Original (grey) and smoothed (black) oral airflow. The three vertical lines indicate the times of (a) closure, (b) voicing offset, and (c) release. In fully voiced tokens like the one shown here, the time of voicing offset was set just preceding the time of release. Second panel: Second time derivative of smoothed oral flow. Third panel: Original (grey) and smoothed (black) intraoral pressure (P_{io}). All signals are temporally aligned.

E. Measurement of voicing and closure duration

Initial data analyses used the CHART™ software accompanying the PowerLab system. A sample token from a 10 year old is given in Fig. 1. All measures were made on the tokens of /p, b/ initiating the third, stressed syllable of the utterance. The times of voicing offset during the consonantal closure were identified visually from the unsmoothed air pressure and airflow signals. To determine the times of articulatory closure and release, the airflow signals were smoothed twice with a 201-point window, the signal was differentiated twice, and the resultant was smoothed. Release and closure were defined by finding those peaks in the second derivative signal that corresponded to the corners of the flat region in the flow signal demarcating the consonantal closure. This method of determining stop closure and release was particularly useful when the flow signals showed effects of supraglottal movement (i.e., baseline shifts) during stop closures, but it differed from that of Müller and Brown (1980), who made closure and release judgments visually from the unsmoothed flow signals. Since smoothing the flow and its derivatives could introduce some temporal noise, the data from one woman (38 tokens) were remeasured using visual inspection of the unsmoothed flow signals, to verify that the two measurement procedures yielded similar results. The closure and release times obtained via the two methods

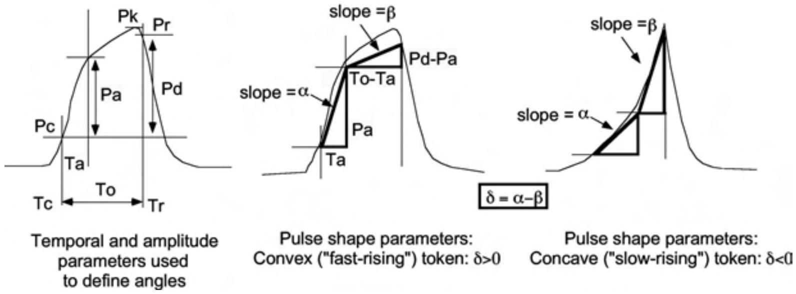

FIG. 2. Schematic signals showing time and amplitude measures made to quantify the shape of the pressure pulse, following Müller and Brown (1980).

differed by average of 2 ms (s.d.=5 ms). This aspect of our methods, therefore, appears not to be of concern for a comparison with Müller and Brown.

Times of oral closure, oral release, and voicing offset permitted calculation of (a) closure duration, (b) voicing duration, and (c) percentage of the closure that was voiced. Absolute duration of voicing was included following Westbury and Keating (1986). Percentage of voiced closure was included because children tend to have slower speech rates and longer segment durations than adults (e.g., Kent and Forner, 1980; Smith, 1978, 1992). Thus, even if children produce the same duration of voicing as adults, they may show proportionally less voicing during a stop, and be perceived to devoice more frequently. Finally, the number of devoiced stops productions of /b/ was assessed, following Smith's (1979) suggestion that these may be more prevalent in children than adults. Drawing on studies that have quantified closure voicing in both voiced and voiceless stops (Docherty, 1992; Flege and Brown, 1982; Westbury, 1979) a cutoff point of 30% voiced closure was selected for designating voiced stops as "devoiced" in production. (In the cited work, voicing was observed to persist into target voiceless stops up to 30% of the closure.) Using this cutoff, each subject's /b/ tokens were classified as (partially) voiced (30+% voiced) or devoiced (<30% voiced).

Since voicing offset was determined visually, a randomly chosen 20% of all tokens was remeasured by the first author to assess reliability. Although most of the original measures were made by graduate-student research assistants, a portion was made by the first author; of the remeasured data, 78% represented inter-rater reliability (original measures made by students) and 22% represented intra-rater reliability. Correlations between the original and remeasured data showed high reliability, both for voicing duration calculated in milliseconds and as a percentage of closure, and for inter- and intra-rater reliability (all r values 0.96 or higher and all p values <0.0001). For intra-rater reliability, the mean absolute measurement error was 5.2 ms for voicing duration (s.d.=6.9) and 0.06 (i.e., 6%) for the proportion of closure voiced (s.d.=0.09). For inter-rater reliability, mean voicing duration error was 3.0 ms (s.d.=6.6) and for voicing percentage it was 0.03 (s.d.=0.08).

F. Pulse shape calculations

The unsmoothed pressure signal for each token of /p/ and /b/ was extracted in the CHART program, using a time window wide enough to include the stop closure and release labels as defined earlier, and read into MATLAB for pressure pulse calculations. Following Müller and Brown (1980), the signals were low-pass filtered at 43 Hz using a sixth-order Butterworth filter, filtering both forwards and backwards to minimize temporal delay. From this smoothed signal, several parameters were calculated to permit characterization of the pressure pulse shape. These parameters are shown for a schematic example at the left of Fig. 2: Tc=time of closure (identified from the second derivative of the flow signal, as indicated earlier). Pc=pressure at closure. Tr=time of release (from second derivative of flow signal). Pr=pressure at release. To=closure duration (Tr−Tc). Ta=time to pressure average. Pa=pressure average relative to Pc. The average was obtained by integrating the smoothed pressure signal between Tc and Tr and Pc was then subtracted from the resultant. Pk=pressure peak. Pd=pressure difference between closure and release (Pr−Pc). α=slope of the hypotenuse of the triangle formed by Ta and Pa. β=slope of the hypotenuse of the triangle formed by (To−Ta) and (Pd−Pa). $\delta=\alpha-\beta$.

As shown in Fig. 2 (middle and right panels), a pressure pulse that rises quickly and then levels off should have a high α slope, low β slope, and $\delta>0$, whereas a slow initial rise followed by more rapidly increasing pressure should yield $\delta<0$.

In addition to the α, β, and δ measures, normalized slopes $(\alpha_n, \beta_n, \delta_n)$ were calculated by multiplying α, β, and δ by To/Pd. Müller and Brown (1980) proposed this procedure to adjust for differences in closure and pressure pulse duration. Specifically, normalization corrects for the fact that lengthening a closure (e.g., as a result of a slower speech rate), given a constant rate of pressure increase, will lead to a higher pressure at release.

G. Statistical analysis

Repeated measures analyses of variance (ANOVAs) were conducted on voicing duration, percentage of closure voicing, δ, and δ_n measures, with consonant as the within-subject factor and age as the between-subject factor. A univariate ANOVA, with age as the independent variable, was used to analyze the percentage of devoiced /b/ for each speaker. The Bonferroni-corrected α level for determining significance in the five ANOVAs was 0.05/5=0.01. To quantify the relationship between voicing and P_{io} characteristics, within-subject correlations were run for δ and the duration of closure voicing. For 24 correlations, the adjusted α level was 0.05/24=0.002.

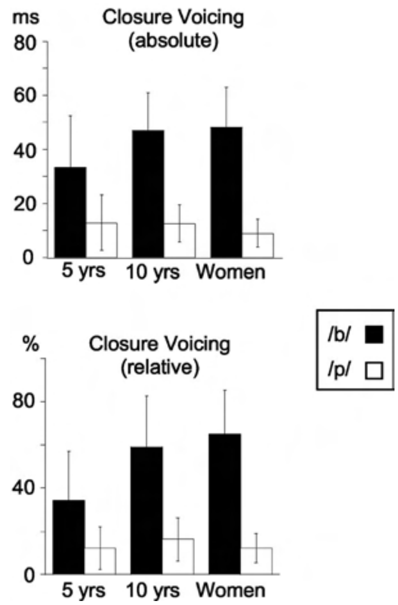

FIG. 3. Amount of closure voicing, in milliseconds (top), and as a percentage of the closure duration (bottom). Closed bars represent /b/; open represent /p/.

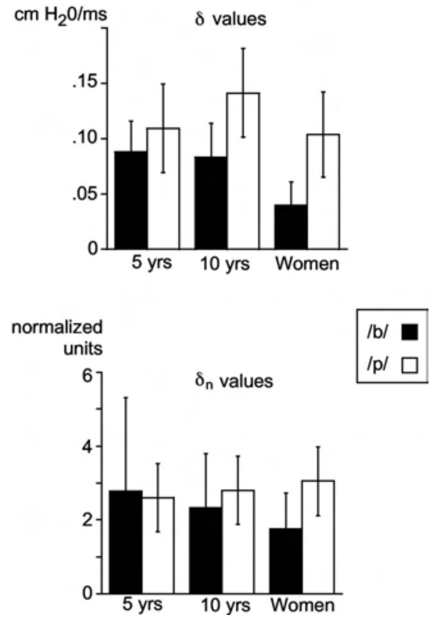

FIG. 4. δ (top) and normalized δ_n (bottom) values for each speaker group. Closed bars represent /b/; open represent /p/.

III. RESULTS

Sections III A and III B address group (i.e., age) effects in voicing and pressure measures. Section III C assesses the relationship between voicing and pressure data. Section III D compares the current data with those of Müller and Brown (1980), incorporating the post-hoc analysis of two men.

A. Stop closure and voicing durations

Closure voicing durations and percentages of closure voicing are shown for each speaker group in Fig. 3. ANOVA results for the two measures are given in Table I. As expected, voicing was more extensive for /b/ than /p/, measured both as a duration and as a percentage of the closure. The consonant effect was highly significant in both ANOVAs. A main effect of age was not significant for either analysis. The group-by-consonant interactions did not reach significance either, although the one for voicing percentage approached it ($p=0.018$). Qualitatively, the percentage of closure voicing for /p/ was similar across ages, whereas for /b/ it increased somewhat over age (see bottom panel of Fig. 3). The actual percentages for /p/ voicing, in ascending age order, were 12%, 16%, and 12%; for /b/, they were 36%, 59%, and 64%.

The proportions of devoiced stops for all speakers are given in Table II. Although devoicing was most common on average in the 5 year olds, the incidence of devoiced /b/ varied considerably within groups, and the group effect did not reach significance [$F(2,21)=3.968$, $p=.035$].

TABLE I. ANOVA results for closure voicing measured as a duration and as a percentage of the closure duration.

Voicing duration			
Effect	dfs	F	p
Consonant	1, 21	115.432	<0.0001
Group	2, 21	0.678	0.518
Consonant × group	2, 21	2.955	0.074
Voicing percentage			
Effect	dfs	F	p
Consonant	1, 21	102.595	<0.0001
Group	2, 21	2.314	0.124
Consonant × group	2, 21	4.927	0.018

B. Pressure contours

The δ analysis was intended to quantify pulse shape, with values of $\delta > 0$ indicating convexity. The δ_n values are the normalized, unitless counterparts designed to correct for speech rate differences, all else being equal. Group results for δ and δ_n are shown in Fig. 4. The ANOVA results are summarized in Table III.

For δ, the consonant effect was highly significant, but the group effect failed to reach significance ($p=0.024$), as did the group-by-consonant interaction. The results for δ_n were rather different: Neither of the main effects nor the group-by-consonant interaction approached significance. As shown in Fig. 4 (lower panel), the 10 year olds and women still had the expected pattern of higher values in /p/ compared to /b/; the 5 year olds did not, and had a markedly higher standard deviation (s.d.) for /b/.

To determine why δ_n means and s.d.s differed so much from those of δ in the 5 year olds, the two parameters used to obtain δ_n from δ, namely closure duration (To) and the pressure difference between release and closure (Pd), were inspected. The results for pressure at closure (Pc) and release (Pr) were also reviewed to clarify the Pd data. The group means and s.d.s for these four measures are given in Table IV.

Table IV shows that the 5 year old's high δ_n s.d.s for /b/ reflect variability in both Pd and To, but compared to women the s.d.s for Pd were proportionally higher than those for To

TABLE II. Proportions of /b/ productions in which 30% or more of the closure was voiced. In the child groups, the first four speakers are females; the last four are males.

	Speakers 1–8 in each group								Group average
5 year olds	0.12	0.35	0.38	0.06	0.79	0.89	1.00	0.11	0.46
10 year olds	0.55	0.75	1.00	1.00	0.88	0.23	0.63	1.00	0.75
Women	1.00	0.82	0.80	0.87	0.48	0.93	0.97	0.92	0.85

(2.1 vs 1.7). Pd variability, in turn, reflects variability in both Pc and Pr: s.d.s for both are higher in the 5 year olds than the women. As for the mean values, both Pd and To are higher in the 5 year olds than the adults, but proportionally more so for Pd (1.8 times the adult value) than for To (1.4–1.5 times the adult value). As laid out in Sec. I, age-related differences in durations and intraoral pressures were expected for a variety of reasons. The δ normalization method proposed by Müller and Brown (1980) is designed to correct for higher pressures that arise simply as a function of longer durations. The current data show both longer durations and higher pressures in 5 year olds than adults, but the pressure differences are proportionally greater. Because these two parameters do not change in parallel with age, it appears that this method of δ normalization is not appropriate for comparing across age groups.

The data presented above indicate that δ differentiated /p/ and /b/ on average for all age groups. To determine how well this held for individuals, the δ difference between /p/ and /b/ was obtained for each speaker. If intraoral pressure rises faster in /p/ than /b/, the difference should be positive. The results are given in Fig. 5. Interspeaker variability is considerable for all groups, but most values are positive; negative values occur only among the children.[2] Thus, the /p/-/b/ difference observed in the δ averages is reflective of most speakers.

C. Relations between stop consonant voicing and pressure measures

To quantify the relationship between pressure pulse trajectories and the degree of stop consonant voicing, within-subject correlations were run on δ and closure voicing duration for /p/ and /b/ combined.[3] The results are given in Fig. 6. As expected, r values are usually negative: As δ becomes more positive (as for a convex pulse), the amount of voicing decreases. The three child speakers with positive r values are the same as those with negative δ differences between /p/ and /b/. Significant correlations (using a criterion of $0.05/24=0.002$) are indicated in Fig. 6 by asterisks. The number of significant correlations increases with age; that is, the relationship between pressure pulse parameters and voicing is more consistent in adults.

TABLE III. ANOVA results for the pulse shape measure δ and its normalized counterpart δ_n.

δ			
Effect	dfs	F	p
Consonant	1, 21	35.006	<0.0001
Group	2, 21	4.497	0.024
Consonant × group	2, 21	2.742	0.087
δ_n			
Effect	dfs	F	p
Consonant	1, 21	1.853	0.188
Group	2, 21	0.153	0.859
Consonant × group	2, 21	1.199	0.321

D. Comparison with Müller and Brown

This section assesses how the current results compare with those of Müller and Brown (1980). Those authors did not explicitly measure closure voicing, so this discussion is limited to the δ measure; δ_n is not considered because of the uneven nature of age-related changes in To and Pd noted in Sec. III B.

As indicated earlier, the current methods differed in a few ways from those of Müller and Brown (1980): Here, closure and release were measured semiautomatically from the acceleration of the flow signal (addressed in Sec. II E); a standard pneumotachograph was used, without employing the adjustments used by Müller and Brown; and the adult group consisted of women rather than men. The mask difference relates only to the airflow-based measures of closure and release, and should not affect the pressure measures themselves. The gender difference, however, could affect pressure measures given that women, on average, have smaller vocal tract sizes than men. Thus, to allow a more valid comparison with Müller and Brown, equivalent data were recorded from two men and analyzed in the same manner as the women and children to obtain δ measures. Values of δ from Müller and Brown were estimated (to the nearest 0.005 cm H_2O/ms) from their plots for bilabial stops in the /ɑ/ vowel context. (That study also included alveolar consonants and a high vowel context). Since Müller and Brown's subjects all produced the same number of tokens ($N=6$), group averages could be estimated from the individual subject averages.

As shown in Table V, δ values obtained here for both /p/ and /b/ were higher than Müller and Brown's (1980), particularly for the children. A general pattern of descending δ values for /b/ across 5 year olds, 10 year olds, women, and men in Table V provides qualitative support for the hypothesis that intraoral pressure tends to rise more slowly in those with larger vocal tracts. (This is consistent with the data in Table IV: The pressure rise during closure, Pd, was higher in children than women, and to a greater degree than closure duration, To). The average δ differences between Müller and Brown's data and the current *adult* speakers appear to reflect sampling error, however. Müller and Brown's data showed considerable intersubject variability in δ, and standard devia-

TABLE IV. Descriptive data for closure duration (To), pressure difference in the closure (Pd), pressure at closure (Pc), and pressure at release (Pr). To and Pd are the two measures used to δ_n from δ; Pd=Pr−Pc. Each cell in the first three rows shows the group mean (standard deviation). The last row provides the ratio of the 5 year olds to the adults (means and standard deviations calculated separately).

	Closure duration (To)		Pressure difference (Pd)		Pressure at closure (Pc)		Pressure at release (Pr)	
	/b/	/p/	/b/	/p/	/b/	/p/	/b/	/p/
5 year olds	106.7 (17.9)	113.7 (21.4)	4.9 (1.9)	5.2 (1.8)	2.5 (0.8)	3.4 (1.1)	7.4 (2.0)	8.6 (1.9)
10 year olds	86.7 (17.9)	82.9 (18.0)	3.9 (0.9)	4.4 (0.7)	2.4 (0.8)	3.9 (1.5)	6.3 (1.2)	8.3 (1.8)
Woman	75.5 (10.4)	75.6 (9.6)	2.7 (0.9)	2.9 (1.2)	1.7 (0.5)	2.9 (0.9)	4.3 (1.1)	5.8 (1.5)
Ratio: 5 year olds to women	1.4 (1.7)	1.5 (2.2)	1.8 (2.1)	1.8 (1.5)	1.5 (1.6)	1.2 (1.2)	1.7 (1.8)	1.5 (1.3)

tions for δ were also fairly large here (refer back to Fig. 4). Review of the women's data showed four cases in which individuals had δ values at or lower than Müller and Brown's averages. (The same was true for one 10 year old.) Thus, the current adult data overlap with those of Müller and Brown, and appear to be generally consistent with the results of the earlier study. Section IV raises some issues concerning δ which may explain the wide variation in δ even in adult speakers.

IV. DISCUSSION

A. Age and stop consonant voicing

Past studies have found that children up to 6 years of age produce fewer voiced stops and less closure voicing than adults (e.g., Barton and Macken, 1980; Kewley-Port and Preston 1974; Smith, 1979; Zlatin and Koenigsknecht, 1976). Qualitatively, the current data showed the least /b/ voicing and the largest number of devoiced /b/ productions in the 5 year olds, but age effects did not reach significance for any of the voicing measures. Four factors should be considered in interpreting this result: (a) nature of the voicing contrast in English; (b) phonetic context; (c) age of the children; and (d) sample size.

Given that closure voicing is not obligatory in stressed, syllable-initial contexts in American English (e.g., Lisker and Abramson, 1964; Zlatin, 1974), all speakers have the option of producing voiceless unaspirated stops, which may be motorically less demanding (Kewley-Port and Preston, 1974). At the same time, the intervocalic frame in which the target consonants appeared here tends to facilitate closure voicing. Children might be particularly susceptible to factors favoring *devoicing* (Westbury and Keating, 1986), but to ascribe a lack of significant age effects here to the intervocalic context would be to assert that children have a stronger positional bias toward *voicing*. Given smaller vocal tract sizes and higher phonation threshold pressures in children, there is no reason to think they should be more likely to voice in an intervocalic position than adults. That is, the phonetic context may have predisposed all speakers to produce voiced stop closures, but this should not have made age differences less likely.

More likely is that the children's ages and the group sizes had the effect of minimizing age effects. Past developmental studies of consonant voicing have mostly concentrated on very young children. The requirements of the experimental task used here precluded recording children younger than about 4 years, and the younger group included individuals nearing their sixth birthday. These children were thus at the upper end of the age range at which group differences have been demonstrated. The intensive within-speaker processing here also limited group sizes. Finally, the children showed considerable intersubject variability, as has often been observed (e.g., Eguchi and Hirsh, 1969; Kent and Forner, 1980). With a larger sample size, the mean group differences may have outweighed the within-group variability to produce a significant age effect (e.g., Kirk, 1999).

In contrast to the 5 year olds, the 10 year olds were qualitatively as well as statistically comparable to the women in their voicing measures. Although a few studies have reported VOTs for voiced stops in children of this age (Kent

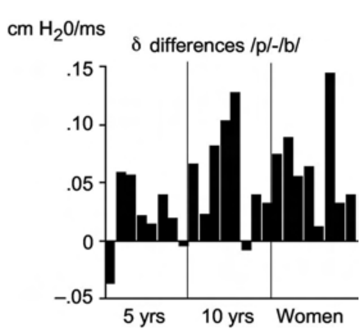

FIG. 5. Differences between δ values of /p/ and /b/ for each speaker.

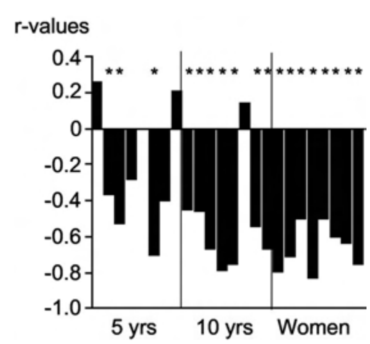

FIG. 6. Results of correlations (Pearson's r values) between δ and duration of closure voicing for each speaker. Asterisks mark speakers for whom the correlation was significant at $p<0.002$.

TABLE V. Comparison of current δ measures with those from Müller and Brown (1980, p. 342). The data from the earlier study are estimated from individual subject plots.

		/b/	/p/
Current study	5 year olds	0.088	0.109
	10 year olds	0.083	0.141
	Women	0.040	0.104
	Men	0.033	0.119
Müller and Brown		0.010	0.067

and Forner 1980; Ohde, 1985; Whiteside *et al.*, 2004), their data do not clearly indicate the degree of closure voicing, since a positive VOT may indicate a truly voiceless stop as well as one in which voicing dies out before the end of the closure. Based on the current results, it appears that 10 year olds demonstrate essentially mature closure voicing in /b/, despite continuing differences from adults in vocal tract sizes, aerodynamic quantities, speech segment durations, and token-to-token variability (e.g., Bernthal and Beukelman, 1978; Eguchi and Hirsh, 1969; Goldstein, 1980; Kent and Forner, 1980; Netsell *et al.*, 1994; Stathopoulos and Weismer, 1985; Walsh and Smith, 2002). These older children may thus have mastered methods of vocal-tract pressure management so as achieve adult-like closure voicing. The same explanation may hold for those 5 year olds whose voicing behavior was more adult-like. One difficulty with this interpretation, particularly for the younger children, is that the correlations between voicing and introral pressure (cf. Sec. IV C) were less often significant in children than adults, and sometimes reversed. Modeling of closure voicing with laryngeal and vocal tract models scaled to child sizes may provide greater insight into the conditions needed to produce voiced stops in child speakers.

B. Quantitative pressure pulse analysis and age

Past work has established that children as young as 4 years of age, like adults, produce higher peak P_{io} in voiceless stops than in voiced (Arkebauer *et al.*, 1967; Bernthal and Beukelman, 1978; Brown, 1979; Lisker, 1970; Malécot, 1966; Miller and Daniloff, 1977; Stathopoulos and Weismer, 1985; Subtelny *et al.*, 1966; Warren and Hall, 1973), thereby demonstrating some aerodynamic differentiation of consonants according to voicing category. At the same time, previous authors (particularly Kewley-Port and Preston, 1974) have attributed limited closure voicing in young children to immature control over intraoral pressure, and Müller and Brown (1980) specifically suggested that P_{io} might rise faster in children than adults. These results led to the prediction that δ and its normalized counterpart δ_n would differ between children and adults.

The data for δ showed a significant consonant effect, but age effects failed to meet significance. Comparison of the women and children's data with two men recorded post-hoc and those recorded by Müller and Brown (1980) showed decreasing δ values for speakers with larger vocal tracts, providing some support for the possibility of a size-related trend, and it may be again that a larger sample size and/or a younger group of children would yield significant age effects. Alternatively, children may perform more extreme volumetric adjustments than adults in order to control P_{io} increases in their smaller vocal tracts (but see again the comments on this point in Sec. IV C).

The results for δ_n showed neither age nor consonant effects. Inspection of the measures used to derive δ_n from δ, namely closure duration (To) and pressure difference in the stop (Pd), showed proportionally greater age differences for Pd. This suggests that δ is a more valid measure for comparing across ages than δ_n. The normalized measure may, however, still be appropriate to adjust for speech rate or loudness differences within individual speakers or age groups.

C. Relationships between P_{io} and voicing

The δ differences between /p/ and /b/ were in the expected direction for most speakers, but reversed for three of the children. Further, correlations between δ and voicing duration were significant for all of the women and for 7/8 of the 10 year olds, but only 3/8 of the 5 year olds. Thus, whereas adults have established consistent relationships between stop consonant voicing and P_{io} characteristics, as measured by δ, many 5 year olds and a few 10 year olds have not. Correlations in the expected direction that were statistically insignificant suggest that some children may have implemented control over P_{io} buildup in target voiced stops which was not extensive enough to maintain voicing, or else that they exercised such control inconsistently. Correlations in the reverse direction suggest that some children have in fact not yet learned how to manipulate intraoral pressure in order to maintain voicing. Both of these cases speak against a general developmental strategy in which children actively increase supraglottal volumes more than adults in an attempt to sustain voicing: In such a situation, one might expect even stronger correlations in children than adults. It is also possible that the δ measure is not sufficient to capture all aspects of aerodynamic control relevant for stop consonant voicing. As discussed in the following, some unexpected values of δ were encountered in the course of this work, lending support to this last interpretation.

D. Comparison with Müller and Brown and critique

The δ measures obtained here were somewhat higher, on average, than those obtained by Müller and Brown (1980). The particularly high δ values for /b/ in children compared to women as well as men may represent a tendency for speakers with smaller vocal tracts to have limited possibilities for supralaryngeal volume adjustments, but the differences among the adults appear to reflect normal cross-speaker variation. Different speech materials may also contribute to δ variance between the two corpora. Whereas the current study placed the target consonants in an intervocalic, running speech context, Müller and Brown elicited their consonants in isolated, symmetrical, nonsense VCV utterances, with instructions to produce equal stress on the two syllables. Conceivably, differences in stress pattern or speaking style may influence δ measures.

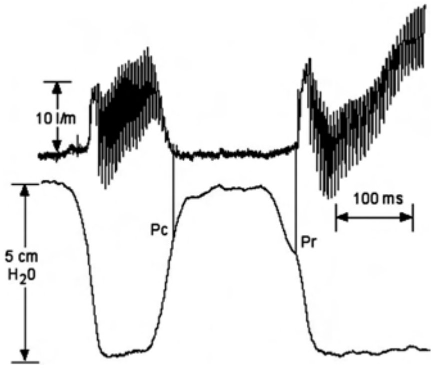

FIG. 7. A token of /b/ produced by a 5-year-old girl which yielded a negative value of Pd (difference between Pc, pressure at closure, and Pr, pressure at release).

Müller and Brown (1980) were unique in proposing methods of measuring time-varying aspects of P_{io} during stop closures. The results of their own and subsequent aerodynamic modeling (e.g., Westbury, 1983; Westbury and Keating, 1986) suggested further that the time course of P_{io} increase during stop consonants could provide information on aerodynamic management of voiced stops. For these reasons, the current work employed the δ measure, proposed by Müller and Brown as a simple metric for capturing aspects of P_{io} pulse shape. Yet the data obtained here, as well as close inspection of Müller and Brown's own data, suggest that this measurement method may have limitations. Specifically, some of the measures used to calculate δ and δ_n yielded unexpected values. These primarily reflected two situations: Cases where Pd (pressure difference between release and closure) and β (angle from average to release pressure) were negative. Pressure pulse depictions like those in Fig. 2 lead one to expect both to be positive. The next paragraphs briefly describe how these values came about.

Negative values of Pd occurred in five tokens (three from children, two from men; four of the five were in /b/). An example from a 5 year old is given in Fig. 7. (This token also had a negative β.) In this production, intraoral pressure decreases right before release. Although these examples are infrequent in our database, they appear to indicate that supraglottal movements affecting pressure contours may be initiated rather late during the closure.

Whereas negative Pd was rare, negative β was more common, occurring in 155 tokens (15% of the data for women and children combined). These were found across age groups (36%, 39%, and 26% came from women, 10 year olds, and 5 year olds respectively), and were about equally distributed across consonants (53% for /p/; 47% for /b/). Tokens with negative β also accounted for 12% of the men's data. Negative β occurs when the rise from closure to average pressure (Pa) is greater than the pressure difference between closure and release (Pd). Such values may also have occurred in Müller and Brown's (1980) data: Their plots show some speaker averages close to zero, with standard deviations consistent with negative values. The occurrence of negative β changes the interpretation of δ: Higher values of δ may result not only from convex wave forms, but also from pressure contours that fall between the time of average pressure and the time of release. To determine whether values of negative β affected the conclusions, all statistics based on δ or δ_n were rerun without tokens whose β values were negative. The results were similar or identical to the original ones, suggesting that the occurrence of negative β does not affect the general pattern of results in this work. Further, case-by-case review of these $-\beta$ tokens did not show them to be atypical in ways other than their β values; that is, they appeared to represent legitimate data points. The main observation to be made here is that Müller and Brown's measurement methods may yield some paradoxical values, and δ may reflect not only the convex/concave nature of a pressure pulse. It appears that more work is needed on how best to assess the time-varying characteristics of intraoral pressure data.

V. CONCLUSIONS

An extensive literature, using VOT as well as other measures, has indicated that stop consonant voicing is more limited in preschool children than in adults. This has been attributed to poor aerodynamic control in the context of anatomical growth and physiological maturation, processes which persist into adolescence. The current study used Müller and Brown's (1980) δ measure to assess the relationship between P_{io} characteristics and stop consonant voicing in children and adults. Unexpectedly, measures of voicing and δ did not differ significantly across age groups. For the 5 year olds, this may reflect limited sample sizes, but it appears that by 10 years of age, children have learned to produce virtually adult-like voicing patterns despite immature physical systems. The correlational patterns between δ and stop consonant voicing do suggest, however, that aerodynamic control of voicing in children is still subject to more variability than in adult speakers, and that some children, particularly at 5 years but maybe also at 10 years, have not yet learned to manipulate intraoral pressure as effectively as adults.

When interspeaker variability is taken into account, δ values for the current adult speakers seem consistent with those of Müller and Brown (1980), although varying stimulus materials may have yielded some differences between the two studies. More interesting is that issues arose relative to the δ measure itself. Paradoxical values of δ appear to have occurred in Müller and Brown's data as well as our own. Although these difficulties do not negate the conclusions of Müller and Brown regarding mechanisms of pressure control in adults, they do suggest that new methods of assessing time-varying characteristics of intraoral pressure data should be devised in order to characterize the data more fully and appropriately. Future work should explore this topic further.

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[1]In addition to convex, concave, and linear, Müller and Brown also categorized a few tokens as bimodal (double-peaked) or delayed (increasing slope, then a flat region, then increasing slope again). These five categories were further divided into tokens that had an abrupt slope change in the rising phase of the curve (breaking tokens) versus those that did not (smooth tokens). Although the original analysis of our data included this categorization, rater reliability was unacceptably low for the full ten-category analysis, so those results are not included here. Because the current paper only presents data for Müller and Brown's quantitative analysis, some details of the qualitative measurement scheme have been supressed in the main text.

[2]The speech of the children with negative values was not obviously remarkable in other ways; for example, it was not the case that more tokens were discarded from these children because of production errors.

[3]The two consonants were combined here in order to provide the most general picture of how voicing and pressure are related. The primary articulatory difference between /p/ and /b/, viz. vocal fold abduction, should lead to a faster pressure increase in /p/ (i.e., higher δ) as well as a reduction in voicing. Voicing in milliseconds is used here following the one study that explicitly compared closure voicing and P_{io} trajectories (Westbury, 1983). Correlations between δ and voicing as a percentage of the closure were qualitatively similar, but most r values were somewhat lower and fewer values reached significance. Finally, correlations for /b/ alone also yielded a majority of negative values (21 of 24 speakers), but only 2 of 24 p values reached significance. Some reduction in statistical significance is to be expected in both cases simply because only about half as many data points were included in each analysis.

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