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Research Article

The development of sex/gender-specific /s/ and its relationship to gender identity in children and adolescents

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ABSTRACT

A growing body of literature has revealed sex/gender differences in the acoustics of the sibilant fricative /s/. It has been suggested that some of this sex/gender-related variation might be socially motivated and acquired. However, the necessary developmental research to corroborate this proposal is absent from the literature. To address this, we examined sex/gender differences in the production of /s/ acoustics in relation to children's physical growth and gender identity. The speech production of children and adolescents aged 4–16 years old was recorded. Additionally, the physical height was measured and gender identity was evaluated through a parent-filled questionnaire. Three acoustic measures were calculated that describe the mean, standard deviation, and skewness of the spectral frequencies of /s/. Results indicated that gender identity played a key role in mediating the difference in /s/ acoustics between boys and girls for all three acoustic measurements. Additionally, for adolescent boys, gender identity explains within-gender variation in /s/. Our results thus highlight the importance of social-behavioral factors in the development of sex/gender difference in /s/ production.

1. Introduction

Phonetic variations have attracted considerable attention in recent years and their role in linguistic theory construction has shifted from peripheral to central (Beckman, Munson, & Edwards, 2007; Browman & Goldstein, 1992; Foulkes, 2010; Foulkes & Docherty, 2006; Goldinger, 1996; Johnson, 1997; Pierrehumbert 2001, 2003). Among different kinds of variations, those related to speaker sex/gender[1] have long been observed and robustly demonstrated. In particular, many studies have focused on vocal characteristics of human speech. Distinct acoustic differences exist between men and women with respect to voice pitch and timbre, as measured by fundamental frequency (f0) and formants respectively (i.e., Hillenbrand, Getty, Clark, & Wheeler, 1995; Peterson & Barney, 1952; Schwartz, 1968; Sachs, Lieberman, & Erickson, 1973). In general, women exhibit higher f0 and formant values than men. These differences were originally attributed to anatomical/physical differences in vocal apparatus between the two sexes as women have shorter vocal tracts and larynxes than men (Fitch & Giedd, 1999; Peterson & Barney, 1952; Rendall, Kollias, Ney, & Lloyd, 2005; Titze, 1994). However, recent studies have discovered that preschool children's voices already contain sex/gender-specific cues, despite the apparent lack of differences in vocal anatomy or physical size between boys and girls (Fitch & Giedd, 1999; Lee, Potamianos, & Narayanan, 1999; Perry, Ohde, & Ashmead, 2001).[2] In addition, children are able to act to speak like girls or boys by raising or lowering f0 and formant values of their natural speech (Cartei, Cowles, Banerjee, & Reby, 2014). Taken together, these studies suggest that sex/gender-related variations in voice are partly social in nature and that children are capable of manipulating

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[1] Following Van Anders (2015), we use the term “sex/gender” to underscore the intricate relationship and the complex interaction between biological and social influences in shaping children's development and the way they talk.

[2] These are English-speaking children. As the majority of the research on this topic is on English, all cited work discuss gender-related variation in English unless otherwise specified.

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these vocal cues to express their intended gender identity. These studies also suggest that the behavioral/social component of speech is semi-independent of and precedent to biologically-determined sex differences in vocal anatomy and physical size.

The current study focuses on a subtle but robust sex/gender-related speech variation: the acoustics of /s/ among English speakers, for which mounting evidence has demonstrated a clear difference between men and women, but the sources of variation are yet to be determined. Women have been found to produce /s/ with higher spectral frequencies than men and this acoustic difference is related to listeners' perceptions of speakers' sex and sexual orientiation (Fox & Nissen, 2005; Fuchs & Toda, 2010; Heffernan, 2004; Johnson, 1991; Linville, 1998; Munson, McDonald, DeBoe, & White, 2006; Schwartz, 1968; Strand, 1999; Stuart-Smith, 2007). When listeners are asked to judge speakers' sex based on isolated segments of /s/, they achieved a high accuracy of 93%, suggesting that this phoneme contains sex-identifying speech cues (Schwartz, 1968).

The sex/gender-related differences in /s/ production could have a biological foundation. The sound /s/ is created by forcing air to rapidly go through the narrow constriction formed by the tongue tip and the alveolar ridge. The spectral characteristics of /s/ are jointly determined by the geometry of the speaker's oral cavity downstream of the lingual constriction, the size and shape of the constriction, the relative position of the tongue tip and the upper incisors, and the configuration of the lips (McGowan & Howe, 2007; Shadle, 1991; Shadle, Proctor, & Iskarous, 2008; Shadle & Scully, 1995). Any sex dimorphic differences in these anatomical structures could potentially affect how differently /s/ could be produced between the two sexes.

Meanwhile, the behavioral/social nature of the sex/gender-related variation in /s/ has also been implicated by the majority of previous research. For example, Fuchs and Toda (2010) examined the acoustics and articulation of /s/ among a sample of English and German men and women. Although no significant sex difference was found with respect to palate length as measured via an artificial palate embedded with electrodes (electropalatography; EPG) molded for each participant, women of both language groups articulated /s/ with more anterior constrictions than did men and such constrictions were associated with higher spectral peaks when producing /s/. Moreover, the acoustic difference in /s/ between the two sexes remained significant after accounting for variations in palate length. The authors attributed the remaining difference to sociophonetic factors. Furthermore, when comparing Canadian-English and Japanese speakers, Heffernan (2004) found that women of both language groups produced a variant of /s/ with concentrations of energy at higher frequencies than did men, however, the sex gap was wider for English speakers than it was for Japanese speakers. The results were interpreted to illustrate a common biology-rooted universal tendency modified by cultural-specific contexts, which enhances the distinction in English and reduces it in Japanese.

The social factors are centrally implicated in sociophonetic grounded work and developmental research. For instance, in Glaswegian English-speaking adults, the degree with which the tongue tip advances during /s/ articulations has been shown to correlate with both speaker sex and social class (Stuart-Smith, 2007). Working-class women produce a more posterior variant of /s/ than those in middle-class, similar to men's /s/ articulation. Furthermore, research on pre-school and school-aged children has revealed a sex/gender-related bifurcation in the production of /s/ (Fox & Nissen, 2005; Flipsen et al., 1999) when no obvious between-sex anatomical differences were evident (Fitch & Giedd, 1999).

Notably, *within* sex/gender differences in /s/ production have also been found between children with and without Gender Dysphoria (GD; previously Gender Identity Disorder), as well as between adults with varying sexual orientation and gender identities. GD is characterized by strong and persistent cross-gender behavior and identity. Along with frequent gender nonconforming behaviors, boys with GD were found to speak in a less male-typical manner than boys without GD (Munson, Crocker, Pierrehumbert, Owen-Anderson, & Zucker, 2015; Zucker & Bradley, 1995). In particular, children with GD were found to exhibit extreme frontal constriction when articulating /s/ that, at times, may be perceived as a /s/-to-[θ] misarticulation. The extreme frontal articulation of /s/ also characterizes stereotypical gay speech in adults, known as lisping, which can serve as a cue for naïve listeners to identify an individual's sexual orientation status (e.g., status as a gay man) and gender identity status (status as a [male-to-female] transgender women) (Munson, Jefferson, & McDonald, 2006; Van Borsel et al., 2009; Zimman, 2013). Zimman (2013) examined the speech patterns of five (female-to-male) transgender men who had received testosterone therapy. Although their voice pitch was indistinguishable from that of straight men, their /s/ production was fronted, toward a female-typical pattern of articulation. Given the link between childhood gender-(a)typical behavior and adult sexual orientation (see Bailey & Zucker, 1995; and Lippa, 2005), these studies together lend strong support to the social root of gender-related variation in /s/ and the mediating role of gender identity in expressing this phonetic variation.

However, to our knowledge, the connection between sex/gender-related variation in /s/ and speakers' gender identity has never been explicitly tested among normal developing children. In addition, most previous studies (particularly those pertaining to children and clinical populations) have not included measures of speakers' physical size. Thus biological factors may confound the results and, because of this, the exact contribution from the two sources (bio-anatomical vs. social-behavioral) remains unknown. Our study sought to fill in these gaps. The objectives of the present study were three-fold. First, as the initial step of our study, we were to confirm previously established sex/gender-differences in acoustic dimensions of /s/ in Canadian-English speaking children. Gendered /s/ fricative production has been reported in adult speech in many varieties of English, including American English (Flipsen et al., 1999; Fox & Nissen, 2005; Munson et al., 2006), Scottish English (Fuchs & Toda, 2010; Stuart-Smith, 2007), and Canadian English (Heffernan, 2004), but its existence in Canadian-speaking children is yet to be confirmed. Second, after verifying this sex/gender-related variation in children's speech, we aimed to identify whether gender identity mediates this variation in children of different age groups. Third, we aimed to examine whether biological factors also contributed to variations in acoustic dimensions of /s/.

The first three moments in spectral moments analysis were computed to evaluate acoustic variation in the fricative /s/. This technique has been extensively used in fricative description of both adult and children's speech (Forrest, Weismer, Milenkovic,

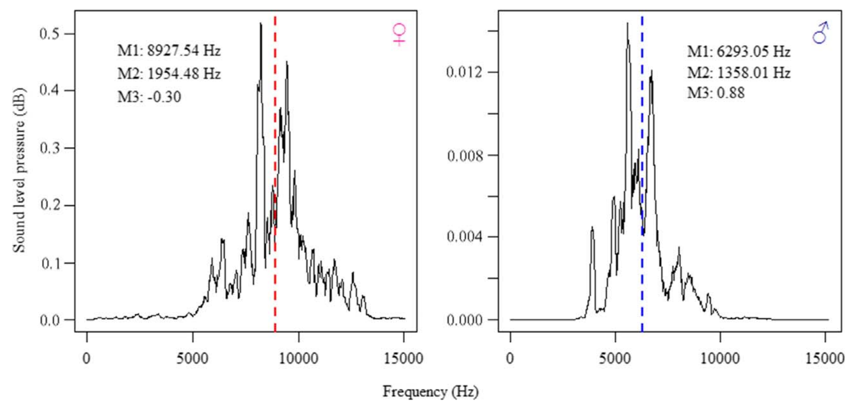

Fig. 1. Spectrum of /s/ slice extracted from the word *soup* produced by a female speaker (left) and a male speaker (right). Values of the three spectral measures, M1, M2, and M3, were indicated on the graph. The values of M1 were also indicated by the dotted lines. The figures only display the frequency range up to 15,000 Hz, which contains the majority of the energy distribution.

& Dougall, 1988; Koenig, Shadle, Preston, & Mooshammer, 2013; Nittrouer, 1995; Shadle & Mair, 1996). These acoustic measures, particularly the first and the third moment, have been shown to be sensitive to speaker sex/gender (Flipsen, Shriberg, Wismer, Karlsson, & McSweeny, 1999; Fox & Nissen, 2005; Fuchs & Toda, 2010; Heffernan, 2004; Stuart-Smith, 2007). The first moment was the weighted spectral mean frequency (hereafter M1), which measures the central tendency of the energy distribution pattern in the fricative spectra. M1 is affected by airflow velocity, lip rounding, and, most importantly, the length of the oral cavity in front of the narrowest constriction (Forrest et al., 1988; Fuchs & Toda, 2010; Shadle, 1991; Shadle et al., 2008). Thus, when the first two factors are held constant (i.e., airflow velocity and lip rounding), M1 is negatively correlated with the length of the oral cavity, and is indicative of the relative tongue tip position in the oral cavity when making the constriction (Fox & Nissen, 2005; Fuchs & Toda, 2010; Heffernan, 2004; Nittrouer, 1995; Stuart-Smith, 2007). This link between M1 and the relative tongue constriction position in the oral cavity has been clearly demonstrated in Fuchs and Toda (2010), which revealed that higher M1 values were associated with more anterior constrictions during the articulation of /s/ in English-speaking adults using EPG. In fact, higher M1 values in women's /s/ production and the lower values in men's have marked the major sex/gender difference in /s/ production in the sociolinguistic literature (Fox & Nissen, 2005; Fuchs & Toda 2010; Heffernan, 2004; Munson et al., 2006; Stuart-Smith, 2007).

The second moment is the standard deviation of fricative spectra (M2 hereafter), which characterizes how diffuse/compact the shape of spectral energy distribution is. M2 is sensitive to the size and shape of the lingual constriction in fricative production and is a critical measure distinguishing /s/ and /θ/ (Baum & McNutt, 1990; Jongman, Wayland, & Wong, 2000). Compared to /s/, which actively involves the tongue tip in the constriction, the greater contact area during the production of /θ/ leads to a more diffuse spectral shape, giving rise to a higher value of M2 (Baum & McNutt, 1990; Jongman et al., 2000; Maniwa, Jongman, & Wade, 2009). M2 is not an acoustic measure that has figured prominently in previous research on sex/gender-related difference in /s/, but the recent study by Munson et al. (2015) discovered the utility of M2 in separating boys with and without GD. In particular, boys with GD are more likely to articulate /s/ with higher M2 values, causing it to be more confusable to /θ/.

The third moment is spectral skewness (hereafter M3). M3 represents the broader shape of the spectrum as well as the degree to which it is balanced or skewed (Forrest et al., 1988; Shadle & Mair, 1996). Higher values of M3 indicate greater amount of energy below the spectral mean than above it and is perceptually associated with more masculine speech. Relatively low values of M3 have been reported for the speech patterns of gay men (Munson, Jefferson, et al., 2006; Munson, McDonald, et al., 2006). The values of M3 can be positive or negative as it is calculated by taking the difference between the energy below the spectral mean and that above the mean. Fig. 1 illustrates the sex/gender differences for all three moments in /s/ spectrum using an example of a single /s/ production from a woman and a man, respectively. As demonstrated in the figure, men have relatively lower M1 and M2, and higher M3 while the opposite is true for women. The directions of sex/gender differentiation in the three acoustic dimensions are in line with previous research (Fox & Nissen, 2005; Stuart-Smith, 2007).

2. Methods

2.1. Participants

Children aged 4–16 years old were recruited through fliers distributed to elementary schools, libraries, recreational facilities, and grocery and toy stores within southern Alberta. All participants had been residents of southern Alberta for the majority of their lives, had the same regional dialect, were monolingual English speakers, and had no known developmental or cognitive disabilities, nor any speech, language or hearing problems, according to parental report. Demographic data were collected from parents to ensure that children participating in the study met the above requirements. In total, 152 children participated in the study. These children were divided into three age groups based on developmental stages: 4–7 years old (early childhood), 8–11 years old (middle childhood), and 12–16 years old (adolescence). Additional details concerning the number and sex of participants are provided in Table 1.

Table 1
Breakdown of participants in each age and sex group. Information of mean age (in months) and standard deviation (in parenthesis) are also included.

Age group	*Total number of participants*	*Mean Age (in months)*	*Number of girls*	*Number of boys*
4∼7 years	$N=67$	71.2 (14.8)	$N=36$	$N=31$
8∼11 years	$N=44$	112.5 (13.0)	$N=24$	$N=20$
12∼16 years	$N=41$	172.3 (15.0)	$N=20$	$N=21$

2.2. Procedure

Children were recorded individually in a quiet room while seated in front of a computer monitor displaying a series of objects with names beginning with the /s/ sound and other distractor words. The target words were *salad, salmon, sandwich, seahorse, seal, seat, soup, suit,* and *suitcase.* Images of these objects were displayed on the screen to serve as visual prompts. The elicitation procedure was facilitated by a program called "Show and Play" that has been used successfully in similar research on young children (Edwards & Beckman, 2008; Li, 2012). This program adds an image of a duck climbing a ladder on the left margin of the screen. Children were told that the duck would climb one step every time they spoke a word and their task was to help the duck climb to the very top of the ladder. Children's speech was recorded using a digital recorder (Marantz PMD 661) connected to a Shure SM87A condenser microphone placed directly in front of them approximately 20 cm from their mouth. Recordings were made using a 44.1 kHz sampling rate and 16-bit quantization. Adolescents were given the same task to ensure consistency with young children, but they were aware of the playful nature of the task and understood that the task was designed to accommodate the needs of younger participants.

Children's height was measured in centimeters by having them stand flatfeet against a metal tape on the wall. We used body height as a measure of anatomical structure. Body height served as a proxy for children's vocal tract length, with the assumption that height and vocal tract size are proportional. Gender identity was assessed using a 12-item Childhood Gender Identity Questionnaire (CGIQ; Johnson et al., 2004) that characterizes male-typical and female-typical behavior. CGIQ has been used previously when interviewing parents about their child's behavior (Johnson et al., 2004; Cohen-Kettenis et al., 2006) and has also been used to measure childhood-gendered behavior retrospectively from adulthood (Bartlett & Vasey, 1996; VanderLaan, Gothreau, Bartlett, & Vasey, 2011; VanderLaan, Petterson, & Vasey, 2015). In CGIQ, questions range from how the child prefers to play at home, the kind of games they play, and the toys they prefer, to whether they prefer male or female company. Parents completed the questionnaire during the child's visit to the lab. When completing the questionnaire, parents were asked to indicate how often each specific behavior occurred. For children younger than age 12, parents were asked to rate how frequently this behavior occurred in the past six months. For adolescents, parents were asked to retrospectively rate how frequently this behavior had occurred during childhood. Parents' responses were subsequently recoded on a 5-point Likert scale by converting the frequency scale to a gender-typicality scale (1=extremely masculine; 5=extremely feminine). An average gender typicality score was calculated for each child.

As a test of questionnaire validity, a subset of children in the 4–7 age group ($n=60$) were given an additional free-play task that provided an independent measure of their gender identity (Jürgensen, Hiort, Holterhus, & Thyen, 2007). This free-play session followed the voice recording and was conducted in a separate room. The room was filled with 23 toys each one rated on a 5-point Likert scale for gender typicality (1=extremely masculine; 5=extremely feminine). The toys included but are not limited to such items as army toys (rated 1), a sports sticker book (2), a Winnie the Pooh puzzle (3), a kitchen set (4) and a princess dress-up set (5). Gender-rating scores for each toy were determined by averaging judgments provided by 20 college-aged students. Children were invited to play alone in the room for 10 minutes. During this time, they were observed from an adjoining room through a one-way glass and the amount of time they spent playing with each toy was recorded. Children's toy preference was coded on a 5-point Likert gender-typicality scale (1=extremely masculine; 5=extremely feminine). An average gender typicality score was calculated for each child. Thus, individual participants received a gender identity summary score (from 1 to 5) for each measure of gender identity with higher values indicative of a more feminine profile.

2.3. Acoustic analysis

During analysis, boundaries for /s/ were identified and labeled using Praat (Boersma & Weenink, 2005). The beginning of the frication was defined as the time point when significant increases in amplitude, both in the waveform and in the spectrum, were present. The end of the frication was defined as the time at which arrhythmic noise subsides and the glottal pulses in the following vowel initiated. Once the beginning and the end of frication were marked, sound segments were extracted and stored as separate sound files and were further processed through the Multitaper package (Rahim, 2010) in R (R Development Core Team, 2011). A spectrum was then made for a 40-ms window extracted from the middle of each sibilant /s/ sound, from which the first three moments were calculated. The spectra were high-pass filtered for energy above 1000 Hz (the low-frequency cut-off) to eliminate potential background noise. The high-frequency cut-off is 22,050 Hz. A total of 1368 (152 children * 9 word tokens) measurements were made for each acoustic parameter.

2.4. Statistical modeling

First, we employed linear mixed effects models to test the previously-reported sex/gender differences in /s/ acoustics in children's speech. For each model, the acoustic values of individual acoustic parameters (i.e., M1, M2, or M3) served as the dependent variable. Children's sex (boy vs. girl), age (in months), and the interaction between the two were included as independent fixed effects variables. Speaker and vowel context (nested under speaker, three levels: /i/, /æ/, and /u/) were included as random effects.

Upon confirmation of significant sex/gender difference in each acoustic dimension, an additive mediation model was adopted to explicate the relationship between gender identity and sex/gender-related /s/ acoustics, in which a base model was constructed by correlating variation in /s/ production solely with children's sex. Following this, other potential explanatory variables, including age, measures of physical growth, and gender identity, were added to the model successively. The variable that was able to significantly reduce the sex gap in the production of /s/ acoustics was assumed to mediate this sex/gender difference. The method of additive modeling has been used frequently in social science research evaluating sex/gender differences and has proved to be effective in explaining the underlying mechanisms for sex/gender-related phenomenon (e.g. depression differences: Goodwin & Gotlib, 2004; longevity differences: Rogers, Everett, Onge, & Krueger, 2010). In the present study, the dependent variable was one of the three acoustic dimensions of /s/ for each model. The independent fixed effects variables were sex (base model, Model 1), age (added in Model 2), height (added in Model 3), and the CGIQ measure of gender identity (added in Model 4). The independent random effects were speaker and vowel context, with vowel nested under speaker. All statistical calculations were carried out in R (R Development Core Team, 2011) using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2013).

Finally, within-sex/gender correlation analysis was carried out between each of the acoustic parameter and the CGIQ scores for boys and girls, respectively. By running the correlational analysis separately for each sex, we were able to determine whether gender identity was relevant to within-sex/gender variation. Acoustic measurements for multiple tokens were averaged to yield a single value per acoustic dimension for each child, which was then correlated with his or her CGIQ gender identity score.

3. Results

3.1. Basic statistical patterns

3.1.1. Sex/gender differences in parameters of /s/ acoustics

Table 2 displays the mean (and standard deviation) values for the individual acoustic parameters of /s/, speaker gender identity, and physical height by age and sex group. Girls tended to have higher M1 and M2 values and lower M3 values than boys, and the difference became more pronounced with the increase in participants' age. Such sex/gender-related differences in the three acoustic parameters were consistent with previous research on both children and adults (Flipsen et al., 1999; Fox & Nissen, 2005; Fuchs & Toda, 2010; Munson et al., 2015; Stuart-Smith, 2007).

A significant interaction between speaker sex and age was found for M1 ($p = .003$) and M3 ($p = .007$). A main effect of age was found for M2 ($p < .001$). The interaction effect for M1 and M3 and the main effect of M2 are shown in Fig. 2. For both M1 and M3, clear differentiation between the two sexes was evident as early as 52 months, as indicated by the divergence of the two regression lines and 95% confidence interval area fitted to each sex group. The sex gap was shown to increase with age. For M2, girls generally had higher values than boys, but the difference stayed fairly constant across age, with M2 values for both sexes declining with age.

3.1.2. Sex/gender differences in behavior and physical growth

Girls exhibited higher CGIQ scores than boys and this difference remained constant across age groups, in accordance with previous studies that have reported stable differentiation in sex/gender-typed behavior throughout childhood (Cohen-Kettenis et al., 2006; Johnson et al., 2004; also see a review in Steensma, Kreukels, de Vries, & Cohen-Kettenis, 2013). CGIQ scores were significantly correlated with gender typicality scores from the free-play task for the youngest age group ($r = .78$, $p < .001$), demonstrating the validity of the CGIQ score in capturing children's gender identity. In addition, boys and girls demonstrated

Table 2
Means (and standard deviations) of /s/ acoustics, speaker gender identity, and physical height for participants in each age and sex group.

Age	Sex	/s/ acoustics			Sex/gender-typed behavior		Body size
		M1 (Hz)	M2 (Hz)	M3	CGIQ	Free play	Height (cm)
4∼7	Girls	7397.06 (1133.97)	2312.97 (764.03)	−0.17 (0.69)	3.84 (0.48)	3.71 (0.86)	116.12 (13.95)
	Boys	6687.26 (868.52)	2118.45 (591.06)	0.46 (0.70)	2.10 (0.44)	2.09 (0.82)	120.60 (9.71)
8∼11	Girls	7718.20 (1048.01)	2259.33 (682.52)	−0.08 (0.57)	3.74 (0.33)	NA	137.52 (7.81)
	Boys	6555.98 (737.75)	1868.36 (516.66)	0.74 (0.72)	1.93 (0.33)	NA	139.71 (9.93)
12∼16	Girls	8137.94 (1048.01)	2012.25 (557.93)	−0.30 (0.70)	3.66 (0.39)	NA	163.71 (7.42)
	Boys	6471.47 (934.59)	1661.46 (350.54)	0.85 (0.92)	2.25 (0.51)	NA	172.86 (7.50)

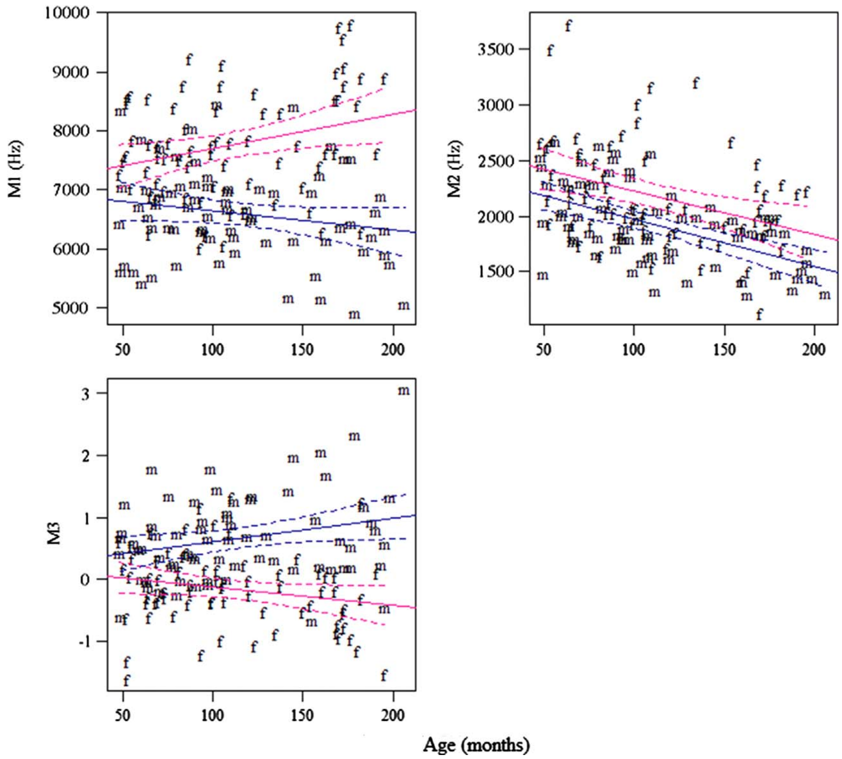

Fig. 2. Scatterplot for the relationship between age (months) and the acoustic measurements (M1, M2, and M3). Solid lines are the best fitted lines regressing each of the acoustic parameter on age, and dotted lines mark the 95% confidence interval of the regression model. Pink lines are for females and blue lines are for males. Speaker sex was represented with "f" for females/girls and "m" for males/boys.

comparable physical growth with significant sex differentiation emerging in adolescence (4∼7: $t=-.79$, $p=0.44$; 8–11: $t=-.49$, $p=.62$; 12∼16: $t=9.16$, $p=.03$).

3.2. Additive mediation models

3.2.1. Additive mediation models for children of all ages

We further investigated the relationship between gender identity and sex/gender-related /s/ acoustics using the additive mediation models. As mentioned previously, one additive model was constructed for each acoustic dimension (each containing four successive steps/models). A variable may be shown to mediate the relationship between gender identity and /s/ production if its inclusion into the model significantly reduces the sex/gender gap in the acoustic parameters of /s/, as evidenced by a significant reduction in the magnitude of difference between coefficients. Coefficients of the additive mediation models for sex/gender-related variation measured by each of the three acoustic dimensions (i.e., M1, M2, and M3) are presented in Table 3.

With respect to the first acoustic dimension, M1, the baseline model revealed a significant sex/gender difference. Girls' mean M1 value for /s/ production was 1170.87 Hz higher than that of boys. The significant sex/gender difference held in both Model 2 and in Model 3. Neither age nor height was shown to diminish the sex gap of M1. However, in Model 4, when CGIQ was included along with the other three fixed effects variables, the sex gap was reduced by nearly half (652.20 Hz in Model 4 vs. 1184.30 Hz in Model 3). This result indicates that girls produce /s/ with a M1 value 1184.30 Hz higher than that of boys, but 532.10 Hz (1184.30-652.20) of such difference is due to gender identity difference between boys and girls.

Meanwhile, the predictor CGIQ was shown to be significant to the overall model ($p=.038$) with a coefficient of 322.01 Hz, suggesting that one unit of increase in CGIQ score is associated with an increase of 322.01 Hz in the M1 value of children's /s/ production. As higher CGIQ scores indicate more girl-typical behaviors, and higher M1 values correspond to more female-typical speech patterns, this result reveals the congruence between sex/gender-typed behavior and sex/gender-typed speech production in our participants.

Similar results were obtained for acoustic parameters M2 and M3. For M2, the baseline model demonstrated a significant sex/gender difference. Girls' mean M2 value for /s/ production was 284.03 Hz higher than that of boys. The significant sex/gender difference held in both Model 2 and Model 3. However, in Model 4, when CGIQ was included along with the other three fixed effects variables, the sex/gender difference was reduced to -4.93 Hz and was no longer significant, suggesting that the sex/gender difference in M2 can primarily be attributed to variation in gender identity. In addition, CGIQ is the only significant predictor in Model 4 with a coefficient of 166.63 Hz. This suggests that one unit of increase in CGIQ score will lead to an additional 166.63 Hz in M2. Because greater M2 values correspond to more diffuse spectral shapes of /s/, which is characteristic of female speech, this result again demonstrates the consistency between sex/gender typed behavior and sex/gender-specific speech pattern.

Table 3
Coefficients of the Linear Mixed Effects models for sex/gender-related variation measured by each of the three acoustic dimensions (i.e., M1, M2, and M3). The random effects are participant and vowel environment (nested under participant). For each acoustic dimension, Model 1 is the base model with only one fixed effect variable, which is speaker sex. From Model 2 to 4, age, height, and CGIQ scores were successively added to the model.

Dependent variable	Independent variable	Model 1	Model 2	Model 3	Model 4
M1 (Hz)	Sex (1 = female)	1170.87***	1171.89***	1184.30***	652.20*
	Age (months)		0.82	−0.78	0.02
	Height (cm)			3.19	1.82
	CGIQ (1∼5)				322.01*
M2 (Hz)	Sex	284.03***	282.23***	273.95***	−4.93
	Age		−3.67***	−2.17	−1.82
	Height			−3.05	−3.64
	CGIQ				166.63*
M3	Sex	−0.71***	−0.71***	−0.71***	−0.39†
	Age		0.01	−0.01	−0.01
	Height			0.01	0.01
	CGIQ				−0.19†

† $p \leq 0.10$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

For M3, the baseline model demonstrated a significant sex/gender difference. Girls' mean M3 value for /s/ production was lower than that of boys (difference value of −.71). This significant sex/gender difference held in both Model 2 and Model 3. However, in Model 4 the sex/gender difference is diminished to −0.39 and was no longer significant, suggesting that, similar to M1 and M2, the sex/gender difference in M3 could primarily be attributed to variation in gender identity. CGIQ is marginally significant in Model 4. This suggests that there exists a trend for CGIQ to contribute to M3 in /s/ such that one unit of increase in CGIQ results in a decrease of 0.19 in the M3 value, a more female-typical pattern. Therefore, for all three acoustic parameters examined, CGIQ is the only predictor that significantly closes the sex gap in our sample. CGIQ is also the only predictor that significantly correlates with /s/ acoustics in the predicted direction of gender-typicality.

3.2.2. Additive mediation models for children of each age group

Given the interaction between children's age and sex in affecting /s/ productions, the additive models for each acoustic parameter were constructed for children of different age groups to determine whether gender identity plays a similar mediating role in /s/ productions across developmental stages. Coefficients of the additive mediation models for sex/gender-related variation measured by each of the three acoustic dimensions for each age group are presented in Table 4. For all three acoustic parameters (M1, M2, and M3), the adolescent group exhibited the greatest sex/gender difference in /s/ production, while the early childhood group exhibited the smallest difference. For children aged 4–7, girls' mean M1 values were 881.70 Hz higher than boys. This difference increased to 1132.57 Hz for children aged 8–11, and to 1595.98 Hz for adolescents. However, even for children in the youngest age group, the sex/gender difference was statistically significant. For children of all three age groups, the significant sex/gender difference persisted when age and height were added to the model, but the significant difference disappeared once CGIQ was entered. These findings suggest that sex/gender differences in M1 can mainly be attributed to variation in gender identity, regardless of developmental stage. The results for M3 were similar to those of M1. Once CGIQ was entered into the overall model, the baseline significant sex/gender difference no longer remained, while entering age and height into the model did not have such an effect on the sex/gender difference.

For M2, significant sex/gender differences existed in the two older age groups, but no significant sex/gender difference was observed in the youngest group. Nonetheless, for the two older age groups, while the addition of age and height into the model had some influence on the sex/gender difference in the M2 parameter of /s/, the inclusion of CGIQ into the model significantly reduced the M2 sex/gender difference. Therefore, CGIQ was, again, shown to serve as the crucial mediator for sex/gender-related difference in M2. Taken together, gender identity appears to be the determining factor for the sex/gender difference for all three acoustic dimensions examined and for children of all age groups, except for the M2 parameter in the youngest group. It is, additionally, worth noting that height is an important predictor in the mid childhood model ($p = 0.03$). However, the inclusion of height in the model does not significantly close the sex/gender gap. Therefore, although height affects M3 values in /s/, it contributes to the part of M3 variation that is independent of speaker sex.

It is also worth noting that CGIQ plays an increasingly significant role in mediating sex/gender difference in M1. The coefficient of CGIQ rises from 102.03 Hz in the youngest age group to 660.67 Hz in the mid age group, and finally to 777.97 Hz in adolescents. This result indicates that with one-unit of increment of CGIQ score, it is associated with an increment in M1 of 777.97 Hz in adolescents, while a similar scale of change in CGIQ only results in an increment of 102.03 Hz in children aged 4 to 7 year olds. However, the increasingly important involvement of CGIQ observed in M1 is less evident in the dimensions of M2 and M3, which suggests that gender identity (as measured by CGIQ) mediates the sex/gender related variation of different aspects of /s/ acoustics to varying degrees.

Table 4
Coefficients for the additive Linear Mixed Effects models constructed for each acoustic dimension and for each age group.

Age group	Independent variable	Model 1	Model 2	Model 3	Model 4
a) Dependent variable: M1					
Early childhood (4–7 years old)	Sex	881.70***	880.14***	892.43***	715.79†
	Age		−0.67	−3.95	−3.72
	Height			5.78	5.77
	CGIQ				102.03
Mid childhood (8–11 years old)	Sex	1132.57***	1137.39***	1122.71***	−51.25
	Age		−8.30	0.32	−1.35
	Height			−28.07†	−27.29†
	CGIQ				660.67*
Adolescence (12–16 years old)	Sex	1595.98***	1542.61***	1860.52***	722.26
	Age		−7.74	−15.58	−9.54
	Height			34.89	24.63
	CGIQ				777.97*
b) Dependent variable: M2					
Early childhood (4–7 years old)	Sex	157.33	155.56	143.60	−310.95
	Age		−7.33	−0.08	0.30
	Height			−6.64	−6.68
	CGIQ				260.47*
Mid childhood (8–11 years old)	Sex	393.45**	389.49**	392.36**	264.04
	Age		−8.30	−8.29	−8.41
	Height			2.66	2.85
	CGIQ				70.94
Adolescence (12–16 years old)	Sex	342.41**	333.77**	325.50*	157.81
	Age		−1.89	−1.66	−0.92
	Height			−0.92	−2.36
	CGIQ				112.24
c) Dependent variable: M3					
Early childhood (4–7 years old)	Sex	−0.45***	−0.44***	−0.44**	−0.19
	Age		0.01	0.01	0.01
	Height			−0.01	−0.01
	CGIQ				−0.14
Mid childhood (8–11 years old)	Sex	−0.74***	−0.74***	−0.72***	−0.85†
	Age		−0.01	−0.01	−0.01
	Height			0.03*	0.03*
	CGIQ				0.07
Adolescence (12–16 years old)	Sex	−1.05***	−0.99***	−1.26***	−0.81†
	Age		0.01	0.02*	0.01†
	Height			−0.03†	−0.03
	CGIQ				−0.30

† $p \leq 0.10$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

3.3. Within-sex correlation analysis between /s/ acoustics and CGIQ

Correlational analyses were conducted to further investigate the relationship between gender identity and sex/gender-related /s/ acoustics within each sex category. When all age groups were combined, CGIQ was not significantly correlated with M2 for either sex. However, CGIQ was marginally and significantly correlated with M1 and M3 respectively for boys (M1: $p=0.06$; M3: $p=0.03$), but not for girls (M1: $p=0.59$; M3: $p=0.34$). In addition, for boys, the correlation between CGIQ and acoustic parameters M1 and M3 were most prominent in the adolescent group (M1: $p=.003$, $r=.61$; M3: $p=.018$, $r=-.05$). For adolescent boys, CGIQ was significantly positively correlated with M1 and significantly negatively correlated with M3 (as illustrated in Fig. 3). Importantly, this correlation pattern was consistent with our prediction that higher CGIQ scores (which are indicative of greater female-typical behavior) would correspond to higher M1 values but lower M3 values. Furthermore, for the M1 and M3 parameters, CGIQ was able to account for at least 25% of the total variation, suggesting the non-negligible involvement of gender identity in within-sex differentiation of /s/ acoustics for boys.

Finally, to identify which behavior was most closely related to differences in /s/ acoustics for adolescent boys, correlations were conducted between each of the three acoustic dimensions and the individual items of the CGIQ. As shown in Table 5, sex/gender-(a) typical /s/ parameter values were most strongly linked to playmate selection, choice of toys, and gender role modeling. More female-typical behavior items (items 2, 4, 5, 10) were associated with the acoustic parameters of /s/ than male-typical behavior items (item 11).

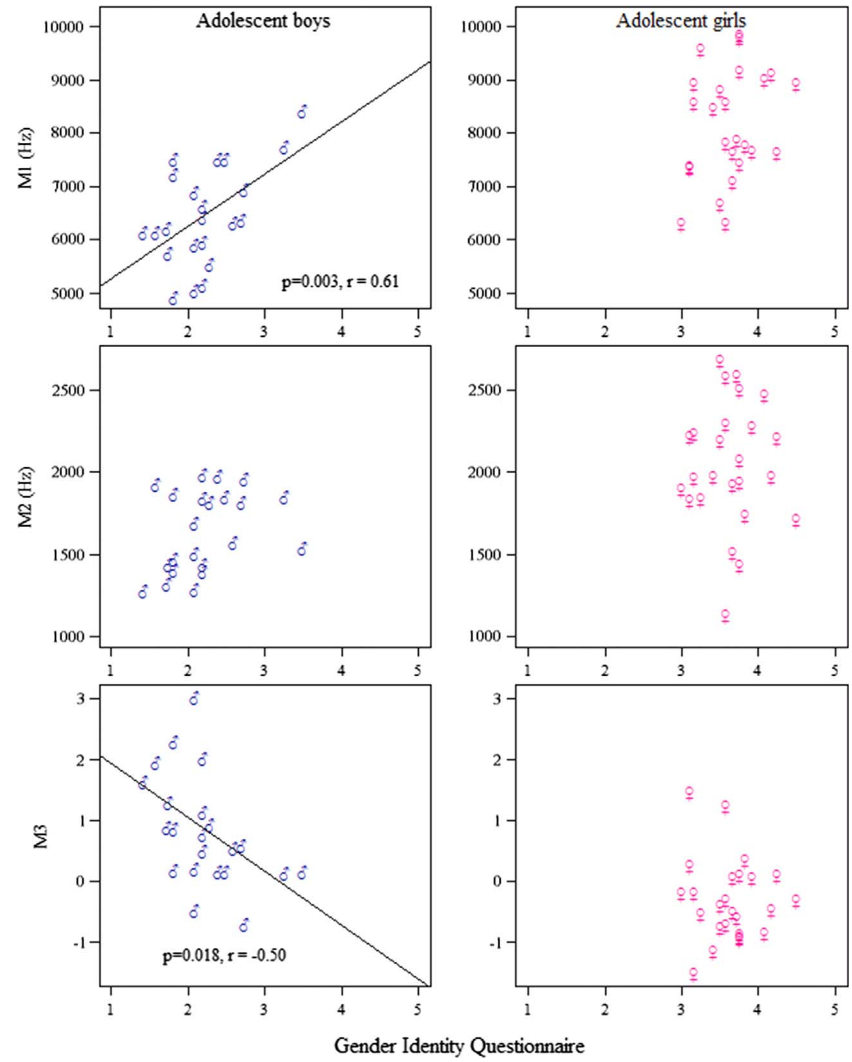

Fig. 3. Scatterplot for the relationship between each acoustic dimension of /s/ (i.e., M1, M2, and M3) and CGIQ scores for adolescent boys and girls.

Table 5
Correlation coefficients between the rating for each question in the CGIQ questionnaire and the acoustics of /s/ for adolescent boys and girls.

	M1		M2		M3	
	Boys	Girls	Boys	Girls	Boys	Girls
1. Favorite playmates are (boys: 1 vs. girls: 5)	0.60**	0.21	0.22	−0.27	−0.38	0.09
2. Plays with girl-type dolls, such as “Barbie”	0.44*	0.38	0.22	0.03	−0.45*	−0.19
3. Plays with boy-type dolls, such as “G.I. Joe” or “Ken”	0.09	0.10	0.01	−0.14	−0.13	0.08
4. Experiments with cosmetics and jewelry	0.49*	0.22	−0.11	−0.16	−0.17	0.09
5. Imitates female characters seen on TV or in the movies	0.54*	0.22	0.30	−0.13	−0.36	0.02
6. Imitates male characters seen on TV or in the movies	0.05	−0.38	0.02	0.05	−0.08	0.30
7. Plays sports with boys	0.34	−0.07	0.44*	−0.07	−0.34	0.09
8. Plays sports with girls	0.07	0.07	−0.13	−0.04	0.17	−0.16
9. In playing “mother/father”, “house”, or “school” games, the child take the role of	0.34	0.02	0.45	0.23	−0.30	0.13
10. Plays “girl-type” games such as “princess”	0.51*	0.33	0.03	0.11	−0.32	−0.38
11. Plays “boy-type” games such as “weapons”	−0.60**	−0.32	0.31	0.13	0.60**	0.09
12. In dress-up games, your child likes to dress up as (men: 1 vs. women: 5)	0.78*	−0.24	0.16	0.28	−0.71*	0.29

4. Discussion

Despite mounting reports which have described the specific sex/gender differences in /s/ acoustics and articulations, how such a sex/gender-specific speech pattern comes about in children and what triggers the differentiation process remain largely speculative (Fuchs & Toda, 2010; Heffernan, 2004; Stuart-Smith, 2007). The present study sought to address this by examining the relative contribution of biological and social factors in shaping sex/gender-related variation of /s/. The present study first replicated the finding that sex/gender-specific /s/ productions arise in early childhood and persist into later childhood and adolescence (i.e., Flipsen et al., 1999; Fox & Nissen, 2005). Specifically, we replicated the finding that girls' /s/ production is characterized by higher M1 and M2 values and lower M3 values, which suggest the /s/ is fronted. The important and unique contribution of the present study to the existing literature is the finding that gender identity played a greater role in differentiating acoustic dimensions of /s/ than did age or height. It should be noted that the congruence that was found between sex/gender-typed speech articulation (as in the case of /s/) and children's gender typed behavior (as measured by the gender identity questionnaire) underscores the social nature of speech production. That is, speech production could be part of a package of behaviors that children learn to utilize in conveying their personal and gender identity.

The selection of /s/ as a socially-determined sex/gender marker may not be accidental. As mentioned previously, the articulation of /s/ mainly involve muscular structures that can be modified. Sex-gender difference in /s/ production can be achieved by manipulating the tongue and by positioning the tongue tip in different locations in the oral cavity, and therefore represents an articulatory gesture that can be learned. Such learning can take place as a result of differential input that boys and girls receive. In an investigation of the gender-marking aspect of the phoneme /t/ in Newcastle English, mothers were found to address to boys using more of the nonstandard variants of /t/, but addressed girls using the standard form (Foulkes, Docherty, & Watt, 2005). It is entirely possible that English speaking parents similarly address boys and girls with different variants of /s/. An investigation of the /s/ characteristics of child-directed speech is certainly warranted and will help identify what specific social mechanism enables the transmission of this gender-specific phonetic variable.

Additionally, learning to produce different variants of /s/ can take place when a child is attempting to model a particular adult role model or conform to a peer group. Adults utilize different speech styles to indicate their affiliation to certain social groups (Eckert & Mcconnell-Ginet, 1999; Pierrehumbert, Bent, Munson, Bradlow, & Bailey, 2004). In addition, developmental research has found that children selectively allocate attention to information providers and the extent to which a child will pay attention to these individuals depends crucially on the relationship between the child and the information provider. Children learn best from people they trust, are familiar with, or who speak the same language with them (Corriveau & Harris, 2009; Kinzler, Corriveau, & Harris, 2011). Therefore, children put more weight on the input they receive from people they identify with, and their learned speech style could, in turn, serve as a way to express their group membership.

Meanwhile, it is interesting to note that, while gender identity accounts for a significant portion of the within-sex variation of /s/ for adolescent boys, the same is not true for adolescent girls. It is possible that such within-sex differentiation occurs later in girls. Or alternatively, the asymmetry of within-sex correlations between speech acoustics and gender-typicality for the two gender groups could suggest that adolescent boys attach more social meaning to /s/ than do girls. It is also possible that, because phonetic variation in /s/ production is linked to adult sexual orientation in men but not women, /s/ production is predominantly a marker of gender expression for only boys (Mack & Munson, 2012; Munson et al., 2006; Zimman, 2013). In addition, the misarticulation of /s/ to [θ] is frequently noted in prepubertal boys with Gender Dysphoria (Munson et al., 2015). Together, this evidence suggests that socialization may not have the same influence on speech development for the two sexes.

Finally, it is important to understand that the present findings should not be taken as completely discounting the relevance of biology in constraining or enabling children's formation of sex/gender-specific speech. The possibility exists that although social processes give rise to gender differences in /s/, these social processes elaborate on sex-typed biological predispositions. It has been shown that biological predispositions interact with parental input and social expectations and both contribute to the development of gender (Serbin, Powlishta, Gulko, Martin, & Lockheed, 1993). For example, the more effeminate a girl behaves, the more parents and other adults use soft-spoken language when addressing her, and the more she can reflect feminine-typical speech in her own speech production (Eccles, Jacobs, & Harold, 1990; Snow, Jacklin, & Maccoby, 1983). Therefore, it is unlikely that the development of sex/gender differences in /s/ can be solely attributed to either biological or social factors in isolation. Instead, both forces are likely to interact in complex ways which lead to the differentiation of /s/ in children.

4.1. Limitations and future direction

Firstly, representing an initial attempt bridging speech articulation with anatomical and gender development, our study is limited in several ways. First, our findings are based on children's performance in a laboratory setting and may not fully capture the dynamic use of /s/ in conveying gender identity. An individual's identity is multi-faceted: people project varying aspects of their identity (i.e., persona) to satisfy distinct social goals through the selective use of linguistic variables (Cartei et al., 2014; Podesva, 2007). Future studies would benefit by identifying the degree to which certain tasks invoke gender norms and the extent to which this, in turn, elicits intra-child variation on linguistic tasks. In addition, parents may have biased their response to the questionnaire items pertaining to their child's gender-type behavior because they hold certain attitudes or expectations about their child's gender presentation. Furthermore, it could be argued that the adolescents tested were engaged in a slightly different task to what the younger children were doing, because adolescent parents recalled their children's gender-typed behaviors in a longer time frame than parents of the younger children. Therefore, more implicit measures of children's gender identity are needed to verify our current results in the future.

Secondly, in the present study, vocal tract length was inferred from overall body size. This measure assumes that vocal-anatomical growth scales proportionally to physical structures during maturation. However, such an assumption may not hold completely. An imaging study of vocal anatomy of 605 individuals from birth to 19 years revealed that the oral cavity follows a growth schedule similar to that of neural structures (i.e., head and neck), such that 80% of maturation is completed before early childhood and is followed by a much slower growth rate to adulthood (Vorperian et al., 2009). In contrast, the pharyngeal cavity of the vocal tract displays a different developmental curve, resembling the growth pattern of body stature (i.e., height) and exhibits relatively evenpaced growth rate to adulthood. This finding is relevant because the source of the /s/ sound articulation is the resonance of the cavity in front of the constriction (ranging approximately from the tongue tip to the teeth). The geometry of this cavity determines the spectral profile of the /s/ sound. Direct measurement of children's oral cavity length through non-invasive techniques such as fMRI will be necessary to verify the absence of contributions from anatomical structures.

4.2. Conclusions

Overall, the current research represents an initial step in advancing our understanding of sex/gender-specific speech patterns in children. Speech is a central tool in our daily functioning and is an essential medium of human interactions. Our research reveals that gender behavior and identity contribute to the development of sex/gender-typed speech patterns. Furthermore, our research underscores the importance of examining processes of speech acquisition in conjunction with concurrently developing behaviors, particularly those which are pertinent to identity formation.

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