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Research Article

Vocalization Rate and Consonant Production in Toddlers at High and Low Risk for Autism

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Background: Previous work has documented lower vocalization rate and consonant acquisition delays in toddlers with autism spectrum disorder (ASD). We investigated differences in these variables at 12, 18, and 24 months in toddlers at high and low risk for ASD.
Method: Vocalization rate and number of different consonants were obtained from speech samples from a prospective study of infant siblings of children with ASD. Three groups were compared: 18 toddlers at low risk for ASD (low-risk control), 18 high-risk siblings without ASD (HRA–), and 10 high-risk siblings with ASD (HRA+).
Results: All groups' mean language scores were within the normal range. HRA+ toddlers showed consistently lower vocalization rate; vocalization rate did not predict number of different consonants at 12 months for HRA+. HRA–, not HRA+, toddlers had the smallest number of different consonants and produced significantly fewer different consonants than predicted by their vocalization rate at 12 months. Consonant-acquisition trajectories differed between groups, with HRA– showing the greatest increase from 12 to 18 months.
Conclusion: Lower vocalization rate was not associated with reduced number of different consonants in these toddlers. Between-groups differences in developmental trajectories are discussed in the context of the social feedback loop and differential ability to benefit from adult feedback between groups.

Autism spectrum disorder (ASD) is characterized by deficits in social communication and by restricted, repetitive behaviors or interests (American Psychiatric Association, 2013). Expressive language is also frequently delayed in ASD (Boucher, 2012; Gamliel, Yirmiya, Jaffe, Manor, & Sigman, 2009; Gernsbacher, Geye, & Ellis Weismer, 2006), but findings on speech development are mixed. Some researchers (e.g., Kjelgaard & Tager-Flusberg, 2001) have found that speech ability in older children with ASD is in the average range, even when language and cognitive ability are not. Other researchers (Cleland, Gibbon, Peppé, O'Hare, & Rutherford, 2010; Rapin, Dunn, Allen, Stevens, & Fein, 2009; Shriberg et al., 2011) have identified subgroups of children with ASD with impaired speech production. These differing results highlight the heterogeneity of speech production ability in children with ASD. This article focuses on early speech development in ASD in order to identify sources of potential difference from typical development, investigating the relationship of vocalization rate to consonant production in the second year of life in toddlers at high and low risk for ASD. Understanding whether consonant production delays are present in toddlers at risk for ASD and whether they are associated with lower vocalization rates or with a diagnosis of ASD provides important information on how spoken language development may be affected by ASD.

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Speech Development in Young Children with ASD

Several groups have examined speech development in young children diagnosed with ASD. Warlaumont, Richards, Gilkerson, and Oller (2014), for example, found a significantly lower vocalization rate in 77 children with ASD aged 16–48 months, as well as a lower rate of speech-like vocalizations, compared with 106 typically developing (TD) children aged 8–48 months.

Plumb and Wetherby (2013) compared 50 toddlers with ASD, 25 with non-ASD developmental delay (DD), and 50 TD toddlers who were between the ages of 18 and 24 months. There were no differences in language scores for the ASD and DD groups; however, the verbal developmental quotient on the Mullen Early Learning Scales (MSEL; Mullen, 1985) for the ASD group was significantly lower than that of the TD group. Compared with the TD group, toddlers with ASD produced a lower percentage of speech-like vocalizations and a higher percentage of nonspeech-like vocalizations. There were no differences between the ASD and DD groups on these measures, however, and

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the speechlike vocalizations did not differ in syllabic complexity between the ASD and TD groups.

Last, a study by Schoen, Paul, and Chawarska (2011) included 30 toddlers with ASD, 11 TD age-matched (TDA) controls, and 23 TD language-matched (TDL) controls, aged 18–36 months. Toddlers with ASD produced the same total number of vocalizations as the other groups but significantly more nonspeechlike vocalizations than the TDA group. The participants with ASD who produced word approximations or words produced significantly fewer of them compared with their TDA peers, but percent consonants correct in those words was the same for both groups.

This growing body of research shows that toddlers with ASD vocalize or produce speechlike vocalizations less often than TD peers. There is conflicting evidence on whether consonant production delays are found in ASD. Previous research has shown a relationship between vocalization rate and phonetic delay in children with expressive language delay (Paul & Jennings, 1992; Rescorla & Ratner, 1996), which has led these researchers and others to suggest that less vocal practice can result in consonant production delays, by reducing the opportunities for articulatory practice, auditory feedback, and feedback from communication partners (Pharr, Ratner, & Rescorla, 2000).

Investigating this question in the context of ASD carries with it complexities, however. First, consonants begin to emerge in babble and speech before the age when diagnoses of ASD are stable, and studies of phonological development in infants at risk for ASD have not always examined those who receive diagnoses of ASD separately from those who do not. Second, consonant inventory size has been shown to be positively related to size of speech sample in general (Van Severen, Van Den Berg, Molemans, & Gillis, 2012), so it is unclear whether smaller consonant inventories might be an artifact of lower vocalization rate. Last, not all studies of toddlers with or at risk of ASD controlled for language level, yet (as noted above; also see Pennington & Bishop, 2009) delays in consonant production are related to delays in expressive language.

Studying Infants at Risk for ASD

To examine how early speech development and risk status for ASD may be related, several groups have adopted the *sibling study* paradigm. Although the prevalence of ASD is approximately one in 68 children in the general population (Christensen et al., 2016), it is approximately one in five in the younger siblings of children with ASD (Messinger et al., 2015; Ozonoff et al., 2011). Following younger siblings of children with ASD thus provides a way to prospectively examine the early development of children who later develop ASD. Sibling studies also include children who have an older sibling with ASD, but who do *not* themselves develop ASD. Although approximately 50% of high-risk (HR) younger siblings develop typically, and approximately 20% develop ASD, the remaining 30% may develop non-ASD disorders such as attention-deficit disorder, language impairment, and other learning disabilities (Messinger et al., 2013). Thus, the presence of this non-TD, non-ASD group of children allows researchers to understand the contributions of both ASD itself and other developmental problems to the heterogeneity in ASD.

Speech Development in Infants at High Risk for ASD

Few studies have examined prespeech vocal behavior in infants at HR for ASD. Paul, Fuerst, Ramsay, Chawarska, and Klin (2011) looked cross-sectionally at infants at HR and low risk (LR) for ASD at 6, 9, 12, and 24 months. Findings for the HR infants were generally consistent with the previously described studies of toddlers with ASD in that, on average, HR infants produced fewer speechlike vocalizations and more nonspeechlike vocalizations than LR infants. HR infants also produced, on average, significantly fewer consonant types than LR infants. In addition, the HR group had lower expressive and receptive language scores than the LR group at 6, 12, and 24 months, though the correlation was only significant at 12 months. The prespeech vocalization differences found in HR infants could not be attributed to more general developmental delay in the HR group, as their nonverbal cognitive skills were no different from those of the LR infants. Instead, delays were specific to acquisition of age-appropriate consonant sounds during the first year of life.

Patten et al. (2014) also prospectively studied 37 infants, 23 of whom were later diagnosed with ASD, examining vocalizations at 9–12 and at 15–18 months of age. The ASD group vocalized significantly less often than the non-ASD group at both ages, and produced a lower proportion of canonical syllables (which contain consonant onsets) than the non-ASD group. Together, these results suggest that vocalization rate and consonant production are sensitive indicators of HR infants' progress in speech acquisition.

The Relationship of Speech Sample Size to Consonant Inventory Size

A principal method of assessing toddlers' phonological development is to assemble a *consonant inventory* (Rvachew & Brosseau-Lapré, 2012). This can be done in two ways: *Independent analyses* tally the number of native-language consonant types and the syllable shapes that a child produces, without reference to the adult target. *Relational analyses,* on the other hand, assess the accuracy of the produced consonant forms relative to adult targets, including in the inventory only correctly produced consonants. Independent, but not relational, analyses can be applied to prespeech babble as well as to words and word approximations. Because the age range for the current study includes ages at which toddlers produce only babble and when they begin to produce words or word approximations, we used independent analyses to investigate the relationship of diversity of different consonants and volubility and to examine how that relationship might change over time.

The size of a child's consonant inventory depends on sample size: The longer the speech sample, the more different consonants are likely to be found. To create speech samples that are comparable between children, researchers generally collect samples of a constant length (e.g., 10 or 20 min; Rescorla & Ratner, 1996). When vocalization rates are the same across children, this method results in comparable inventory sizes. However, when individual vocalization rates differ, this method disadvantages toddlers who vocalize less often (Van Severen et al., 2012).

Using 60 min of speech collected monthly from 30 Dutch toddlers between the ages of 22–24 months, Van Severen et al. (2012) confirmed that consonant inventory size was positively correlated with the number of words included in the sample. Their results showed that inventory size increased rapidly with sample size for small sample sizes, but reached a plateau with larger sample sizes. The sample size required to reach the plateau varied between children, though specific figures were not reported. To normalize sample size between highly voluble and less voluble children, these authors recommend comparing speech samples containing the same number of consonant tokens from each child. When vocalization rates vary, this means that the sample size will be limited to that of the least voluble child. As a result, long assessment times (e.g., longer than 60 min) may be necessary to collect enough consonant tokens to analyze but such lengthy samples are difficult to obtain. Van Severen et al. (2012) acknowledged this disadvantage to their method. An alternative to collecting extremely long speech samples and comparing the absolute consonant inventory size across children whose vocalization rate differs, however, is to investigate whether the *relationship* between consonant inventory size and vocalization rate differs between groups.

The Current Study

In this investigation, in addition to asking whether vocalization rate and consonant inventory size from 30-min speech samples differed across groups, we also asked whether the relationship between the two variables differed across groups—that is, we asked whether the consonant inventory size across groups was similar *for a given vocalization rate,* allowing us to understand whether toddlers at risk for ASD produced fewer consonant types than would be expected given their vocalization rates. A positive answer to this question would suggest that some factor other than low vocalization rate (smaller sample size) affected consonant inventory size. The relation between vocalization rate and consonant production has not previously been examined in the second year of life in toddlers at risk for ASD.

We included three groups of toddlers: toddlers at LR for ASD, toddlers at HR for ASD who developed ASD, and toddlers at HR for ASD who did not develop ASD. This allowed us to investigate whether the relationship of vocalization rate to consonant inventory size was similar across groups and whether lower vocalization rate was associated with differences in consonant inventories in ASD specifically. Last, because language delay is associated with speech delay (Pennington & Bishop, 2009), in this study we controlled for expressive language. We asked the following questions: In toddlers at HR and LR for ASD without language impairment,

1. Are there between-groups differences in vocalization rate at 12, 18, and 24 months?
2. Are there between-groups differences in consonant inventory size at these ages?
3. Does vocalization rate predict consonant inventory size concurrently or prospectively?
4. If so, is the relationship between the two the same across groups?

Method

Participants

Our sample included 46 infants: 18 LR controls (LRC) with a TD older sibling and no family history of ASD (five boys, 13 girls) and 28 toddlers at HR for ASD (HRA) who had an older sibling with ASD. Ten HRA toddlers (seven boys, three girls) received diagnoses of ASD at 36 months and are referred to as HRA+ (i.e., HR siblings with ASD). The remaining 18 HRA toddlers (eight boys, 10 girls) did not develop ASD and are referred to as HRA− (i.e., HR siblings without ASD).

Family history of ASD was queried during a pre-enrollment phone screen. Diagnosis of ASD in the relevant older siblings (and confirmation that the older siblings of the LRC participants did not have ASD) was corroborated via parent report using an age-appropriate screener prior to enrollment: For older siblings over 4 years old, the Social Communication Questionnaire was used (Rutter, Bailey, & Lord, 2003); for older siblings under 4 years old, the Pervasive Developmental Disorders Screening Test–II was used (Seigel, 2004). After initial screening, participants were enrolled in a longitudinal infant sibling project and asked to participate regularly until 36 months in various tasks, with data collected through parent report, behavioral, eye-tracking, and neural measures of development.

To be included in this study, infants needed to complete lab visits at 12, 18, and 24 months and have received an Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000) assessment from a research-reliable experimenter at 36 months. The ADOS is a dynamic assessment in which the examiner provides a variety of activities designed to elicit social interaction and notes the spontaneous behaviors the child shows (e.g., requesting, responding to their name being called or to a social smile, sharing of enjoyment, repetitive behaviors) that relate to the two main diagnostic criteria for ASD. Diagnosis of ASD was made on the basis of an ADOS score ≥ 7. Table 1 details language scores on the MSEL for the LRC, HRA+, and HRA− groups. Project approval was obtained from the Institutional Review Boards of Boston Children's Hospital and Boston University, and informed consent was obtained from the parents of each infant participant.

Table 1. Descriptive characteristics of the participants.

Characteristic	Low-risk controls (LRC)	High risk + ASD (HRA+)	High risk – ASD (HRA–)
Number	18	10	18
Sex	5 M, 13 F	7 M, 3 F	8 M, 10 F
ADOS score (36 mo.)[a], *M* ± *SD*	2.1 ± 2.2	8.5 ± 4.3	2.6 ± 1.8
Language *T* scores[b]			
12 months EL	50.1 ± 7.3	41.1 ± 5.2	45.8 ± 8.6
12 months RL	45.9 ± 9.5	39.6 ± 9.8	43.7 ± 7.0
18 months EL	50.8 ± 5.8	40.2 ± 11.3	53.1 ± 8.1
18 months RL	52.2 ± 13.6	48.0 ± 9.2	50.6 ± 15.3
24 months EL	55.6 ± 10.5	48.0 ± 9.2	55.7 ± 7.7
24 months RL	54.9 ± 8.5	49.4 ± 10.9	56.4 ± 7.8

Note. ASD = autism spectrum disorder; ADOS = Autism Diagnostic Observation Schedule (Lord et al., 2000); EL = expressive language; RL = receptive language.

[a]Diagnosis of ASD was made on the basis of an ADOS score ≥ 7. [b]Mullen Early Learning Scales (Mullen, 1985) *T* scores: 20–30: very low, 31–39: below average, 40–60: average, 61–69: above average, 70–80: very high.

Measures

The ADOS was used to ascertain diagnostic status at 36 months. The Receptive and Expressive Language scales from the MSEL were used to assess language at 12, 18, and 24 months. Up to 32 months, the MSEL Expressive Language subtest consists mainly of items pertaining to types of speechlike vocalizations, babbles, and first words. Thus, it is more specific to speech and to word production than assessments that include use of gestures. It is important to note that it includes no information about how often a child produces babbles or speech. MSEL *T* scores are reported for all groups at all ages (see Table 1). The *T* scores are based on $M = 50$ and $SD = 10$, so scores between 40 and 60 are considered within normal limits.

Speech samples lasting 30 min were collected from all participants, taken from the Autism Observation Schedule for Infants (Bryson, Zwaigenbaum, McDermott, Rombough, & Brian, 2007) at 12 months and from the ADOS at 18 and 24 months. Though Kover, Davidson, Sindberg, and Ellis Weismer (2014) found that 36–53-month-old children with ASD produced fewer utterances, fewer different words, and a lower mean length of utterance during the first 15 min of the ADOS than during a 15-min play-based language sample with either a parent or an examiner, we found it to be superior to a 10-min parent–child interaction as a speech sample. Although some 12-month-olds produced no consonants during the parent–child interaction, all produced at least some vocalizations containing consonants during the first 30 min of the Autism Observation Schedule for Infants or ADOS.

Vocalization Coding

All toddler vocalizations in the 30-min samples were divided into breath groups (Lynch, Oller, Steffens, & Buder, 1995; Oller & Lynch, 1992) and coded as speechlike, nonspeechlike, or obscured. *Obscured* vocalizations could not be clearly heard because of interfering toy noise or adult speech, and were subsequently excluded from analysis. *Speechlike* vocalizations included babbles, word approximations, and words. They possessed articulatory movements sufficient to produce the percept of a transcribable English phoneme and included vocalic nuclei, multiphthongal sequences (long vowel-like vocalizations with changing vowel quality), canonical babbles (consonant–vowel or vowel–consonant sequences with clear, adultlike transitions to consonants or glides), word approximations, or recognizable words. *Nonspeechlike* vocalizations were not considered to constitute speech because of abnormal phonation amplitude, source, type, or pitch. Trills and raspberries, for example, were produced with a vibratory source other than the vocal folds. Grunts were short sounds of mental or physical effort, bordered by glottal stops. Laugh and cry were vocal but nonspeech utterances.

Consonant inventories for each toddler were assembled from broad transcriptions of the speechlike vocalizations. Number of different consonants represented how many of the 24 consonants of English were present in a participant's inventory at a particular age. Because we wished to compare our results to previous studies (e.g., Paul et al., 2011), we included a consonant in children's inventories regardless of its position within a syllable. Last, a consonant was considered to be present in a participant's inventory at a particular date if it appeared at least three times during the 30-min sample (Bleile, 2003).

Coding Reliability

An additional coder, blind to subject status, independently scored 14 randomly selected audio files (10% of the total). Files from all three groups and ages, and with a representative range of vocalization rates, were included. Interrater reliability for identifying speechlike vocalizations was 97.2% and for identifying nonspeechlike vocalizations was 93.7%. Overall Cohen's κ (Cohen, 1960) for vocalization coding equaled .908, $p < .0005$, indicating that vocalizations were reliably classified as speechlike or nonspeechlike.

The reliability of values for number of different consonants was ascertained by having a second judge listen to 15 audio files representing a range of vocalization rates, ages, and groups, tallying the consonant types that each child produced. The first judge found a mean number of different consonants of 11.3 (SD = 6.5), the second 11.1 (SD = 6.7). Because the variable of interest is the mean number of consonant types, and because a t test examines the difference between two means, a two-sample t test for equal variance was used to ascertain whether the mean number of different consonants across judges was reliable. The t test showed that the two means were not significantly different, $p = .9345$, indicating that number of different consonants was reliably tallied.

Analyses

Several types of analyses were used. Repeated-measures analyses of variance (ANOVAs) with age (12, 18, 24 months) as a within-subjects factor and group (HRA+, HRA−, LRC) as a between-subjects factor were used to identify the presence of between-groups differences in expressive language, speechlike vocalization rate, and number of different consonants over time. Then, to determine the extent to which expressive language and speechlike vocalization rate predicted number of different consonants, both concurrently and prospectively, linear regression analyses were performed with these variables as predictors and number of different consonants as a dependent variable.

Last, because larger speech samples provided more chances to hear different consonants, the mathematical modeling procedure from Van Severen et al. (2012) was used to determine whether the relationship between speechlike vocalization rate and number of different consonants differed across groups. First, curve-fitting (Garson, 2012) was used to find the best-fit relationship between speechlike vocalization rate and number of different consonants for each group. This is described in more detail in the Appendix. Then, the equation best characterizing that relationship for the LRC group was used to predict number of different consonants for HRA+ and HRA−, using each group's own speechlike vocalization rate. The predicted mean number of different consonants for each group from the LRC equation was compared with the actual mean number of different consonants at each age and for each group using two-tailed t tests. The t test shows whether the mean predicted number of different consonants for HRA+ or HRA− at a particular age was significantly smaller or larger than the actual number of different consonants. If it were, this would indicate that the group was producing more or fewer consonants than predicted by its speechlike vocalization rate.

Results

Expressive Language

Because of the apparent between-groups differences in expressive language scores in Table 1, we wanted to understand whether there were statistically significant between-groups differences. We performed a repeated-measures ANOVA on expressive language with age (12, 18, 24 months) as a within-subjects factor and group (HRA+, HRA−, LRC) as a between-subjects factor. There was a significant main effect of age, $F(2, 78) = 7.022$, $p = .022$. Overall mean score was 46.6 (SD = 8.2) at 12 months, 49.7 (SD = 9.1) at 18 months, and 53.9 (SD = 9.9) at 24 months. The 24-month score was significantly different from the 18-month score, $p = .018$. There was also a significant main effect of group, $F(2, 39) = 9.769$, $p < .0005$. The HRA+ group's overall mean expressive language score was 46.6 (SD = 8.2), that for HRA− was 49.7 (SD = 9.1), and that for LRC was 53.9 (SD = 10.0). Post hoc, Bonferroni-corrected comparisons showed that the difference between HRA+ and HRA− was significant at $p = .001$ and the difference between HRA+ and LRC was significant at $p < .0005$. All groups included some toddlers whose expressive language scores were slightly below the average range (i.e., < 40) at one age. There was no significant Age × Group interaction. Though the mean score for each group was within the average range (40–60) at each age, we included expressive language in subsequent analyses (below).

Vocalization Rate

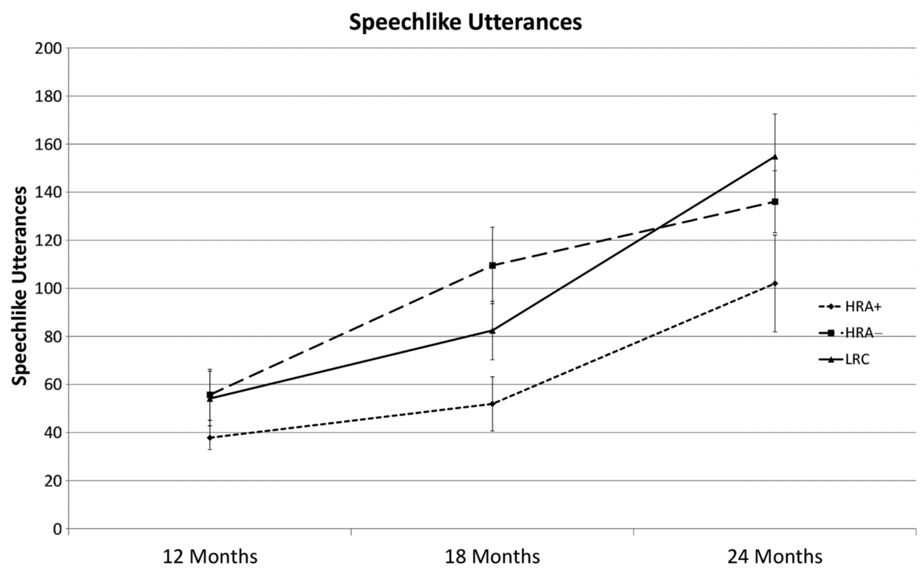
Because some groups (Paul et al., 2011; Plumb & Wetherby, 2013; Schoen et al., 2011) found that toddlers with or at risk for ASD produced higher numbers or rates of nonspeechlike vocalizations than controls, we performed a repeated-measures ANOVA on nonspeechlike vocalization rate with age as a within-subjects factor and group as a between-subjects factor. There was no significant main effect of age or group, and no Age × Group interaction on nonspeechlike vocalization rate. Participants produced an overall mean of approximately 20 nonspeechlike vocalizations per session (approximately 17% of their total).

A repeated-measures ANOVA was then computed on speechlike vocalization rate with age as a within-subjects factor and group as a between-subjects factor. There was a significant main effect of age, $F(2, 86) = 26.939$, $p < .0005$. Pairwise comparisons with Bonferroni correction showed that toddlers produced significantly more speechlike vocalizations at 18 months than at 12 months (105.6 ± 58.6 vs. 77.6 ± 64.3, $p = .004$) and at 24 months than at 18 months (150.4 ± 69.4 vs. 105.6 ± 58.6, $p < .0005$). There was also a significant main effect of group, $F(2, 43) = 3.842$, $p = .029$. Pairwise comparisons with Bonferroni correction showed that the HRA+ group produced a mean of 78.0 ± 43.2 speechlike vocalizations, significantly fewer than both the HRA− (123.1 ± 42.4, $p = .027$) and LRC (118.4 ± 41.2, $p = .05$) groups. HRA− and LRC did not differ in speechlike vocalization rate ($p = 1.0$). There was no significant Age × Group interaction, $F(4, 86) = 0.87$, $p = .483$. Figure 1 shows speechlike vocalization rates by age and group.

Number of Different Consonants

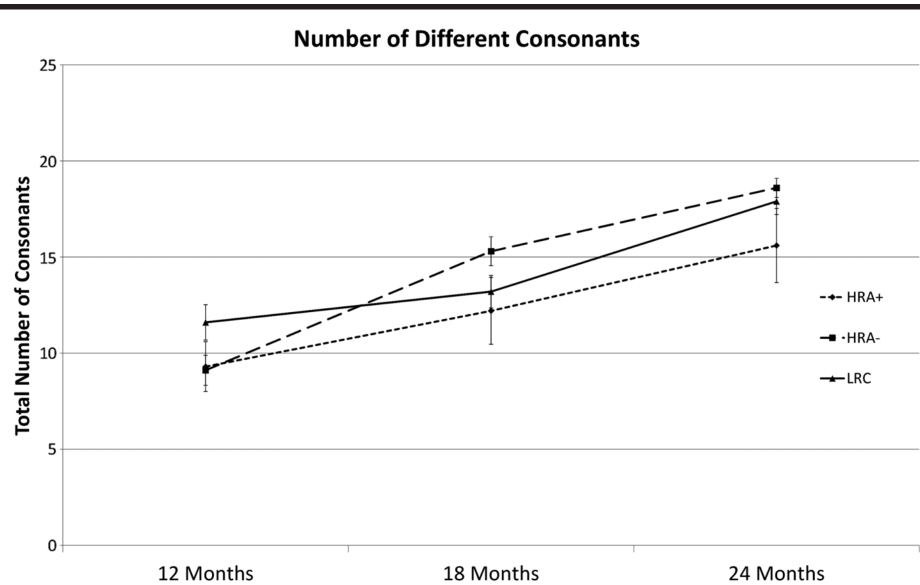
Figure 2 shows the number of different consonants for each group over time. A repeated-measures ANOVA was carried out on number of different consonants, with age as a within-subjects factor and group as a between-subjects factor. There was a significant main effect of age,

Figure 1. Speechlike vocalization rate by age and group. Error bars: ±1 *SEM.* Vocalization rate for HRA+ was significantly smaller than for the other two groups. HRA+ = high risk + ASD. ASD = autism spectrum disorder.



$F(2, 86) = 56.415$, $p < .0005$. Bonferroni-corrected pairwise comparisons revealed that all pairwise comparisons were significant at $p < .0005$, indicating that children produced more consonant types with increasing age. At 12 months participants produced a mean of 10.1 different consonants ($SD = 3.8$), at 18 months 13.8 ($SD = 4.0$), and at 24 months 17.7 ($SD = 3.6$). There was no main effect of group, $F(2, 43) = 2.003$, $p = .147$. There was a significant Age × Group interaction, $F(4, 86) = 2.563$, $p = .044$, indicating that change in number of different consonants over time differed by group. Bonferroni-corrected comparisons revealed that at 12 months HRA− toddlers produced a mean of 9.1 different consonants ($SD = 3.3$) compared with 11.6 ($SD = 3.9$) for LRC, $p = .05$. The mean number of different consonants at 12 months for HRA+ ($M = 9.3$, $SD = 4.1$) was not significantly different from either of the other two groups. At 18 and 24 months, there were no between-groups differences in number of different consonants.

Figure 2. Number of different consonants by age and group. Error bars: ±1 *SEM.* Number of different consonants was significantly smaller only for HRA– at 12 months.



Concurrent and Prospective Predictors of Number of Different Consonants

Because of the significant between-groups difference in expressive language scores, we asked whether expressive language score predicted number of different consonants, concurrently or prospectively, using linear regression. Table 2 details the concurrent results. Expressive language did not predict number of different consonants for any group at 12 months. At 18 months, expressive language predicted number of different consonants only for LRC, $F(1, 16) = 6.707$, $\beta = .347$, $p = .021$. At 24 months, expressive language again predicted number of different consonants only for LRC, $F(1, 16) = 7.185$, $\beta = .151$, $p = .016$.

Next, we investigated the relationship between speechlike vocalization rate and number of different consonants using linear regression. Speechlike vocalization rate significantly predicted number of different consonants at 12 months for the LRC group, $F(1, 16) = 15.210$, $\beta = .057$, $p = .001$, and for the HRA− group, $F(1, 16) = 12.813$, $\beta = .049$, $p = .003$. However, speechlike vocalization rate did not significantly predict number of different consonants for the HRA+ group at 12 months. At 18 months, speechlike vocalization rate significantly predicted number of different consonants for all three groups: LRC $F(1, 16) = 11.614$, $\beta = .045$, $p = .004$; HRA− $F(1, 16) = 9.199$, $\beta = .029$, $p = .008$; and HRA+ $F(1, 8) = 14.062$, $\beta = .124$, $p = .005$. In a similar manner, at 24 months, speechlike vocalization rate significantly predicted number of different consonants for all three groups: LRC $F(1, 16) = 5.082$, $\beta = .045$, $p = .039$; HRA− $F(1, 16) = 9.879$, $\beta = .029$, $p = .006$; and HRA+ $F(1, 8) = 8.883$, $\beta = .124$, $p = .018$.

Table 2. Concurrent predictors of number of different consonants.

Parameter	Low-risk controls (LRC)	High risk + ASD (HRA+)	High risk – ASD (HRA–)
Expressive language			
12 months			
Adjusted R^2	.047	.019	.028
p value	—	—	—
18 months			
Adjusted R^2	.309	.190	.064
p value	.021	—	—
24 months			
Adjusted R^2	.310	.078	.057
p value	.016	—	—
Vocalization rate			
12 months			
Adjusted R^2	.455	.210	.410
p value	.001	—	.003
18 months			
Adjusted R^2	.384	.602	.325
p value	.004	.005	.008
24 months			
Adjusted R^2	.194	.467	.343
p value	.039	.018	.006

Note. Nonsignificant *p* values are represented by dashes. ASD = autism spectrum disorder.

In terms of prospective relationships between the two variables, expressive language at 12 months significantly predicted number of different consonants at 18 months only for HRA+ at 12 months, $F(1, 9) = 7.730$, $\beta = -.738$, $p = .024$. Expressive language at 18 months did not predict number of different consonants at 24 months for any group.

The 12-month speechlike vocalization rate did not significantly predict number of different consonants at 18 or 24 months for any group. The 18-month speechlike vocalization rate also did not predict number of different consonants at 24 months for any group.

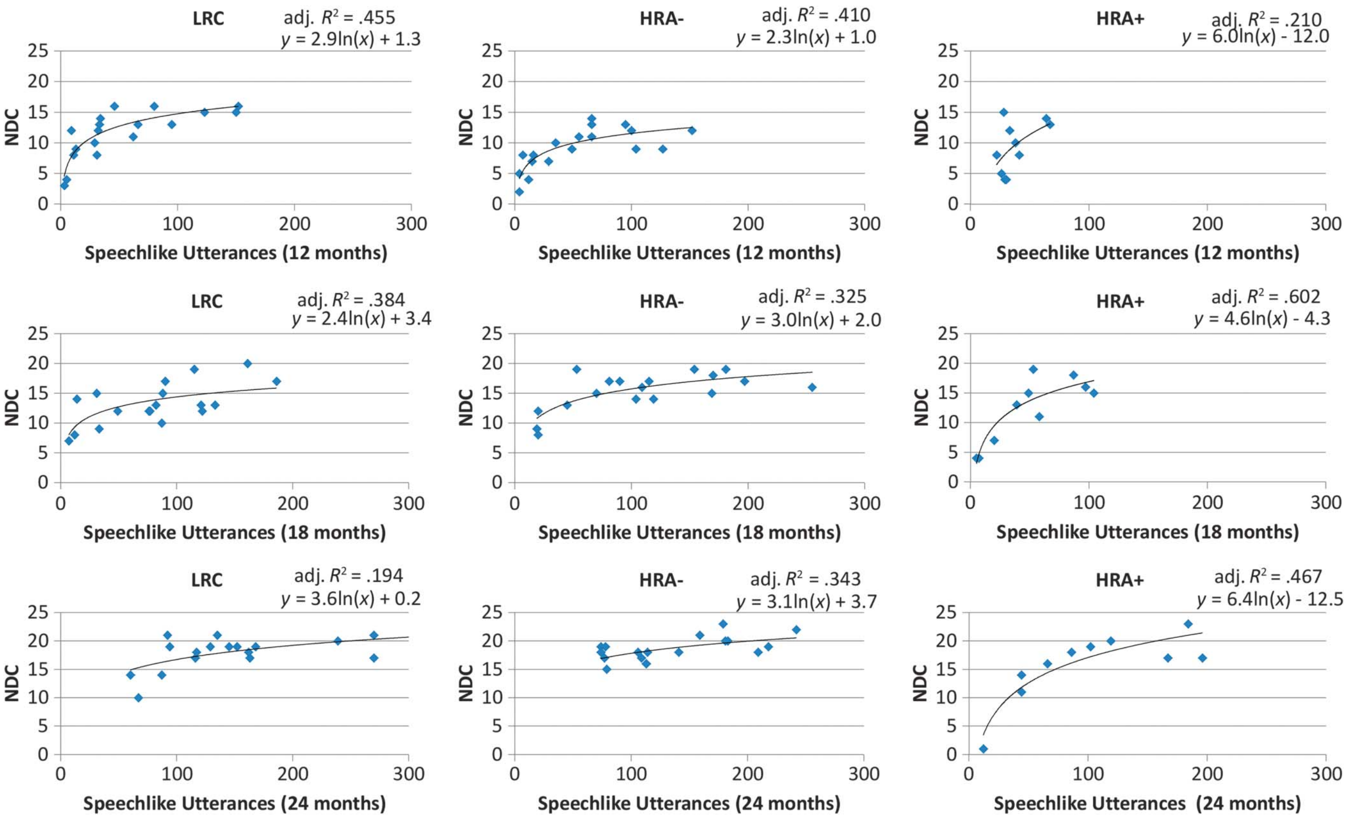
Between-Groups Differences in the Relationship of Speechlike Vocalization Rate to Number of Different Consonants

To understand the relationship between speechlike vocalization rate and number of different consonants for each group of toddlers, and to determine whether that relationship was the same across groups, the two variables were plotted against each other and a best-fit curve was calculated for each, as described in the Appendix. In each case, the best-fit curve was logarithmic. Figure 3 shows the best-fit curve for each group by age, along with the adjusted R^2 value, an unbiased estimate of the proportion of variance explained in each case.

Having ascertained the equations that best described the relationship between speechlike vocalization rate and number of different consonants for each group at each age, we next asked whether the relationship was statistically similar across groups (i.e., whether number of different consonants for HRA+ and HRA− was commensurate with their vocalization rate, taking the LRC group as a reference). We used the speechlike vocalization rates for the HRA+ and HRA− groups with the LRC group's equation to yield a predicted number of different consonants for HRA+ and HRA−. Then, we compared the predicted number of different consonants to the actual number of different consonants for all groups at all three ages using two-tailed *t* tests. If the predicted number of different consonants was significantly different from the actual number of different consonants for HRA+ or HRA− at any age, that would indicate that the relationship between speechlike vocalization rate and number of different consonants was different for those groups than for the LRC group.

At 12 months, the predicted number of different consonants for HRA− ($M = 11.6$, $SD = 1.0$) was significantly different from the actual number of different consonants ($M = 9.1$, $SD = 3.2$), $p = .03$. The predicted number of different consonants for HRA+ at 12 months ($M = 11.6$, $SD = 3.3$), however, was not significantly different from the actual value ($M = 9.3$, $SD = 3.9$), $p = .1133$. There were no significant differences between predicted and actual number of different consonants at 18 or 24 months for any group. Table 3 shows the mean difference between predicted and actual number of different consonants by group and age.

Figure 3. Number of different consonants as a function of speechlike vocalization rate: best-fit curves by group (columns) and age (rows).



Discussion

In this study, we sought to investigate whether there were differences in speechlike vocalization rate and the number of different consonants produced between HRA+, HRA−, and LRC toddlers at 12, 18, and 24 months; whether speechlike vocalization rate predicted the number of different consonants concurrently or prospectively; and whether the relationship between the two variables was the same across groups. Several findings emerged from the study. First, HRA+ toddlers had lower rates of speechlike vocalization, though their rates of nonspeechlike vocalization were not different from LRC or HRA− toddlers. Second, HRA+ toddlers in this study were not, as a group, significantly different from LRC in the number of different consonants they produced. Third, although in general vocalization rate is a strong concurrent predictor of number of different consonants, it did not significantly predict number of different consonants at 12 months in HRA+. Fourth, it was in fact the HRA− group, not the HRA+ group, who produced a significantly lower number of different consonants at 12 months than predicted by vocalization rate. Last, there was no predictive relationship between speechlike vocalization rate and number of different consonants for any group. Each of these findings will be discussed in turn.

The lower speechlike vocalization rate for HRA+ toddlers is consistent with previous research (Patten et al., 2014; Paul et al., 2011; Plumb & Wetherby, 2013; Schoen et al., 2011; Warlaumont et al., 2014). The current study

Table 3. Mean (standard deviation) of actual minus predicted number of different consonants.

Months	Low-risk Controls (LRC)	High risk + ASD (HRA+)	High risk – ASD (HRA–)
12	1.6 (1.2)	3.4 (2.5)	2.6 (1.7)*
18	2.4 (1.3)	2.8 (1.6)	2.0 (1.4)
24	1.7 (1.5)	2.6 (2.1)	1.5 (1.1)

Note. ASD = autism spectrum disorder.
*$p < .05$

extends this finding to a group of HRA+ toddlers whose mean language score was within the average range on the MSEL. This suggests that lower speechlike vocalization rate may be associated with a variety of conditions, including ASD (as discussed here), non-ASD developmental delay (Plumb & Wetherby, 2013), and expressive language delay, (Paul & Jennings, 1992; Rescorla & Ratner, 1996) among them. In ASD, lower speechlike vocalization rate may be closely associated with reductions in some types of communicative acts (Shumway & Wetherby, 2009; Wetherby, Prizant, & Hutchinson, 1998; Wetherby, Watt, Morgan, & Shumway, 2007). In contrast with some previous studies (Paul et al., 2011; Schoen et al., 2011; Plumb & Wetherby, 2013; Warlaumont et al., 2014), the HRA+ toddlers in our study did not also have a higher rate of nonspeechlike vocalizations. The reason for this difference is unclear, but may be related to varying degrees of language impairment, cognitive ability, or autism severity across participant groups.

In this study, we also found that HRA+ toddlers were not delayed in the number of different consonants they used at any age relative to LRC toddlers. This is inconsistent with reports of smaller independent consonant inventories in HR toddlers compared with LR peers (Paul et al., 2011) and in toddlers with ASD compared with age-matched TD peers (Schoen et al., 2011). However, it is consistent with the finding from Schoen et al. (2011) that toddlers with ASD had a number of different consonants that was similar to that of language-matched peers.

One framework in which we might interpret these findings is the *social feedback loop*, proposed in Warlaumont et al. (2014) and Patten et al. (2014). Under this view, infants' speech production is shaped by caregiver responses, as demonstrated by work showing that infants who receive contingent feedback to their babbles restructure them to include phonological patterns from their caregivers' speech, whereas infants who receive noncontingent feedback do not (Goldstein & Schwade, 2008). In ASD, there are three possible ways that the social feedback loop might be disordered. First, lower vocalization rate provides infants with ASD with fewer opportunities for adult feedback. Second, adult responses to infants with ASD might be less contingent on the infants' speechlike vocalizations, possibly because of a reduced social quality to those vocalizations. Third, social impairment might reduce the ability of infants with ASD to make use of adult feedback.

The current results show that, at least in HRA+ toddlers whose expressive language is largely within normal limits, lower vocalization rate by itself does not always result in significantly smaller consonant inventories. With regard to the second possibility, and drawing on the same groups of participants as in this study, Talbott, Nelson, and Tager-Flusberg (2015) demonstrated that mothers of HR infants do contingently reinforce their infants' speechlike vocalizations at the same rates as do mothers of LR infants. Therefore, it is unlikely that, in these participants, the social feedback loop is impaired by reduced parental feedback. The remaining alternative from the social feedback loop is that, in general, HRA+ toddlers are not as able to make use of feedback to modify their own speech production to match the ambient model. In the largely language-normal HRA+ toddlers investigated here, this factor may be operating, but may not have resulted in frank consonant production delays.

Consistent with the results of Van Severen et al. (2012), we found that, in general, there is a positive concurrent relationship between vocalization rate and number of different consonants. However, this was not true of the HRA+ group at 12 months in our study. In the context of the social feedback loop, it appears that any reduction in the ability to use adult feedback to modify speech production in the HRA+ toddlers at 12 months was not reflected in their number of different consonants. However, for these toddlers it may be reflected in more subtle aspects of speech production that were not examined here, such as use of intonation or percent consonants correct in words. Older verbal children with ASD have been shown to produce unusual intonational contours in speech and a higher rate of residual speech errors (Cleland et al., 2010; Shriberg et al., 2011).

Our fourth finding was that the number of different consonants for the HRA− group at 12 months was significantly lower than that of the LRC group and quite similar numerically to that of the HRA+ group. Yet vocalization rate for the HRA− toddlers was similar to that for the LRC group, with the result that the relationship between the two variables was significantly different for the HRA− group relative to the other two groups. The significant Time × Group interaction in change in number of different consonants over time revealed that the HRA− group's developmental trajectory for this measure was also significantly different from those of the other two groups.

The social feedback loop provides a likely explanation for this finding. If the similar mean number of different consonants for HRA+ and HRA− reflects shared risk for speech delay (subtle, in the case of these particular participants) and the reduction in vocalization rate in HRA+ is seen as stemming from social impairment, the dramatic increase in number of different consonants from 12 to 18 months for the HRA− group could be interpreted as indicating that HRA− toddlers are able to leverage their vocalization rate and their ability to benefit from adult feedback to acquire more new consonants in a shorter amount of time than their HRA+ peers.

Last, we address the finding that no predictive relationship was found between vocalization rate and number of different consonants for any group. This may stem from the fact that the factors affecting vocalization rate and number of different consonants arise from different sources and result in effects of different magnitudes. Note that the average vocalization rate across all three groups increases from 12 to 18 months by almost 35 (51.2 ± 41.3 to 86.4 ± 58.3), but the number of different consonants increases over the same time period by only approximately four consonants (10.1 ± 3.8 to 13.8 ± 4.0). From 18 to 24 months, the increases are approximately 50 (86.4 ± 58.3 to 136.0 ± 66.0) and, again, four (13.8 ± 4.0 to 17.7 ± 3.6), respectively. Thus, the two variables are not tightly related, and the relationship diminishes over time: vocalization rate increases faster than number of different consonants. Furthermore, the number of different consonants a child can show is limited by the number of consonants in English (24), whereas speech movement speed (and thus vocalization rate) continue to increase with age (Nip, Green, & Marx, 2009) until well into adulthood. It is clear that factors contributing to increase in number of different consonants and increase in vocalization rate, and the interplay between them, demand more investigation.

The lack of a prospective relationship between vocalization rate and number of different consonants has implications for the idea that less vocal practice can result in consonant production delays (Pharr et al., 2000). Research has shown that children who are prevented from babbling by tracheostomy but who are language-normal do show lower rates of canonical babbling and delays in consonant acquisition (Bleile, Stark, & Silverman McGowan, 1993; Locke & Pearson, 1990). However, the present results demonstrate that the relationship between vocalization rate and number of different consonants is complex, nonlinear, and furthermore can differ between different groups of children. Although it may be true in the largest sense that amount of vocalization experience is related to later size of consonant inventory, the precise relationship of these two variables for each child is not well understood. For TD children, once a stable and accurate motor program for producing a speech sound has been established, further practice may result in only diminishing improvements. For children at risk for speech delay, there may be a stronger relationship between the amount of premastery practice for speech sounds, and more extensive practice may be needed in order to establish a stable and correct motor program for a particular speech sound.

The present results have two clinical implications. First, for children with a low vocalization rate, use of an elicited speech sample may be a more efficient way to determine the size of a child's independent and relational consonant inventories. Spontaneous samples may be too time-consuming to acquire for these children and, if they are not long enough, may give the impression that their consonant inventories are reduced. Second, although residual speech errors may be present in children with ASD whose language scores are within the average range, these may be (in the words of Shriberg et al., 2011) "negligible for handicap." Thus, developmental time may be better spent teaching social pragmatics skills than remediating residual derhotacized rhotic or dentalized sibilant consonants.

This study has several limitations. Though it focused on toddlers with expressive language scores within the average range, which has the advantage of distinguishing between speech and language development and having closely matched homogeneous groups, our findings may not extend to HR toddlers with language impairment. For toddlers with ASD or at HR for ASD with language impairment, lower vocalization rate may indeed drive consonant production delays. However, factors other than lower vocalization rate may be identified that contribute to consonant production delays. The conclusions from the present study are also limited by its small sample size. As is clear from the introduction, findings on speech development in infants and toddlers who develop ASD are mixed, and more work needs to be done to disentangle the multiple factors that give rise to the phenotypic heterogeneity we see in ASD. Future work should also investigate the phonological production of these toddlers in more detail, including information about phoneme classes used, the syllable positions they are used in, and the use of different syllable shapes. Last, this study was limited by using only perceptual analysis methods. Acoustic analyses, which have the power to reveal potential subperceptual differences in the speech of toddlers with or at risk for ASD, were not included. Future work should aim to use acoustic methods to investigate the existence of potential subperceptual differences in the speech of toddlers at risk for ASD.

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References

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.). Washington, DC: Author.

Bleile, K. (2003). *Manual of articulation and phonological disorders: Infancy through adulthood* (2nd ed.). Clifton Park, NY: Delmar Learning.

Bleile, K., Stark, R., & Silverman McGowan, J. (1993). Speech development in a child after decannulation: Further evidence that babbling facilitates later speech development. *Clinical Linguistics & Phonetics, 7,* 319–337.

Boucher, J. (2012). Research review: Structural language in autistic spectrum disorder – characteristics and causes. *Journal of Child Psychology and Psychiatry, 53,* 219–233.

Bryson, S., Zwaigenbaum, L., McDermott, C., Rombough, C., & Brian, J. (2007). The autism observation scale for infants: Scale development and reliability data. *Journal of Autism and Developmental Disorders, 38,* 731–738.

Christensen, D. L., Baio, J., Braun, K., Bilder, D., Charles, J., Constantino, J. N., . . . Yeargin-Allsopp, M. (2016). Prevalence and characteristics of autism spectrum disorder among children aged 8 years — Autism and developmental disabilities monitoring network, 11 sites, United States, 2012. *Morbidity and Mortality Weekly Report (MMWR), 65,* 1–23. http://dx.doi.org/10.15585/mmwr.ss6503a1

Cleland, J., Gibbon, F., Peppé, S., O'Hare, A., & Rutherford, M. (2010). Phonetic and phonological errors in children with high functioning autism and Asperger syndrome. *International Journal of Speech-Language Pathology, 12,* 69–76.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement, 20,* 37–46.

Gamliel, I., Yirmiya, N., Jaffe, D., Manor, O., & Sigman, M. (2009). Developmental trajectories in siblings of children with autism: Cognition and language from 4 months to 7 years. *Journal of Autism and Developmental Disorders, 39,* 1131–1144.

Garson, G. (2012). *Curve fitting and nonlinear regression*. Asheboro, NC: Statistical Publishing Associates.

Gernsbacher, M., Geye, H., & Ellis Weismer, S. (2006). The role of language and communication impairments within autism. In P. Fletcher & J. Miller (Eds.), *Language disorders and developmental theory*. Philadelphia, PA: John Benjamins.

Goldstein, M., & Schwade, J. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychological Science, 19,* 515–523.

Kjelgaard, M., & Tager-Flusberg, H. (2001). An investigation of language impairment in autism: Implications for genetic subgroups. *Language and Cognitive Processes, 16,* 287–308.

Kover, S., Davidson, M., Sindberg, H., & Ellis Weismer, S. (2014). Use of the ADOS for assessing spontaneous expressive language in young children with ASD: A comparison of sampling contexts. *Journal of Speech, Language, and Hearing Research, 57,* 2221–2233.

Locke, J. L., & Pearson, D. M. (1990). Linguistic significance of babbling: Evidence from a tracheostomized infant. *Journal of Child Language, 17,* 1–16.

Lord, C., Risi, S., Lambrecht, L., Cook, E., Jr., Leventhal, B., DiLavore, P., . . . Rutter, M. (2000). The Autism Diagnostic Observation Schedule– Generic: A standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30,* 205–223.

Lynch, M., Oller, D., Steffens, M., & Buder, E. (1995). Phrasing in prelinguistic vocalizations. *Developmental Psychology, 28,* 3–25.

Messinger, D., Young, G. S., Ozonoff, S., Dobkins, K., Carter, A., Zwaigenbaum, L., . . . Sigman, M. (2013). Beyond autism: A baby siblings research consortium study of high-risk children at three years of age. *Journal of the American Academy of Child & Adolescent Psychiatry, 52,* 300–308.

Messinger, D., Young, G. S., Webb, S. J., Ozonoff, S., Bryson, S. E., Carter, A., . . . Zwaigenbaum, L. (2015). Early sex differences are not autism-specific: A Baby Siblings Research Consortium (BSRC) study. *Molecular Autism, 6,* 32.

Mullen, E. (1985). *Mullen Scales of Early Learning*. San Antonio, TX: Pearson.

Nip, I., Green, J., & Marx, D. (2009). Early speech motor development: Cognitive and linguistic considerations. *Journal of Communication Disorders, 42,* 286–298.

Oller, D. & Lynch, M. (1992). Infant vocalizations and innovations in infraphonology: Toward a broader theory of development and disorders. In C. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 509–536). Timonium, MD: York.

Ozonoff, S., Young, G., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., . . . Stone, W. (2011). Recurrence risk for autism spectrum disorders: A Baby Siblings Research Consortium study. *Pediatrics, 28,* e488–e495.

Patten, E., Belardi, K., Baranek, G., Watson, L., Labban, J., & Oller, D. (2014). Vocal patterns in infants with autism spectrum disorder: Canonical babbling status and vocalization frequency. *Journal of Autism and Developmental Disorders, 44,* 2413–2428. https://doi.org/10.1007/s10803-014-2047-4

Paul, R., Fuerst, Y., Ramsay, G., Chawarska, K., & Klin, A. (2011). Out of the mouths of babes: Vocal production in infant siblings of children with ASD. *Journal of Child Psychology and Psychiatry, 52,* 588–598.

Paul, R., & Jennings, P. (1992). Phonological behavior in toddlers with slow expressive language development. *Journal of Speech and Hearing Research, 35,* 99–107.

Pennington, B., & Bishop, D. V. M. (2009). Relations among speech, language, and reading disorders. *Annual Review of Psychology, 60,* 238–306.

Pharr, A., Ratner, N., & Rescorla, L. (2000). Syllable structure development of toddlers with expressive specific language impairment. *Applied Psycholinguistics, 21,* 429–449.

Plumb, A., & Wetherby, A. (2013). Vocalization development in toddlers with autism spectrum disorder. *Journal of Speech, Language, and Hearing Research, 56,* 721–734.

Rapin, I., Dunn, M., Allen, D., Stevens, M., & Fein, D. (2009). Subtypes of language disorders in school-age children with autism. *Developmental Neuropsychology, 34,* 66–84.

Rescorla, L., & Ratner, N. (1996). Phonetic profiles of toddlers with specific expressive language impairment (SLI-E). *Journal of Speech and Hearing Research, 39,* 153–165.

Rutter, M., Bailey, A., & Lord, C. (2003). *Social Communication Questionnaire*. Los Angeles, CA: Western Psychological Services.

Rvachew, S., & Brosseau-Lapré, F. (2012). *Developmental phonological disorders: Foundations of clinical practice*. San Diego, CA: Plural.

Schoen, E., Paul, R., & Chawarska, K. (2011). Phonology and vocal behavior in toddlers with autism spectrum disorders. *Autism Research, 4,* 177–188.

Seigel, B. (2004). *Pervasive Developmental Disorders Screening Test, Second Edition*. San Antonio, TX: Pearson.

Shriberg, L., Paul, R., McSweeny, J., Klin, A., Cohen, D., & Volkmar, F. (2011). Speech and prosody characteristics of adolescents and adults with high-functioning autism and Asperger syndrome. *Journal of Speech, Language, and Hearing Research, 44,* 1097–1115.

Shumway, S., & Wetherby, A. (2009). Communicative acts of children with autism spectrum disorders in the second year of life. *Journal of Speech, Language, and Hearing Research, 52,* 1139–1156.

Talbott, M., Nelson, C., & Tager-Flusberg, H. (2015). Maternal gesture use and language development in infant siblings of children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 45,* 4–14.

Van Severen, L., Van Den Berg, R., Molemans, I., & Gillis, S. (2012). Consonant inventories in the spontaneous speech of young children: A bootstrapping procedure. *Clinical Linguistics & Phonetics, 26,* 164–187.

Warlaumont, A., Richards, J., Gilkerson, J., & Oller, D. (2014). A social feedback loop for speech development and its reduction in autism. *Psychological Science OnLineFirst, 25,* 1314–1324.

Wetherby, A., Prizant, B., & Hutchinson, T. (1998). Communicative, social/affective, and symbolic profiles of young children with autism and pervasive developmental disorders. *American Journal of Speech-Language Pathology, 7,* 79–91.

Wetherby, A., Watt, N., Morgan, L., & Shumway, S. (2007). Social communication profiles of children with autism spectrum disorders late in the second year of life. *Journal of Autism and Developmental Disorders, 37,* 960–975.

Appendix

This section details the procedures used to mathematically model the relationship between speechlike vocalization rate and number of different consonants for the LRC, HRA+, and HRA- groups. A mathematical model is a description of a system using numerical relationships, which can be linear or nonlinear. Two general steps comprise the analysis described here. First, a curve type (linear, logarithmic, s-curve, etc.) was identified that best described the relationship between the two variables for each group. Second, the equation representing the best-fit curve for the LRC group was used as a basis for determining whether the relationship between these two variables was the same for the HRA+ and HRA- groups.

Step 1: Identifying Best-Fit Curves

In the first part of the analysis, we asked what mathematical function best described the relationship between speechlike vocalization rate and number of different consonants. The SPSS Curve Estimation Model (SPSS v.22) was used for this purpose. Vocalization rate was entered as the independent variable and number of different consonants was entered as the dependent variable. Several curve types (e.g., linear, logarithmic, and s-curve) were selected to compare. The function performs an ANOVA and saves the residuals (error values) for each model as additional variables in the dataset.

Next, the error values were converted to absolute values using the Transform -> Compute option in SPSS. Then, using paired t-tests, pairs of absolute error variables were compared to assess whether the mean absolute error was significantly lower for one curve type than any other. The curve type with the lowest mean absolute error was selected as the best fit for the two variables. For each of the three groups (LRC, HRA-, HRA+), and for each of the ages tested (12, 18, and 24 months), the best-fit curve was a logarithmic one. The equations for each group's curve at each age are presented in Figure 3.

Step 2: Comparing Curves Across Groups

In the second part of the modeling analysis, we asked whether the relationship between the two variables (speechlike vocalization rate and number of different consonants) was the same for the HRA+ and HRA- groups as for the LRC group. To do this, we used a simple Excel procedure. Starting with the 12-month data, we entered the actual speechlike vocalization rate and number of different consonants data points for each group onto a spreadsheet. Then, we entered the speechlike vocalization rate data points for the HRA+ group into the LRC group's equation. This allowed us to predict how many different consonants each HRA+ participant would have produced had the relationship between speechlike vocalization rate and number of different consonants been the same as for LRC. This step was repeated for the HRA- group's 12-month data.

Next, we performed independent-samples t-tests to compare the actual number of different consonants to the predicted number for the HRA+ groups. A significant t-test would indicate that the number of different consonants for HRA+ predicted by the LRC equation was different from the actual number for that group and that the relationship between speechlike vocalization rate and number of different consonants was significantly different than for LRC. A nonsignificant t-test would indicate that the relationship between the two variables was within normal limits (i.e., not significantly different from LRC). We performed the independent samples t-tests on the actual and predicted number of different consonants for the HRA+ and HRA- groups.

As described in the text, the relationship between speechlike vocalization rate and number of different consonants was within normal limits for the HRA+ group at 12, 18, and 24 months, despite a significantly lower vocalization rate at all ages and a significantly lower number of different consonants at 18 months. In contrast, for the HRA- group, the relationship between these two variables was significantly different from normal at 12 months, despite no significant difference in vocalization rate at any age and no significant difference in number of different consonants at any age.