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A Child Specific Compensatory Mechanism in the Acquisition of English /s/

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1. Introduction

A long tradition of research in child language acquisition has focused on describing and explaining the non-target-like outputs that children produce in the course of development. Among the consonants for which English learning children show difficulties, /s/ is particularly noteworthy, from the perspective of the outputs that children produce, the prosodic positions in which difficulties manifest themselves and the protracted developmental path observed. The challenges that /s/ presents in development are in stark contrast to the observation that /s/ is typologically highly frequent (Maddieson, 1984) and has a privileged status within languages (i.e. it can occur in marked positions, namely in coda as well as in initial and final clusters).

One may be tempted to conclude from this mismatch between development and typology that the difficulties that children have are attributable to misperception. In the case of /s/, an explanation along these lines is unlikely. First and foremost, /s/ is acoustically highly salient (Wright, 2004). Misperception can be further ruled out by the fact that /s/ has been observed to emerge earlier in coda than in onset position (Dinnsen, 1996; Dinnsen & Farris-Trimble, 2008; Ingram et al., 1980). This is surprising, given that coda is a prosodically weak position where gestures tend to blend, leading to phonological processes such as weakening, assimilation or deletion in the world's languages (Browman & Goldstein, 1988; Solé, 2010). Coupled with this is the observation that some children show /s/ weakening (gliding) or deletion in onset (e.g., Smith, 1973), a prosodically strong position.

In view of the fact that children's difficulties with /s/ are unlikely to be rooted in perception, several production-based accounts have been proposed, which we detail as follows. Research from the traditional generative perspective proposes that children's non-target-like outputs reflect developmental phonological processes, which do not formally deviate from those observed in typologically existing adult grammars (Gnanadesikan, 2004; Pinker, 1994; Smith, 1973). This view, however, fails to adequately account for the substitutions commonly observed for onset /s/, namely glides (/s/ → [j]) and stops (/s/ → [t]), as well as deletion which, to our knowledge, are not processes that target onset /s/ in adult languages. This problem is not confined to /s/ but is

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reflected more broadly in the segmental domain through the emergence of typologically unattested patterns such as consonant harmony (Drachman, 1978) and velar fronting (Inkelas & Rose, 2007). The root of the problem appears to be that this approach does not consider the important fact that the speech organs of children are not a miniature version of those of adults (Green et al., 2002; Mugitani & Hiroya, 2012); consequently, functional differences between the motoric and phonatory systems of children and adults are not viewed as a source of explanation for patterns observed in development.

Another approach argues for the existence of child-specific[1] grammars that emerge from children's motoric constraints (Locke, 1993). Following this approach, McAllister Byun (2011, 2012) proposes that young children's speech production is controlled by child-specific constraint sets that ban effortful movements of their immature lingual articulators. Child-specific grammars, then, reflect phonologically planned grammatical processes (such as substitution and deletion) that conform to children's speech motor limitations and are highly susceptible to vowel context effects. In the case of onset /s/, the output of this type of grammar could be the target phone, another phone from the language (e.g., [t] or [j]) or deletion, and production should be more target-like in high vowel contexts where the narrow constriction required for /s/ is facilitated by the tongue posture assumed for the following vowel. This view is supported by results from a case study of one developmentally-delayed child (aged 3.9-4.4) (McAllister Byun, 2011).

Although these two approaches diverge considerably in their views on the character of the developing grammar, they share the position that children's production target for /s/ is not fundamentally different from what the adult perceives: if the adult perceives the child to have produced [t] for target /s/, this is because the child 'intended' [t], that is, that [t] is the output of the grammar. We propose a contrasting view. We agree with Locke (1993) and McAllister Byun (2011) that when children produce forms that are phonetically different from the adult target, this is due to the limitations of their articulatory system. However, we depart from their view in proposing that children's production goal for /s/ is the adult target [s], even when their outputs are not perceived as such. We see that the non-target-like forms that emerge can be explained by considering how functional differences between children's and adults' articulatory systems interface with an adult-like phonological grammar (Goad, in press). Consequently, children's typologically unusual non-target productions for target /s/ are not the product of the grammar.

An important consequence of our view is that we consider children to be more active learners than Locke and McAllister Byun suggest. We support this position by showing that children use a compensatory mechanism, which is different from adults, to approximate the target phonetic output in contexts that are articulatorily or functionally more challenging. One prediction of this approach that we also observe is that gender differences in children's

[1] Throughout this paper, the term 'child-specific' should be interpreted as different from adults, rather than specific to a particular child or children.

productions, such as those previously observed for vowels (Busby & Plant, 1995; Mugitani & Hiroya, 2012), emerge relatively early in development, as female children actively strive to match their phonetic targets with female adults and male children do so with male adults.

The data that we use to support our position come from word-initial [sV] productions from 79 children aged from 2 to 5 (Paidologos corpus, Edwards & Beckman, 2008). We compare these data with word-initial [sV] syllables produced by 13 adults. The analyses are performed using mixed-effects regression models based on acoustic measurements. The results show that in the context of non-high vowels, young children compensate for the less tight constriction arising from the jaw and tongue body lowering required for the following vowel. They do this by increasing airflow during /s/ production, a more accessible mechanism that is not used by adults. We also show that they develop gender-specific targets for /s/.

The remainder of the paper is structured as follows. Section 2 reviews vowel context effects on the production of English /s/. Section 3 discusses the data and methodology. Section 4 provides statistical results that show how adults' and children's production of /s/ is modulated by vowel context and other factors. A child-specific compensatory strategy involving an aerodynamic mechanism is introduced in Section 5, supported by acoustic analysis. The findings are discussed in Section 6.

2. Vowel contexts

The production of target /s/ has several aerodynamic and articulatory constraints which may be challenging for children. The characteristic stridency of /s/ is formed by a jet produced from a narrow channel passing over the front part of the grooved tongue raised against the hard palate; the jet of air forcefully hits the upper incisors, which increases the magnitude of turbulence and amplitude of noise (Shadle, 1991; Shadle et al., 2011). Therefore, it is crucial to maintain a narrow constriction at the front cavity during the production of /s/, even while lowering the tongue body for a following non-high vowel. Adults can achieve this by relying on their ability to independently move the tongue tip from the tongue body (Iskarous et al., 2011); while the tongue body lowers for the production of a following non-high vowel, the tongue tip can remain high against the hard palate maintaining a narrow constriction.

However, this skillful articulatory strategy may be difficult for young children, given that their speech organs are not only different from adults but also exhibit non-uniform growth rates among different articulators (Cheng et al., 2007; Green et al., 2000; Green et al., 2002; Kent, 2004; Vorperian et al., 2005). Cheng et al. (2007) observed that the subparts of the tongue develop with different growth rates and undergo a consistent refinement in relation with the jaw movements into late adolescence. Given this, the production of /s/ in non-high vowel contexts may be especially challenging for young children as it requires well-coordinated tongue tip, tongue body and jaw gestures. To test this hypothesis, our analysis will examine the effect of vowel height on /s/ production. We also consider vowel backness in our analysis as the fronting or retraction of the tongue body has been shown to affect /s/ production gestures in both adults' and children's speech (Nittrouer & Whalen, 1989; Nittrouer et al., 1996; Noiray et al., 2013; Sereno, 1987). However, we will not discuss the effect of vowel backness in detail since our primary interest is to observe how vowel height differently modulates the spectral distributions of /s/ in adults' and children's productions.

2.1. Effects of vowels on spectral distribution of /s/

The interplay between the aerodynamic mechanism and articulatory gestures should be reflected in the acoustics of /s/. We expect that canonical /s/ productions – less coarticulated /s/ in adults' productions and target-like /s/ in children's productions – will be spectrally similar. Compared to other productions of /s/, we expect these productions to have spectral distributions characterized by energy generally concentrated (low SD) in higher frequencies (high CoG) while low frequencies are deamplified (low skewness), as summarized in Table 1. In our study, the first vowel formant (F1) (normalized[2] to minimize vocal tract differences) represents the height of the tongue posture for each vowel production. Our expectation is that F1 does not modulate adults' /s/ but that it impacts children's productions for the articulatory reasons described above. In children's productions, there are at least two possible correlational patterns between F1 and the spectral distribution of /s/. First, low F1 (i.e. raised tongue body gestures) may be correlated with a spectrally more canonical /s/ if children are vulnerable to motoric requirements. On the other hand, high F1 (i.e. lowered tongue body gestures) could correlate with spectrally more canonical /s/ if children try to overcome their lingual limitations by maneuvering a non-lingual mechanism and target overshoot occurs in the process. Such an effect would support our hypothesis that children, as active learners, target gender-specific adult /s/ during acquisition and show a child-specific compensatory strategy to overcome their articulatory limitations.

Table 1. Expected spectral distribution for canonical /s/

	Canonical /s/	Spectral shapes
Spectral moments	higher CoG	mean energy in high frequency regions
	smaller SD	narrow dispersion of spectral energy
	smaller skewness	greater energy above the mean

3. Data and methodology

3.1. Data

Two sets of English data were analyzed in this study. One set is part of the Paidologos project (Edwards & Beckman, 2008a), which investigated the

[2] All the vowel formants in this study were normalized based on the Nearey 2 method using the 'norm.nearey' function embedded in the R package called 'Vowels' (Kendall & Thomas, 2012).

phonological acquisition of various word-initial lingual consonants across five languages. The English data, which are publicly available on the CHILDES website, were collected from monolingual 2- to-5-year-old children by recording their speech during a picture-prompted word repetition task. From the Paidologos recordings and transcriptions, /s/-initial tokens were extracted for the purpose of the current study. Initial /s/ in the tokens occurs in one of eight different vowel contexts, /i, u, ɪ, eɪ, oʊ, ɪ, ʌ, ɑ/. Tokens with noise interruptions and inaudible or unrecognizable sound files were excluded before any measurements were taken. A total of 1141 tokens for 15 words[3] from 79 child speakers were analyzed in our study.

The other data set is adult speech data collected for a project investigating how multiple acoustic cues vary in different speech conditions. The data in the study contain word-initial /s/ and /ʃ/ followed by four different vowel contexts, /i, ɪ, æ, ɑ/, in real English words.[4] 5 male and 8 female adult participants were instructed to read the words (which were embedded in sentences and preceded by 'the') presented on a computer screen as their productions were recorded. Since the current study is interested in examining the correlation between word-initial /s/ and the following vowel, only /s/-initial words were examined and analyzed. A total of 364 tokens consisting of 4 different vowels in 11 different words were analyzed.

3.2. Acoustic measurements

The boundary between /s/ and the following vowel was marked by hand. Boundaries were chosen at the point where a zero-crossing of the periodic wave form is as close as possible to the emergence of the first formant in the spectrogram. Formants were measured at two points, at the CV boundary and 33% into the vowel. The one third location rather than the mid point was chosen because some vowels are diphthongs or diphthongized in the children's productions and we were interested in the relationship between /s/ and the first part of the vowel in case of diphthongs or diphthongized vowels. To better accommodate coarticulation effects, vowel formants were measured at the CV boundary as well.

Before calculating any measurements for frication noise, frequencies below 550 Hz were filtered using 'Stop Hann Band' in Praat (Boersma & Weenink, 2014) in order to remove any voicing and associated harmonics from the frication portion. The first three spectral moments (CoG, SD and skewness) were obtained using DFTs (Discrete Fourier Transforms) computed by averaging 6 spectra taken at different time points across the fricative (following Shadle, 2011). Each spectrum was created from a window 15ms long. Six windows were evenly distributed across the middle 80% of the fricative.

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[3] The words include 'seal', 'seashore', 'soup', 'suitcase', 'super', 'sister', 'safe', 'same', sodas', 'soak', 'soldier', 'seven', 'sun', 'sauce' and 'soccer'.

[4] The words include 'seep', 'seat', 'sip', 'sin', 'sack', sag', 'sass', 'sash', socks', 'sought' and 'sop'.

We were also interested in the intensity of the frication noise because high CoG in turbulent noise is known to be primarily associated with amplifying higher frequencies as well as a small front cavity (Shadle, 2011; Stevens, 1998). Therefore, we measured the intensity of the fricative and the following vowel. All the average intensity values were obtained from the middle 80% of each token. In order to minimize the effects of any recording environments, we calculated the relative intensity of /s/ to the following vowel (V) by subtracting V-intensity from s-intensity for each token (IntDiff). No pre-emphasis was applied to the measurements.

3.3. Procedure

We address the primary question – how are spectral distributions of /s/ modulated by vowel context differently in adult and child productions? – based on mixed-effects model fits in R using the lmer() function from the lme4 package (Bates et al., 2014). We built three models for each of the two datasets by taking CoG, SD and skewness separately as a response variable. Each model includes four or six predictors; the three models for the adult data include F1 (height) and F2 (backness) measured at the boundary, IntDiff and Gender as predictors. Two additional predictors Age and the interaction between Age and Gender are included in the child models. Relative intensity of /s/ to the following V (IntDiff) is introduced to observe how intensity of noise modulates the spectral distribution of /s/. Gender is included to see if children have gender-specific production targets for /s/. Finally, Age is added to examine if spectrally canonical /s/ (or target-like /s/ in children's data) occurs in older children's productions. The four predictors, aside from Gender, were treated as continuous variables while Gender was coded using sum coding. To avoid collinearity and to make the effect sizes comparable, all the variables were centered and divided by 2 standard deviations.

In our models, the variables were introduced as fixed-effect terms to observe the impact of these predictors on the acoustic qualities of /s/ described in Table 1. All models also included uncorrelated by-subject random slopes for F1, F2 and IntDiff and by-word random slopes for Gender, Age and the interaction between the two as well as by-subject and by-word random intercepts.

4. Results

4.1. Adults

Table 2 below summarizes the estimated effect of each predictor ($\hat{\beta}$), its standard error (se($\hat{\beta}$)), *t*-static and *p*-value acquired from a Wald test. Significant main effects of Gender were found as predicted. The fricative produced by female speakers has a higher spectral mean than that produced by male speakers, (partly) reflecting the shorter vocal tract size of female speakers.

Table 2. Uncorrelated multilevel models for adults (n=364)

	COG				SD				Skewness			
Predictor	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*
(Intercept)	7013	98	71.38	<.0001	1382	25.9	53.26	<.0001	0.172	0.101	1.69	0.09
gender (male)	**-1297**	**204**	**-6.37**	**<.0001**	59.3	53.1	1.12	0.263	**0.679**	**0.207**	**3.28**	**0.001**
IntDiff(dB)	4.5	76	0.06	0.952	35.6	34.7	1.03	0.3	0.134	0.102	1.31	0.189
F1	25.7	81	0.32	0.749	13.6	24.7	0.55	0.582	-0.078	0.101	-0.78	0.437
F2	**225.8**	**77**	**2.94**	**0.003**	**-60.3**	**24.5**	**-2.46**	**0.014**	**-0.251**	**0.097**	**-2.58**	**0.01**

As seen in Figure 2, the mean CoG of the male speakers is lower ($\hat{\beta}$= -1297, *t*= -6.37, *p*< .0001) and the mean skewness is higher ($\hat{\beta}$= 0.679, *t*= 3.28 *p*= 0.001) than that of the male speakers, which is consistent with the previous literature (Haley et al., 2010; Jongman et al., 2000). As illustrated in Figure 1 (top right panel), the lower skewness value on average in female productions suggests heavily left-skewed spectral distribution for female /s/ productions across all vowel contexts. Its effect on SD suggests that male speakers tend to have a higher SD on average than female speakers but this effect does not reach statistical significance ($\hat{\beta}$= 59.3, *t*= 1.12, *p*= 0.263).

The statistical results show that F2, representing frontness and backness of the constriction, significantly modulates CoG in a positive direction ($\hat{\beta}$= 225.8, *t*= 2.94, *p*= 0.003) and SD ($\hat{\beta}$= -60.3, *t*= -2.46, *p*= 0.014) and skewness ($\hat{\beta}$= -0.251, *t*= -2.58, *p*= 0.01) in a negative direction (figures not given). These results suggest that /s/ produced in front vowel contexts is acoustically more canonical than the one produced in back vowel contexts.

There is no significant effect of IntDiff and F1 on any of the spectral measures. The lack of F1 effect coincides with earlier production studies where invariable constriction formations were found regardless of different vowel contexts by a tongue tip compensation gesture to achieve the production goal (Iskarous et al., 2011; Stevens, 1998).

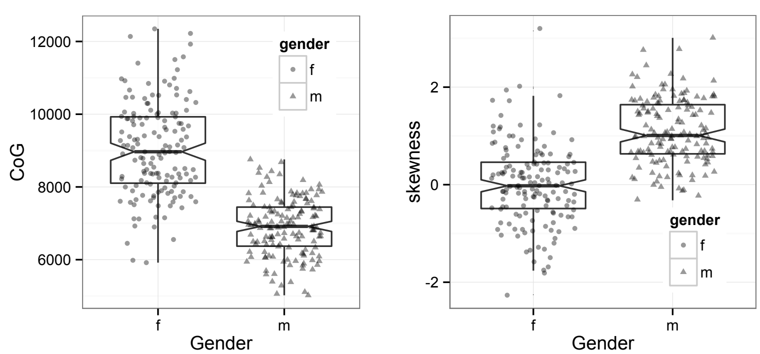

Figure 1. The main effect of Gender for (f)emale and (m)ale speakers on CoG (left) and skewness (right) in the adult data.

4.2. Children

Using the same statistical models as in the previous section and by including two additional predictors, Age and an interaction term between Age and Gender, we analyze how each of the three spectral moments of /s/ produced by children is modulated by the predictors and examine if the directions of the coefficients are in accordance with the predictions made earlier. Table 3 summarizes the estimated effect of each predictor ($\hat{\beta}$), its standard error (se($\hat{\beta}$)), *t*-static and *p*-value acquired from a Wald test again.

CoG and SD change significantly as a function of Age; older children have higher CoG ($\hat{\beta}$= 627, t= 1.96, *p*= 0.05) and smaller SD ($\hat{\beta}$= -228, *t*= -2.1, *p*= 0.004) than younger children. The effect of Age is as predicted: older children produced more canonical /s/. The effect is also in the right direction for skewness while not reaching statistical significance ($\hat{\beta}$= -0.177, *t*= -1.499, *p*= 0.134).

Table 3. Uncorrelated multilevel models for children (n=1141)

	COG				SD				Skewness			
Predictor	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*	$\hat{\beta}$	se($\hat{\beta}$)	*t*	*p*
(Intercept)	8212	2067	39.82	*<.0001*	2813	51.201	54.93	*<.0001*	0.313	0.066	4.761	*<.0001*
age	**627**	**323**	**1.96**	***0.05***	**-228**	**109**	**-2.1**	***0.004***	-0.177	0.118	-1.45	*0.134*
gender (male)	-431	919	-0.47	*0.638*	-132	172	-0.77	*0.441*	0.054	0.122	0.44	*0.673*
age:gender	**-1790**	**609**	**-2.94**	***0.003***	-361	187	-1.93	*0.054*	**0.474**	**0.233**	**2.03**	**0.042**
IntDiff(dB)	**493**	**124**	**3.96**	***<.0001***	**-473**	**75**	**-6.35**	***<.0001***	-0.083	0.078	-1.07	*0.284*
F1	**318**	**145**	**2.19**	***0.029***	**142**	**46**	**3.12**	***0.002***	**-0.192**	**0.079**	**-2.44**	***0.015***
F2	258	154	1.49	*0.136*	5	55	0.09	0.928	-0.038	0.099	-0.38	*0.705*

There is no significant effect of Gender across all age groups. However, the interaction term suggests that adult-like gender differences emerge for CoG (top left plot in Figure 2 and skewness (top right) after age 3 and the difference increases for older age groups. The mean CoG is considerably lower and skewness is higher for male children in the five-year-old group compared to their female peers, which coincides with the gender-specific properties found in the adult data. SD also diverges between male and female children around the same age and shows a marginal effect ($\hat{\beta}$= -361, *t*= 1.93, *p*= 0.054) but it is not comparable with the adult data because Gender is not a significant predictor for SD in adults.

Greater intensity in the frication relative to the vowel (IntDiff) significantly increases CoG ($\hat{\beta}$ = 493, *t*= 3.96, *p*< .0001) and decreases SD ($\hat{\beta}$ = -473, t= -6.35, *p* < .0001) (figures not given). The effect of IntDiff on skewness is not statistically significant ($\hat{\beta}$= -0.083, *t*= -1.071, *p*= 0.284), even though the direction is as expected. The effects of IntDiff suggest that higher noise intensity is correlated with spectrally canonical /s/.

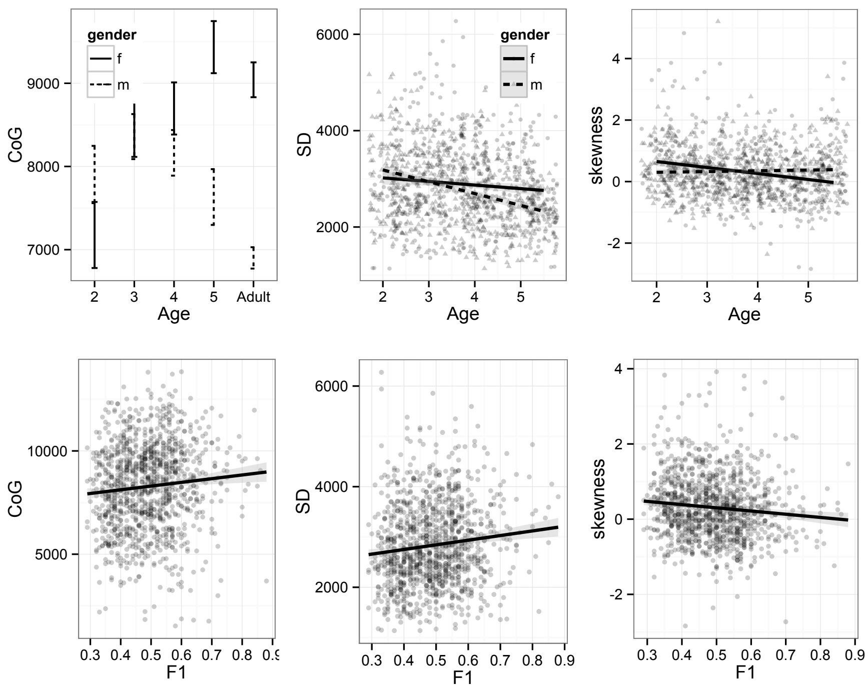

Figure 2. The plots in the top panels show the effects of the interaction term, Age and Gender, on CoG (left), SD (middle) and skewness (right). The bottom panels show empirical plots of F1 measured at the CV boundary for CoG (left), SD (middle) and skewness (right). All the plots are drawn from the child data.

The effect of F1 is significant on all three spectral measurements, as seen in the plots in the bottom row in Figure 2. Increasing F1 significantly raises CoG ($\hat{\beta}$= 318, *t*= 2.19, *p*= 0.029) and SD ($\hat{\beta}$= 142, *t*= 3.12, *p*= 0.002) while it significantly lowers skewness ($\hat{\beta}$= -0.192, *t*= -2.44, *p*= 0.015). The direction of F1 on CoG and skewness is unexpected and in contrast with what the physiologically-grounded views of Locke (1993 and McAllister Byun (2011, 2012) would predict because /s/ before non-high vowels is more target-like despite it being articulatorily more challenging. In the next section, we discuss how children may achieve their production goals in articulatorily challenging contexts using a child-specific compensatory mechanism in relation with the findings in this section.

5. A child-specific compensatory mechanism

Our results show that despite the challenging articulatory requirements of low vowel contexts and children's immature lingual skills, young children produce acoustically more canonical /s/ in non-high vowel contexts compared to high vowel contexts. If children's production goal for /s/ is the (gender-specific) adult target and they are aware of their articulatory limitations, it is possible that young children employ a more accessible mechanism to achieve their goal. We test this hypothesis by exploring an aerodynamic mechanism relevant to the production of frication noise.

In the previous sections, we observed that the effects of IntDiff are significant on CoG and SD; higher IntDiff (greater intensity of /s/ versus the vowel) is associated with acoustically well-defined /s/ in children's productions but not in the productions of adults. High noise intensity amplifies higher frequencies, which especially increases CoG (Shadle, 2011; Stevens, 1998). There are two primary ways to increase the sound power of noise. Noise becomes greater when an opening or constriction area is smaller or when volume airflow is greater (Stevens, 1998). Since the tongue tip likely moves downwards following the direction of the jaw when children articulate /s/ in a non-high vowel context, the constriction area should increase, which will consequently decrease /s/ intensity. Following this logic, we can infer that if /s/ is more canonical in low vowel contexts, it is likely because children manipulate airflow and overshoot occurs.

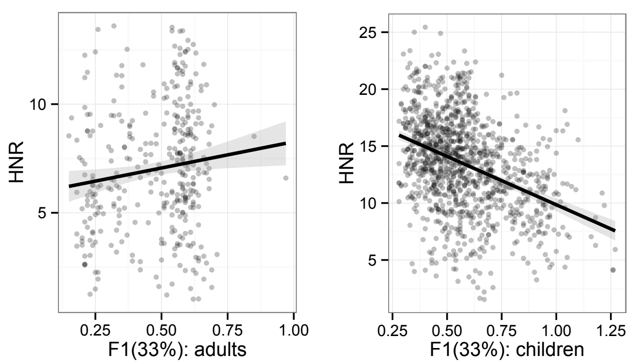

Figure 3. Empirical plots of F1 measured at the 33%[5] point of vowels versus HNR (Left: adults, Right: children). The lines and shadings show a linear fit and 95% CIs.

Gesturally, more airflow is produced with wider glottal opening and stiffer vocal folds (Kent, 2004). These gestures should make the following vowel breathier due to progressive coarticulation. Therefore, we predict that if the following vowel is a non-high vowel, it will have decreased periodicity (more breathiness) in children's productions but not in the productions of adults. We measured periodicity using the harmonics to noise ratio (HNR) obtained in the center 80% of the vowel interval. Figure 3 shows that non-high vowels are

[5] The plots look very similar when we plot them against F1 measured at the boundary. We used F1 measured at the 33% point of the interval instead because we expected to observe the effect of the target vowel rather than coarticulation for this analysis.

indeed noisier and less periodic in children's productions while high vowels are noisier and less periodic in adults' productions.[6] This supports the claim that children make an effort for noise production in articulatorily more challenging environments during the acquisition of English /s/ when they are not equipped with adult-like control of lingual gestures. If their production goals were not adult-like, they would have produced more target-like /s/ in high vowel contexts because this is a functionally or articulatorily less demanding environment.

6. Discussion and conclusion

In the current study, we examined different patterns of vowel context and gender effects on /s/ by using quantified spectral moment analysis between adults and children. We found distinct gender patterns in both adults and older children, which supports the hypothesis that children have a gender-specific target for /s/. As for vowel context effects, the lack of F1 effects in adults is consistent with the prediction that the effect of vowel height is minimal on /s/ due to their fine control of lingual gestures. In contrast, in children's productions, higher F1 was associated with more target-like /s/. The direction of F1 effects called for an interpretation beyond articulatorily grounded vowel effects. This finding raised the possibility that children use different strategies from adults to achieve their production target for /s/. By examining the intensity of frication noise relative to the vowel and the relationship between F1 and breathiness in the vowel, we found evidence that children increase airflow to produce /s/ before a non-high vowel – a strategy that adults do not use. This finding suggests that young children, as active learners, adopt a more accessible mechanism different from adults to compensate for their immature lingual gestures, possibly as an attempt to maximize phonological contrasts in word-initial position. Even though the current study indirectly inferred kinematic behavior of the lung and tongue during language development, it has shed light on the existence of a developmental speech mechanism that reflects young children's adult-like phonetic knowledge of the target sound.

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