

Social and endogenous motivations in the emergence of canonical babbling in infants at low and high risk for autism

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Abstract

There is a growing body of research emphasizing the role of social and endogenous motivations in human development. The present study evaluated canonical babbling across the second-half year of life using all-day recordings of 98 children with typical or elevated likelihoods of autism i.e., at “low risk” or “high risk”, respectively. Canonical babbling ratios (CBRs) were calculated from human coding along with Likert-scale ratings on vocal turn taking and vocal play in each segment. We observed no main effect of risk on CBRs. CBRs were significantly elevated during high vocal play. High turn taking yielded a weaker significant effect. We conclude that both social and endogenous motivations may drive infants’ tendencies to produce their most advanced vocal forms.

Introduction

Canonical babbling has been long established as a robust stage of prelinguistic vocal development, occurring prior to the emergence of early words, having been argued to constitute a necessary foundation for vocabulary development (Koopmans-van Beinum & van der Stelt, 1986; Oller, 2000; Stark, 1980). To our knowledge, there is no published research evaluating the role of exploratory motivation in infants’ production of canonical babbling and no direct evaluation of the extent to which social engagement in vocal turn taking affects it. In the present research, we observed babbling in infants at low and high risk for autism (LR and HR) in naturalistic settings. Segments extracted from all-day home audio recordings were rated for levels of infant turn taking and independent vocal play to measure the degree of social and non-social vocal activity (and thus, social and exploratory motivations, respectively). We examined these findings within an evolutionary developmental biology (evo-devo) framework (Bertossa, 2011; Carroll, 2005; Newman, 2000, 2012), in part to inform our understanding of how babbling may be used to signal developmental progress to caregivers (Locke, 2017; Oller & Griebel, 2005, 2008). Comparing differences between autism risk groups may help to elucidate exploratory tendencies and potential breakdowns in social motivation in autism, as well as provide clinically useful perspectives on the development of language foundations.

Canonical Babbling Development in Typical Development and Autism

Throughout the first half year of life, infants evidence an emerging capacity to control and coordinate the respiratory, phonatory, and articulatory mechanisms. Within the second half year, and rarely later than 10 months, infants begin canonical babbling (Oller, 1980; Stark, 1980), defined as the production of mature consonant-vowel syllables with well-formed transitions between the consonant- and vowel-like elements (e.g., [baba], [dada]). These syllables provide a basis for interaction and play with repeated and varied syllables, foundational for the production of words (Oller, 2000). The onset of canonical babbling is known to be a robust predictor of typical speech development (Nathani et al., 2006; Oller et al., 1998), with delays observed in several disorders, including deafness (Eilers & Oller, 1994; Oller & Eilers, 1988), Down

syndrome (Lohmander et al., 2017; Lynch et al., 1995), Fragile X syndrome (Belardi et al., 2017), cerebral palsy (Levin, 1999; Nyman & Lohmander, 2018), and William syndrome (Masataka, 2001). Lang et al. (2019) reviewed the mixed evidence on canonical babbling onset in autism spectrum disorder, summarized below.

Autism spectrum disorder (ASD) is a neurodevelopmental condition characterized by deficits in social communication and restricted interests and repetitive behaviors (American Psychiatric Association, 2013). The average age of diagnosis for children is now reportedly around 60 months (van 't Hof et al., 2020) but can occur at much younger ages (Zwaigenbaum et al., 2015). Symptoms in early infancy include reduced or absent dyadic interaction, social responsiveness, and joint attention (Kellerman et al., 2019; Mundy, 2017; Ozonoff et al., 2010), and there is evidence suggesting prelinguistic vocal developmental anomalies (e.g., Sheinkopf et al., 2012). Two studies previously analyzed *canonical babbling ratios* (CBRs, the number of canonical syllables divided by the number of all syllables in a sample) in infants with ASD. Patten et al. (2014) showed significantly lower ratios in children with autism at 9-12 months and 15-18 months compared to controls, and Paul et al. (2011) found lower ratios at 9 months in infants at high risk for autism compared to low-risk infants, but not in a 12-month group. Two retrospective video analysis studies also found mixed results when analyzing *canonical syllables per minute*. Werner et al. (2000) found no differences between infants later diagnosed with autism relative to typically developing controls between 8-10 months but significant differences at 12 months in complex babbling rates, and Chericoni et al. (2016) found no differences between the two groups at ages 6-12 months. Two other studies observed *ages of onset* for the canonical babbling milestone in infants at low and high risk for autism. Iverson & Wozniak (2007) reported that high-risk infants had a wider range for age of onset for canonical babbling (5-18 months) compared to the low-risk group (5-9 months), but LeBarton & Iverson (2016) found 33/37 infants at high risk for autism reached the canonical babbling stage by 14 months, with a typical average mean age of onset (7.67 months). In a feasibility study analyzing *syllable complexity*, Pokorny et al. (2017) found that an equal number of neurotypical and autistic infants in each group (4/10) produced more complex types of utterances than single canonical syllables by 10 months.

Thus, there is a lack of conclusive evidence on canonical babbling developmental differences in infants at low risk or at high risk for autism or for infants later diagnosed with ASD. Inconsistent findings across studies may be attributed to the well-established variability in autism characteristics, the varying methodologies used to analyze babbling development, or the differing group types included (for example, children diagnosed versus children at risk). Additional research including larger sample sizes would also be helpful to provide a smaller margin of error when comparing typically developing and autistic infants. In the present study, we compare the emergence of canonical babbling for infants at low and high risk for autism using the largest sample size to date (98 infants) and with evaluation based on sampling from all-day recordings across the second half-year of life (483 total recordings).

An Evolutionary-Developmental Perspective on the Role of Social Motivation in Canonical Babbling

When evaluating the emergence of canonical babbling, there is reason to consider potential differences in intrinsic motivations behind production of prelinguistic protophones between autism risk groups. The present paper is influenced by evolutionary-developmental biology (evo-devo), an approach emphasizing that natural selection tends to target developmental processes (Bertossa, 2011; Müller & Newman, 2003). Natural selection of advantageous characteristics also tends to build new characteristics upon existing ones. Often there is a sort of natural logic where early characteristics in development or evolution form foundations for later characteristics, tending to keep the order of appearance of evolved structures or behavioral capabilities consistent with their order of development (Carroll, 2005; Newman, 2016).

Following this line of thinking, we and others have hypothesized positive selection pressure on the production of infant protophones, which are foundations for speech in that protophones manifest a capacity to produce phonation and other speech characteristics voluntarily, in the absence of external stimulation, as is required in speech. Such baby sounds can be seen as fitness signals, selected because they tend to elicit long-term investment from caregivers, required across the lengthy period of relative helplessness, or altriciality, of infant humans (Locke, 2017; Long et al., 2020; Oller et al., 2016, 2019). In accord with the fitness signaling hypothesis, the *quality* of infant vocalizations can be considered a salient and reliable signal of fitness. Parents throughout hominin history can be viewed as having implemented the selection of the infant trait of endogenous protophone production.

In line with this reasoning, it might be seen as advantageous for infants to produce their most advanced vocal forms during periods of caregiver attention. Empirical evidence has been presented to show that caregivers are keenly aware of their infants' developmental capabilities, including their vocal capabilities (Bodnarchuk & Eaton, 2004; Lyytinen et al., 1996; Oller et al., 2001). Higher rates of canonical syllables (as opposed to less advanced protophones) during social interaction than during periods of aloneness could suggest a social motivation for producing more advanced protophones. If the idea is on target, we might propose that canonical babbling was selected as a salient signal of developmental progress, especially during social interaction. Furthermore, a breakdown in the social motivation of infants as a result of a neurodevelopmental condition such as autism could potentially result in lower rates of canonical babbling during social interaction than would occur in typically developing infants.

The *social motivation theory* (Chevallier et al., 2012) posits that reduced social attention in infancy leads to the social-cognition developmental differences observed in autism spectrum disorder. Additional research supports this notion, showing social information is less salient in individuals with autism (Chevallier et al., 2013; Schultz et al., 2000; Weeks & Hobson, 1987) and less intrinsically rewarding in individuals with autism compared to typical controls (Bottini, 2018; Gray et al., 2018; Scott-Van Zeeland et al., 2010; Sepeta et al., 2012). Reductions in social orienting may also affect language development (Baranek et al., 2013; Dawson et al., 2004; Su et al., 2020), a supposition supported by speculations predicting positive associations between social motivation and language emergence; these speculations

have yielded, for example, the continuity hypothesis (Bruner, 1974), the speech attunement framework (Shriberg et al., 2011), and the elicited bootstrapping hypothesis (Camarata & Yoder, 2002), which has been recently elaborated by Su et al. (2020). This body of research and theory highlights the importance of identifying early differences in social interaction in infants at risk for autism in order to provide support and intervention as early as possible. The research also highlights the possibility that parents may, with or without intervention, tend to adjust to the patterns of communication of their infants and thus to mitigate possible negative effects of the possibly low social motivation of their infants at risk.

Interestingly, there is limited research examining endogenously-motivated vocal learning in infancy (but see Long et al., 2020; Moulin-Frier et al., 2014; Moulin-Frier & Oudeyer, 2013). Instead, the great majority of research has focused on parental activity, rather than on internal motivations of the infant as influencing vocal development (e.g., Albert et al., 2018; Elmlinger et al., 2019; Franklin et al., 2013; Goldstein et al., 2003; Goldstein & Schwade, 2008; Gros-Louis et al., 2014; Hsu & Fogel, 2001; Iyer et al., 2016; Kuhl, 2007; Lee et al., 2018). In a salient recent example of such research, Su and colleagues (2020) found early social motivations around 23 months predicted language skills 2 years later—specifically, higher performance on social motivation tasks was significantly correlated with functional language abilities. Such literature is consistent with the expectation that reduced social attention and inclinations in early infancy may affect the infant’s motivation to produce advanced vocal forms during interaction, and thus may yield reductions in vocal fitness signaling in infants with low social motivation. It is thus consistent with the social motivation theory and also with our evo-devo approach, to predict that infants with typically developing levels of social motivation will produce higher rates of canonical syllables during periods of high vocal interaction than infants with low social motivation.

The present body of data offers the opportunity to evaluate this prediction during periods where infants engage in high or low amounts of vocal turn taking (i.e., social interaction) with caregivers, while comparing canonical babbling rates of infants who are at low risk for autism (presumably with *typical* levels of social motivation) and infants who are at high risk for autism (presumably with *lower* levels of social motivation). In accord with the evo-devo perspective alongside the social motivation theory, we anticipate that low risk infants will use higher rates of canonical babbling during periods of high turn taking as a result of an evolved mechanism involving social motivation that causes increases in advanced vocal production during interaction and signals fitness to caregivers, but that high risk infants will not show higher rates during high turn taking due to reduced social motivation and thus a reduced capability to signal developmental fitness.

On the Role of Exploratory Vocal Play in Typical Development and Autism

Contradicting the seemingly implicit assumption in child development literature that infant vocalizations are routinely interactive, several researchers have recently emphasized the role of intrinsic motivation in the development of emotional and cognitive systems, including those related to vocal development

(Davis & Panksepp, 2018; Moulin-Frier et al., 2014; Moulin-Frier & Oudeyer, 2013). We are influenced by the literature-based hypothesis that infants at low autism risk should be expected to produce more canonical syllables during social interaction, while high-risk infants should not be expected to do so, but recent evidence suggests a contrasting possibility. Research by Long et al. (2020) has shown that typically developing infants produce protophones (both canonical and precanonical) predominantly endogenously. Even in laboratory recordings, during periods when parents seek social interaction with infants, most protophones (~60%) appear not to be directed to parents, and this predominance of endogenous vocalization is even stronger (~80%) when parents are present with infants but not attempting to engage them. The results suggest that research on infant tendencies to vocalize at varying levels of advancement should compare circumstances showing high vocal turn taking with circumstances showing high endogenous vocal activity, which we shall refer to here as *vocal play* (Stark, 1980, 1981). Thus, we deem it important to examine not only social motivations for the production of canonical syllables but also intrinsic, exploratory motivations.

During vocal play, infants explore sensorimotor aspects of the vocal apparatus and practice with various properties of sounds such as syllabic structure, amplitude, and pitch control. Play has been well established to be important throughout development (Berk, 1994; Davis & Panksepp, 2018; Panksepp, 2005; Panksepp et al., 1984; Panksepp & Biven, 2012; Piaget, 1952). Stark described vocal play as highly variable, with infants producing sounds in new and repeated combinations, modifying patterns and features during bouts of independent infant vocal activity (Stark, 1980). This description evokes the notion that vocal play can be considered a sensorimotor exploration of the vocal mechanism, which may be necessary to learn and master speech production.

Although it appears that infants in general are endogenously motivated to produce protophones, the social motivation theory of autism hints at the intriguing possibility that infants with autism may be relatively more inclined to vocalize independently/endogenously than neurotypical infants. Further, the reasoning might be extended to suggest that the rate of canonical babbling would be relatively higher during vocal play for infants with autism than for typically developing infants. These speculations are perhaps supported by the fact that children with autism have been shown to spend more time participating in isolated play with objects and to produce more repetition of physical actions in play compared to typically developing peers (Atlas, 1990; Naber et al., 2008; Sigman & Ungerer, 1984; Williams et al., 2001). These patterns suggest that as infants with autism begin to produce canonical syllables, they may be particularly interested in the physical, articulatory properties of these sounds—not unlike their often-intense interest in the physical characteristics of objects—and they may produce these sounds with greater repetition, perhaps enjoying the self-stimulatory nature of the repetition.

Specific Aims and Hypotheses

The present research compares canonical babbling ratios (CBRs) of infants at low and high risk for autism during recorded segments with high and low levels of both turn taking and vocal play across three

age ranges during the second half-year of life. We first analyzed for possible differences in CBR between infants of high and low maternal education level, treated as a proxy for socioeconomic status (SES), and found no significant differences; therefore, we do not report maternal education effects in the data below. Sex differences were evaluated in a recent study from our laboratory using the present dataset, and no significant sex differences for CBR were found (Oller et al., 2020); therefore, we do not include sex as a variable in the present work.

We view our effort here as first step in a process that is ongoing to help reveal predictors of autism using human coding of all day recordings. We address a single dependent variable, CBR. Canonical babbling can be viewed in terms of a variety of features including for example, differences among syllable types or in terms of differences in the ordering of syllable types occurring across time, neither of which is reflected in the CBR measure. Further, the methods of assessment of both the dependent and independent variables can be expected to be improved in the future. Whatever the results of the present work, subsequent efforts addressing infant vocalizations at higher granularity and greater methodological sophistication may greatly add to the results presented here. The following presents hypotheses to be evaluated in the present paper.

Predicted Interactions

Our primary analyses addressed Turn Taking (TT) and Vocal Play (VP) separately. Consequently, one analysis included three variables: Age, Risk, and TT, and another: Age, Risk, and VP. Based on the social motivation theory of autism, we predicted two interactions involving TT and VP in the following two hypotheses:

1. CBRs in low-risk (LR) infants will be higher during segments with high TT than low TT, while high-risk (HR) infants will not show higher CBRs during high TT.
2. CBRs in HR infants will be higher during segments with high than low VP, while LR infants will not show higher CBRs during high than low VP.

As a followup to the broader interaction analyses, we also examined the possible interaction between Risk and Age including only those two independent variables (TT and VP not included). This analysis is exploratory because traditional statistical approaches only recommend full-model analyses. The exploratory analysis is justified, however, because the work is ongoing and relevant variables still under consideration need to be evaluated from a variety of perspectives. We posed the following exploratory hypothesis:

3. CBRs will increase to a greater extent in LR infants across the three ages than in HR infants.

Predicted Main Effects

For interpretive perspective, we also conducted an exploratory analysis addressing main effects (no interactions) for CBR in a single analysis including Age, Risk, TT, and VP. We posed four exploratory hypotheses:

- a. Higher CBRs will occur at the later ages than earlier ages, highlighting infants' increasing ability to control the speech mechanism.
- b. Higher CBRs will occur in the LR group compared to the HR group, a prediction based on the predominant, albeit inconsistent findings of the existing literature (Lang et al., 2019).
- c. Higher CBRs will occur during segments with high TT compared to low TT.
- d. Higher CBRs will occur during segments with low VP compared to high VP.

Methods

The institutional review boards of the [UNIVERSITY #1] and [UNIVERSITY #2] approved the procedures used in this study. Families provided written consent prior to participation.

Participants

As part of an NIH-funded Autism Center of Excellence conducted at the [RECRUITMENT CENTER] in [LOCATION], 100 families of newborn infants were recruited via flyers, advertisements, social media and community referrals to participate in a longitudinal sibling study of development across the first three years of life. We analyzed data from 98 infants (two infants did not complete recordings at the ages studied). Infants were recruited as being either at high risk (HR, n=49) or low risk (LR, n=49) for autism. Infants were deemed HR if they had at least one older biological sibling with a confirmed autism diagnosis, and LR if they had no familial history of autism in 1st, 2nd, or 3rd degree relatives. Risk status, rather than ASD outcome, was treated as a primary variable here, because thus far only a small number of infants in our dataset have a confirmatory diagnosis of autism—our research is ongoing, and we plan to report later on a sample size about three times this large, along with a correspondingly larger number of infants with a confirmatory diagnosis. Thus, in the present study we assess factors associated with an elevated likelihood (i.e., statistically “high risk”) and typical likelihood (i.e., statistically “low risk”) for an autism diagnosis (Chawarska et al., 2014; Ozonoff et al., 2011; Rogers, 2009). Sex and maternal education (as a proxy for SES) measures[1] were balanced to the extent possible in accord with known autism male-to-female ratios (Loomes et al., 2017) and SES make-up of participants living in the greater [LOCATION] area who were willing and able to participate in a 3-year longitudinal study. Table 1 presents demographic information for the infants included in this study.

*Table 1. Numbers of infants by Risk, Sex, and maternal education as a proxy for socio-economic status (SES). *One infant's family did not report maternal education.*

		High-Risk	Low-Risk	Total
Total		49	49	98
Sex	Male	34	30	64
	Female	15	19	34
SES*	Low SES	26	18	44
	High SES	22	31	53

Families were asked to complete audio recordings once a month from 1-36 months of age. This study used data collected between 6.5 and 13 months of age to represent the typical range of expected onset for and high infant activity in canonical babbling. These data were grouped into three age ranges for analysis and labeled with reference to the approximate mean age within each group: 6.5-8.49 months (7.5 months), 8.5-10.49 months (9.5 months), and 10.5-13 months (12 months). It should be noted that the 12-month age group included a slightly larger age range (2.5 months) than the 7.5- and 9.5-months age groups (2 months). There were no significant within-age-group differences between risk groups, as shown in Table 2.

Table 2. Descriptive statistics (mean age, age range) for the three age groups, 7.5, 9.5, and 12 months, separated by risk group, LR and HR.

Age Group	Risk Group	Mean Age	Age Range (SD)
7.5	LR	7.50	6.51 - 8.48 (.59)
	HR	7.53	6.51 - 8.48 (.59)
9.5	LR	9.41	8.52 - 10.42 (.54)
	HR	9.53	8.52 - 10.49 (.57)
12	LR	11.64	10.52 - 12.92 (.69)
	HR	11.65	10.52 - 12.92 (.67)

Audio Recordings

Audio recordings were completed using LENA recording devices (Gilkerson et al., 2017; Zimmerman et al., 2009). These devices are battery powered and secured inside the pocket of a special vest or clothing item with button clasps and can record up to 16 hours of audio per charge. LENA devices have a 16 kHz sampling rate and given the low mouth-to-microphone distance, usually offer excellent audio quality for human coding of recorded material.

Recording Procedures

Families completed all-day recordings starting from the first month. Once a month, parents were provided with a LENA recording device and were supplied regularly with appropriately sized clothing for their infant

to wear throughout the day, as well as full instructions on how to carry out recordings. The device was returned to the research project staff at the [RECRUITMENT CENTER] each month following recording days for data processing. Each family completed ~5 total recordings (range: 1-7) across the ages studied, with an average recording time of approximately 11 hours per day.

Coding Procedures

Twenty-one 5-minute segments were randomly extracted from each recording and coded in real-time for infant utterance counts by 16 trained graduate student coders[2] at the [CODING LABORATORY]. [CODING LABORATORY] staff were blinded to all diagnostic and demographic information associated with each infant recording throughout the coding process. From these 21, eight segments with the highest infant vocalization volubility and a range of infant-directed speech[3] were selected by an automated method from each recording, yielding a total of 3799 segments. Fifteen of these segments were later excluded on the basis of having no infant vocalizations; therefore, final analyses were completed on a total of 3784 segments.

Canonical Babbling Ratios as a Measure of Advanced Prelinguistic Vocal Forms

In a second pass of coding, the 8 selected segments were coded in real-time for infant canonical and non-canonical syllable counts. Listeners identified a total of 30,263 canonical syllables, and 233,877 noncanonical syllables across the segments. To measure the emergence of advanced vocal forms, a *canonical babbling ratio* (CBR) was calculated as the total number of canonical syllables divided by the total number of syllables in each segment. Means and standard deviations of CBRs were calculated for each infant at each age. These data were then averaged within each age (7.5, 9.5, and 12 months) and risk group (HR and LR). Occasionally, families did not complete a monthly recording, and for those cases there were no data at the infant's age to include in the analysis. In cases where there were multiple recordings within an age for an infant, the means and SDs of these recordings were averaged for analysis.

Turn Taking and Vocal Play as Measures of Infant Vocal Function

Following syllable coding of each 5-minute segment, coders answered a 17-item questionnaire regarding how often infants used vocalizations for various functions based on the audible context of the infant's environment in each segment. See Long et al. (2020) for theoretical perspectives on making intuitive judgments of infant vocal functions. We used two items from the questionnaire to broadly assess rate of vocalizations judged to be social or exploratory within each segment. Specifically:

1. Were any of the infant's protophones used in vocal turn taking with another speaker?
2. Were any of the infant's protophones purely vocal play or vocal exploration?

Coders were trained on the identification of a variety of infant vocal functions including the two items listed. *Turn-Taking* was defined to refer to infant vocalizations produced during the audible back and forth of vocalizations (and/or speech in the case of a verbal partner) between the infant and another person (i.e., caregiver, sibling, etc.); turn-taking in this definition requires that the infant be perceived as responding to infant-directed speech, not merely vocalizing during caregiver talk, which is often directed to other speakers.

Vocal Play was defined as inspired by Stark (1980), as infant vocalizations produced independent of social interaction or an attempt on the part of the infant to initiate an interaction, as in calling to the caregiver. Often in vocal play, the infant appears to be manipulating vocalic (pitch level, pitch change, and loudness) and even consonant-like elements without any social intention. The vocalizations of vocal play must be judged to be of sufficient magnitude to be noticed and to have been voluntarily produced (not accidentally, as in the case of effort grunts).

Vocal play and turn-taking, in accord with our definitions, are in principle independent of each other—no infant utterance can properly be treated as both, according to the definitions. Thus vocal play in our definition is not socially-directed, and excludes socially interactive playful vocalization.

After listening to each segment, coders responded to each question using a Likert Scale which aligned to the following rating designations: *1 = Never, 2 = Less than half the time, 3 = About half the time, 4 = More than half the time, 5 = Close to the whole time*. For example, a TT rating of 5 was applied to segments where a caregiver was clearly speaking to the infant, and the infant was vocalizing in an apparent back and forth vocal interaction for essentially the whole segment. Segments with a VP rating of 5 would indicate the listener perceived the vast majority of infant vocalizations across the segment as playful and exploratory and not directed to another person in any way. The subjective, Likert Scale response system is intended to simulate the kinds of judgments caregivers make (we presume often unconsciously) regarding the function of vocalizations produced by infants throughout the day.

Although TT and VP are in principle mutually exclusive, a particular segment can include both TT and VP at different points during the segment. Vocal play can be a catalyst for parent-initiated social interaction (Long et al., 2020) If, for example, the infant is playing with the characteristics of a new sound, parents may repeat these sounds to the infant, initiating a back-and-forth vocal sequence. Thus in segments with high infant vocal activity containing both interactive and non-interactive protophones, a segment could be coded as having high TT and high VP. This happened rarely, but still, 0.42% of segments rated high on TT (rating of 4 or 5) were also rated high on VP (rating of 4 or 5). 18% of segments were rated as having any TT (ratings 2-5) and any VP (ratings 2-5).

Ratings for TT and VP very were dissimilarly distributed across the Likert-scale range, as shown in Table 3. In order to compare levels of TT and VP with maximally similar numbers of segments at two levels in

both cases, we split TT ratings into “No Turn Taking” (rating of 1) vs. “Any Turn Taking” (ratings 2-5), and VP ratings into “Low Vocal Play” (ratings 1-3) vs “High Vocal Play” (ratings 4-5) levels. Even with this procedure, the TT split yielded a dramatic imbalance, with > 80% of all segments pertaining to the No TT grouping and 82% of the Any TT segments rated 2 (“less than half the time” on TT). On the other hand, VP was very common, with only 8% rated as having no VP, and 55% rated as having high VP, occurring either “more than half the time” or “close to the whole time.” Crosstabulation counts and percent of total segment ratings across TT and VP variables for both Risk groups are provided in Supplementary Material, Appendix A, illustrating that the distributions for TT and VP were very similar for both groups.

Table 3. Frequency distribution of segments coded for TT and VP. Following the coding of infant syllables in 3784 segments, coders rated each 5-minute segment on the frequency of vocal turn taking (TT) and Vocal Play (VP) for infants at low risk (LR) and high risk (HR) for autism. The distribution of segments along the rating scale for TT and VP was similar for both risk groups. Ratings for each variable were combined into two levels for maximally similar numbers within each category: “No TT” (TT rating: 1) vs “Any TT,” (TT: 2-5) and “Low VP” (VP: 1-3) vs “High VP” (VP: 4-5).

Likert scale rating	Interpretation (Level of occurrence)	TT Level	TT count		VP Level	VP count	
			HR	LR		HR	LR
1	Never	No TT	1564	1482	Low	164	147
2	Less than half the time	Any TT	295	312	VP	307	254
3	About half the time		42	55		431	383
4	More than half the time		18	14	High	506	526
5	Close to the whole time		2	0	VP	513	553

Coder Agreement

Inter-rater agreement was examined for CBRs, TT level, and VP level using a secondary LENA recording dataset coded by 7 of the same graduate student coders following the coding protocol used in the present study and in Oller et al. (2019). The agreement coding for canonical babbling ratios revealed high agreement for both the entire set, with ages ranging across the entire first year ($r = .89$), and for the subset that pertained only to the second half year ($r = .87$), a time period during which CBR varies substantially above 0 across the entire range of ages. Both the questionnaire items yielded far better than chance levels of agreement on the Likert-scale judgments categorized binarily as in the present work (No TT = 1, Any TT = 2-5; Low VP = 1-3, High VP = 4-5) based on Chi square analysis ($p < .001$). For VP there was agreement on 66% of pairings, while for TT there was agreement on 87%, with only fair agreement on kappa (TT = .40, VP = .33). This level of agreement should offer little surprise, given the subjective nature of the judgments. We have been surprised, however, by the power to significantly predict CBR that these blunt measures offer, as will be seen below. See Supplementary Material, Appendix B for additional methodological rationale and empirical information regarding Coder Agreement.

Statistical Approach

We used Generalized Estimating Equations (GEE) (Liang & Zeger, 1986) implemented in R for all analyses (see Supplementary Material, Appendix B for rationale).

Results

The results reported below pertain only to our listed hypotheses. See Supplementary Material, Appendix C for an expanded discussion of findings on all four models.

Hypothesis 1: Turn Taking and Risk

Based on predictions derived from the social motivation theory, Hypothesis 1 predicted higher CBRs in low-risk (LR) infants during segments with some turn taking but no such pattern in high-risk (HR) infants. However, the results did not confirm the hypothesis ($p = .144$, $b = .04$). The mean CBR for HR and LR infants was quite similar for segments with no TT, but showed a complex relation between risk and age (though not significantly) for segments with any amount of TT. CBRs increased in HR infants to a greater extent between 7.5 and 9.5 months compared to LR infants across these two ages ($p < .001$, $b = .06$). Figure 1 provides graphic illustration of the results from the full model for Age, Risk, and TT level.

Hypothesis 2: Vocal Play and Risk

For Hypothesis 2, we predicted an increase in CBRs in HR infants from segments with low to high VP, and a lesser increase or no increase from low to high VP for LR infants, again based on predictions derived from an evo-devo informed perspective on the social motivation theory. There was indeed a significant interaction between VP level and Risk group ($p = .021$, $b = -.03$), but the direction of the effect was the opposite of that predicted. Figure 2 shows that mean CBRs at low VP were comparable (HR = .079, LR = .080), while those at high VP differed more, favoring the LR group (HR = .119, LR = .124).

Post hoc analyses also revealed a significant two-way interaction for CBR between VP level and Age for 7.5 to 9.5 months ($p < .001$, $b = -.06$), reflecting the fact that CBRs differed more between high VP and low VP at 9.5 than at 7.5 months. The difference between VP level and Age for 9.5 to 12 months approached significance ($p = .059$), and the effect was in the opposite direction, namely CBRs differed less for high VP vs low VP at 12 than at 9.5 months.

Additionally, we observed a significant three-way interaction between VP level, Risk, and Age for ages 9.5 and 12 months ($p = .039$, $b = .06$). The three-way interaction for Risk, VP level, and Age at 7.5 and 9.5 months approached significance ($p = .063$). Figure 2 helps illustrate the nature of the three-way interactions. The data from segments rated as having high VP (right-hand panel) suggest a tendency of CBR to grow rapidly from 7.5 to 9.5 months in the HR infants, but to grow less rapidly in the LR infants. The opposite growth pattern (LR more rapid, HR less rapid) is seen from 9.5 to 12 months. No such

differentiation is observable in the left panel. Thus, the data suggest the LR and HR infants show very different patterns of growth in CBR with age, but only in cases of high VP.

Exploratory Hypothesis 3: Age and Risk

Based on the preponderance of prior research in autism, exploratory Hypothesis 3 predicted that CBRs of LR infants would increase to a greater extent across the three ages than CBRs of HR infants. The results did not conform simply to the prediction; in fact mean CBRs for HR infants rose *more* in the first age interval (from 7.5 to 9.5 months, $\sim .067$ CBR units) than for LR infants ($\sim .015$), while they rose *less* in the second interval for HR infants ($\sim .010$) than for LR infants ($\sim .065$), illustrated in Figure 3. These patterns corresponded to a significant interaction of Risk by Age at the first interval (7.5 to 9.5 months, $p = .017$, $b = .04$), but a non-significant interaction of Risk by Age at the second interval (9.5 to 12 months, $p = .192$). This interaction is related to the three-way interactions in the analyses of Age, Risk, and VP as well as to the analyses of Age, Risk, and TT (described in the expanded results, Supplementary Material, Appendix C). See Appendix D for comments on the magnitude of the CBRs and the .15 criterion portrayed in Figure 3.

Exploratory Main Effects Hypotheses

Regarding main effects, the exploratory analysis revealed a significant effect of Age at both intervals (7.5 to 9.5 months, $p < .001$, $b = .04$; 9.5 to 12 months, $p < .001$, $b = .04$), evidencing a strong and near linear increase of CBRs over time for data amalgamated across the Risk groups and independent of TT and VP. There was also a significant effect for both TT ($p < .001$, $b = .04$) and VP ($p < .001$, $b = .06$). The effect sizes, reflected in the b values from the GEE analysis, can be placed in perspective by considering that TT had an effect roughly of the same magnitude as 2-3 months of growth in CBR, and that VP had an even larger effect.

The magnitude of the significant effects by Cohen's d , computed from the raw data—with means and SEs weighted for the number of infants who contributed data in each Risk group at each Age—was 0.29 (small) for both TT and VP. The Age effect size was 0.36 (small) for the first interval, 0.21 (small) for the second, and 0.55 (medium) for a comparison of 7.5 months with 12 months. There was no main effect of Risk ($p = .742$). Figure 4 displays these main effects, including significantly higher CBRs during both any TT and high VP compared to periods of no TT and low VP, respectively.

Discussion

The present work evaluated canonical babbling ratios (CBRs) in 98 infants either at low or high risk for autism across 3784 five-minute segments, selected from all-day recordings in the infants' homes across the second half-year of life. Our work is a first step—in the sense that further research by our group on additional infants is ongoing—to help reveal predictors of autism using human coding of all day

recordings. Additionally, these initial analyses are based only on CBR as a dependent variable, even though canonical babbling will be possible to monitor in much greater detail in the future, and we can hope to improve the methods of evaluation of the independent variables as well.

The recorded segments were coded by a team of highly trained listeners, who determined CBRs and subjective rates of occurrence of vocal turn taking (TT) and vocal play (VP) in each segment. We addressed these data with expectations derived from an evo-devo informed perspective on the social motivation theory of autism. We posited that early language development is driven by the interplay between infant social motivation (presumably reflected in infant interest in caregiver vocalizations and in protoconversation) and infant endogenous inclination to produce copious amounts of vocalization, a tendency that appears to have been naturally selected as a signal of fitness. Specifically, we proposed that infants with an elevated likelihood for having autistic characteristics (being at “high risk”, due to the presence of an older sibling diagnosed with ASD) may have reduced social motivation to signal fitness as compared to infants with a typical likelihood for ASD (being at “low risk” due to having no siblings or other near relatives diagnosed with autism). These theoretical views led us to propose ways that risk for autism might play an important role in the emergence of advanced vocal capabilities such as canonical babbling. Canonical babbling was selected as the targeted measure because words are overwhelmingly composed of canonical syllables.

Our particular predictions about effects of risk did not, however, play out in the data. We observed no main effect of autism risk on CBRs. The finding adds further uncertainty to the already mixed evidence on canonical babbling emergence in both autism diagnosis and risk. The results support the argument that canonical babbling may be a robust developmental phenomenon and may be more resistant to effects of risk than has been expected. Furthermore, and in contradiction to our initial expectation, we did not observe an overall tendency for CBRs to grow faster across Age in LR than HR infants. Instead, we found a tendency for CBRs of HR infants to grow faster in the first age interval (7.5 to 9.5 months) while CBRs of LR infants grew faster in the second (9.5 to 12 months). This pattern proved to be especially associated with segments where infants engaged in high VP, that is, when they were not vocalizing to other people, but vocalizing endogenously.

Overall main effects revealed, of course, the expected significant effect of Age on CBRs, a finding consistent with all prior longitudinal studies of canonical babbling. The present data do, on the other hand, provide new findings: we observed high CBRs in both Risk groups during segments with TT and during segments with high VP. The effect of TT was considerable, being equivalent to 2-3 months of growth in CBR, and the effect was even larger for high VP. Thus the results suggest that both social interaction and exploratory vocalization stimulate canonical babbling.

Social Motivation in Early Infancy

The social motivation reasoning behind our predictions is based in the assumption that HR infants may present with a greater likelihood for reduced experience of social reward compared to LR infants and thus

may demonstrate reductions in vocal performance during social interaction. The findings for CBRs during TT, however, suggest similar levels of social motivation in both groups, with both showing the tendency to produce higher CBRs during segments rated as having any TT compared to those rated as having no TT. These findings suggest robustness of social motivations for infant vocalization. Our hypotheses were based on an expectation of anomalous development in HR infants, assuming social motivation for vocalization may break down in the presence of neurodevelopmental differences affecting social cognition. The results suggest a stronger mechanism where human infant vocal tendencies may have been selected to withstand neurodevelopmental deficits associated with autism. Alternatively, the results might hint at adaptation by parents, who may adjust their interactive styles to be more effective in eliciting canonical babbling from their infants at risk than in the case of parents whose infants are not at risk.

There can be no doubt that humans are highly social. Clearly, early hominins' relatively large living groups necessitated a high level of social bonding which created a need for an efficient communication method, resulting in positive selection pressures on the evolution of language (Dunbar, 1993, 1996, 2004). Chevallier (2012) noted that "social motivation constitutes an evolutionary adaptation geared to enhance the individual's fitness in collaborative environments" (p. 2). Thus, it is reasonable to assume that precursors to language such as canonical babbling must be robust during development to drive its evolution. Although often reported to be delayed in developmental disorders, including autism (Chericoni et al., 2016; Iverson & Wozniak, 2007; Patten et al., 2014), canonical babbling is well-established as a robust stage of development, known to emerge even (Eilers & Oller, 1994; Oller & Eilers, 1988). Our results indicated no overall differences in CBRs over time between Risk groups—only the patterns of growth in CBR appeared to differ, suggesting that the most advanced prelinguistic vocal forms (i.e., CBR) produced during early face-to-face interactions may be robust with respect to these evolutionary pressures even in the face of a potentially elevated likelihood for social communication deficits.

One important consideration and potential limitation in our evaluation of social motivations in early infancy relates to the measures we used to assess the sociality of vocalizations. To measure social and exploratory vocal functions, coders were asked to estimate on a Likert scale how often infants engaged in TT and VP for each segment. This subjective measure, obtained immediately after coding for CBR for each segment, can be portrayed as a blunt instrument, subject to only fair inter-observer agreement, but it is founded in the notion that human judgments are the gold standard for any such measure; in addition, our method of obtaining the judgments was convenient and workable. A perhaps more reliable measure would require labeling the social or exploratory function of each utterance individually with repeat-observation (and especially with both audio and video), a measure that requires at least tenfold more time to obtain (see Long et al. (2018) for an analysis using this method). Future studies using this more expensive measure to address the role of TT and VP in infant vocalization are planned. Additional considerations include examining the role of infant-directed speech (see Supplementary Material, Appendix E) using methods similar to those employed in this study, as well as taking account of initiation of turn-taking (i.e., whether it is infant-initiated or caregiver-initiated) and Risk to further study potential social motivations of the infant.

TT occurred, according to the coders, in only about 20% of the segments at all (and the vast majority of such segments were rated 2, meaning TT occurred during less than half the segment), a pattern that applied roughly equally to both Risk groups. This low rate of TT surprised us, given that so much of the literature on early language development focuses on protoconversation and its presumable importance in development. The low rate of TT may also have imposed a power limitation on the statistical analyses of the effects of TT and its interactions with the other variables in the present work.

Endogenous Motivation and Canonical Babbling

The VP measure was also based on a Likert scale, where coders were asked to judge each segment on how much of the time the infant had engaged in independent, not socially-directed vocalization (presumably endogenously motivated). Unlike TT, VP was found by the coders to be present in the vast majority of segments, and again this was true of both Risk groups—the plurality of segments having been rated 5 (VP present in close to the whole segment) by the coders for both Risk groups. Our surprise in finding low rates of TT in the all-day recordings is matched by our surprise at the near omnipresence of VP.

Our hypotheses regarding VP were also based in part on the social motivation theory. We expected HR infants to show elevated likelihood of vocal behaviors similar to motoric behaviors characteristic of autism, such as frequent isolated play, stereotypic repetition of motoric behaviors, and preference for physical properties of objects (and thus acoustic-perceptual properties of sounds). Therefore, we anticipated HR infants would show a tendency to produce higher rates of canonical syllables (especially repetitive syllables) during high VP compared to LR infants.

Overall, infants in both Risk groups produced more canonical syllables during high VP than low VP, but perhaps the most interesting outcome was the three-way interaction in the full VP model. The interaction suggests different rates of growth in CBR between the two groups during the first and second age intervals (specifically, HR infants progressed faster in the first interval, while LR infants progressed faster in the second), but only during segments rated as having high VP. Low VP segments showed no such differentiation of Risk groups.

The social motivation theory posits that reduced early social reward processing affects later social cognitive functioning; however, Bottini, (2018) as well as others (Dichter et al., 2012; Kohls et al., 2013) described alternative hypotheses that have also been proposed to describe differences observed in autism, including general reward processing deficits in both social *and* non-social domains (Benning et al., 2016; Kohls et al., 2014; Sasson et al., 2012), and greater reward processing for non-social stimuli (American Psychiatric Association, 2013). Our findings hint at the possibility that whatever the social motivation or reward systems are, they may function differentially at different points in time for infants at low and high risk for autism. One might propose that infants at high risk for autism may be more likely to experience a greater intrinsic reward when producing canonical syllables during bouts of vocal play (i.e.,

as non-social stimuli) compared to low risk infants; yet this pattern was observed in our dataset only across the first age interval, but not the second.

As previously mentioned, one of the primary diagnostic characteristics of autism is the presence of restricted interests and repetitive behaviors (RRBs) (Arnott et al., 2010). RRBs are present in typically developing infants (Richler et al., 2007; Rogers, 2009), but occur more frequently in infants with autism than in neurotypical controls as young as 6 months of age (Shriberg et al., 2011). High rates of canonical syllables (especially in reduplicated babbling of repeated syllables, one of the most salient types of canonical babbling) observed during bouts of VP may represent manifestations of vocal stereotypies, a common characteristic of autism. It is thought that autistic infants may prefer playing with the sensorimotor characteristics of a syllable through repetition (reduplication), while their neurotypical counterparts may be more likely to play with varying aspects pertaining to individual syllables, modifying duration, placement, and various articulatory patterns from utterance to utterance. Thus, producing repetitive physical and acoustic properties of sounds during bouts of VP may be more intrinsically rewarding to infants with autistic characteristics compared to those without them, the latter perhaps tending more to explore phonetic nuances. This idea may be supported by the speech attunement framework (Heaton et al., 2008; Järvinen-Pasley et al., 2008; Mottron et al., 2006), which proposes that autistic children process acoustic-perceptual characteristics more easily than semantic-linguistic information (Heaton et al., 2008; Järvinen-Pasley et al., 2008; Mottron et al., 2006).

If HR infants' increased CBRs in the first age interval are the result of autism-like repetition and stereotypy, there must be some other force at stake in the second age interval. Perhaps the robust tendency for canonical babbling to develop—based on the critical requirement for command of canonical syllables—drives all infants to reach a minimal level of canonical babbling control by the time word learning begins to take off at the end of the first year. Delays in the emergence rate of advanced vocal forms in infants at risk may become more evident at later ages as greater social and linguistic demands are placed on children who will show deleterious effects of autism. Such later delays may be foreshadowed in our finding of a plateauing of CBRs in HR infants from 9.5 to 12 months. An alternative interpretation for these findings may fall closer in line with evo-devo informed neurodiversity frameworks suggesting that autistic characteristics may have been positively selected as evolved compensatory adaptations (Crespi, 2016). Perhaps infants with an elevated likelihood of disorder (such as the HR infants in this study) achieve higher CBRs at earlier ages to compensate for their limitations in language learning or to elicit greater parental investment. Additional research is, of course, needed to support such speculation.

A potential limitation of this study is that we only evaluated the production of *canonical babbling* as a measure of advanced vocal forms. Infants are known to produce a wide range of vocal sounds throughout the first year. Given previous findings that RRBs are observed in infants as young as 6 months, infants diagnosed or at risk for autism may demonstrate vocal or auditory self-stimulatory behaviors in the production of non-canonical sounds such as raspberries or simple vowel sounds. A more in-depth evaluation of the production of both canonical and non-canonical sounds is necessary to better understand the emergence of vocal RRBs in autism.

Conclusions

The findings observed in the present study offer perspective possible developmental differences in infant vocal turn taking and independent vocal production as potential indicators of autistic characteristics. We observed a similar emergence of canonical babbling in infants at low and high risk for autism, with higher rates of canonical babbling overall during segments rated as having any turn taking and high vocal play. Our findings offer support for a potentially robust social motivation in infancy to produce higher rates of canonical syllables during interaction, even in the presence of an elevated likelihood for social communication deficits. Differences observed between Risk groups did occur when comparing low and high levels of vocal play across ages. Evolutionary pressures may play a role in high-risk infants' increased rate of canonical syllables during vocal play early in the canonical babbling stage as a result of the need to signal fitness prior to vocal delays at later ages or as a result of an evolved compensatory adaptation. These differences also hint at an age-varying intrinsic reward mechanism for producing and attending to acoustic-perceptual characteristics of vocal sounds potentially linked to genes associated with autism.

Our findings and additional research on this topic may have the potential to inform early autism diagnosis and therapeutic intervention in order to provide support for social communication and language development at younger ages. The findings support the ideas that babbling in both high risk and low risk infants is socially interactive only occasionally in the natural environment of the home, while endogenous, exploratory vocalization occurs in both groups very often throughout the day.

Declarations

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Ethics approval

This study was carried out in accordance with the recommendations of the Institutional Review Board (IRB) guidelines for the University of Memphis and Emory University in accordance with the Declaration of Helsinki. The protocol was approved by the University of Memphis (No. 2143) and Emory University (No. IRB0000059383) IRB committees.

Consent to participate and publish

Written informed consent was obtained from parents to publish data collected and used for the purposes of this study.

Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose. The authors declare no competing interests.

Author contributions

GR collected recorded data used for coding and analysis. HLL, DKO, MMR, and DDB designed and analyzed the results of the study. DDB completed formal statistical analyses. All authors assisted in interpretation of results, writing, and revising the manuscript prior to submission.

Data accessibility

The analyzed data and code that support the findings of this study are openly available on the Figshare repository platform and on the Open Science Framework at <https://osf.io/ery6b/>. Due to the nature of this research, participants of this study did not agree for audio recordings to be shared publicly, so raw recording data is not available.

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Footnotes

¹ Maternal education was self-reported. Low/High SES groups were based on a median split of maternal education in the entire cohort.

² Graduate student coders were trained to differentiate canonical and non-canonical syllables during real-time coding and to rate the extent to which infants produced socially interactive (TT) and endogenous (VP) vocalizations during completion of the questionnaire that was filled out at the end of coding of each 5-minute segment. The six-week training procedure is detailed in Oller et al. (2019).

³ The amount of infant-directed speech (IDS) was rated using the questionnaire that followed each of the 21 segments coded in the first coding pass. The questionnaire was also used to indicate environmental contextual factors for each segment, including audibility, other-person activity level, and aloneness of the infant. For both coding passes, each questionnaire item required a 5-point Likert-scale response to the relevant question, e.g., for IDS, “How often did someone talk to the infant?”

Figures

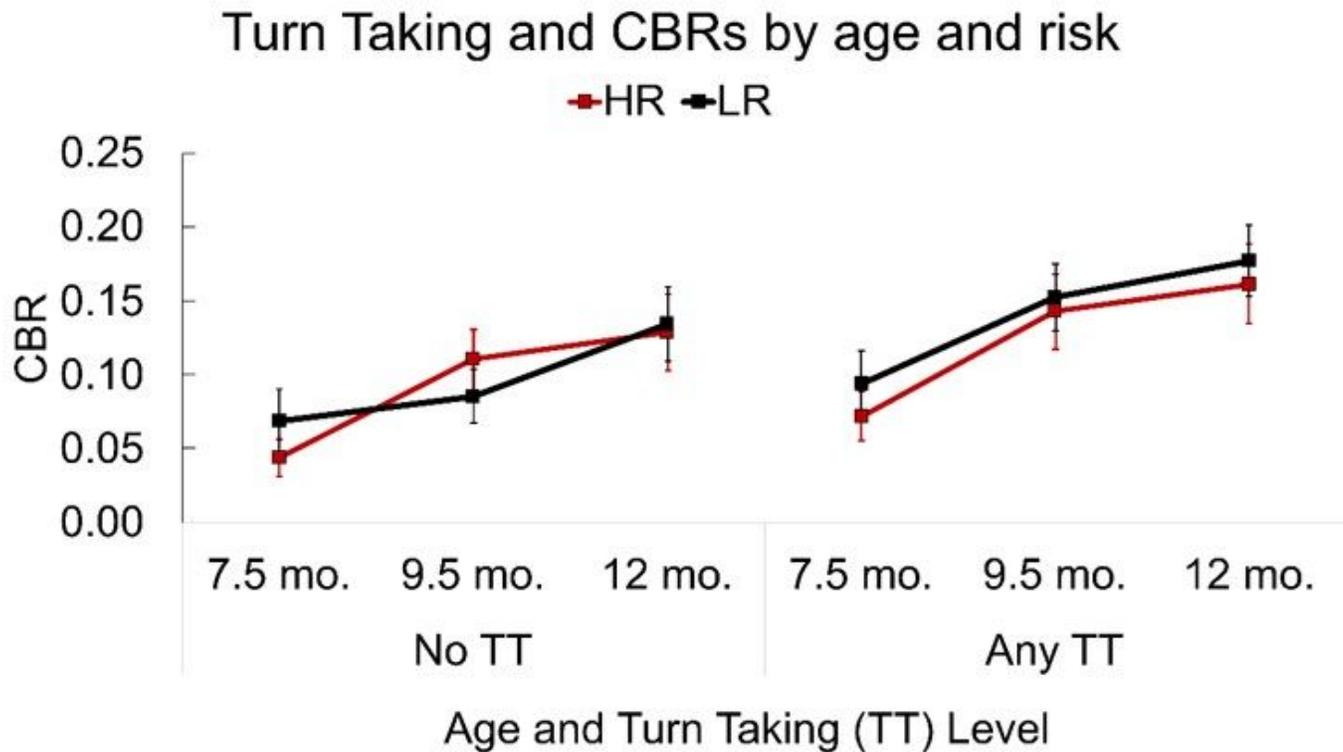


Figure 1

Canonical babbling by Age, Risk, and Turn Taking level. Canonical babbling ratios of infants at high-risk (HR) and low-risk (LR) for autism during segments with no vs any turn taking (TT) across three age ranges, 6.5-8.49 (7.5 months), 8.5-10.49 (9.5 months), and 10.5-13 (12 months) months. CBR was significantly higher from 7.5 to 9.5 months ($p < .001$, $b = .06$), and there was a significant two-way interaction of Risk and Age again between 7.5 and 9.5 months ($p = .004$, $b = .05$). There were no significant interactions including TT as a variable, including the three-way interactions of Age, Risk, and TT level. The values presented in the figure were computed from the raw data with means and SEs weighted for the number of infants who contributed data in each Risk group at each Age.

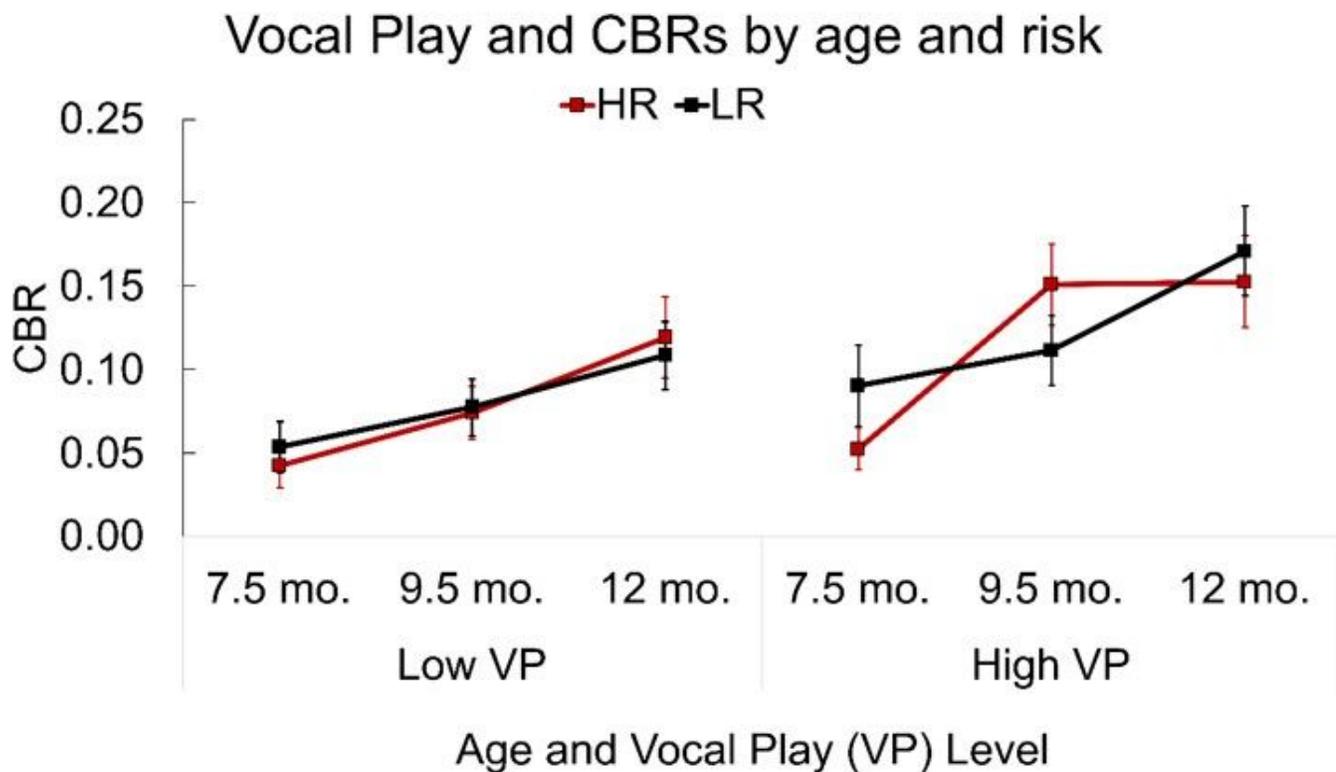


Figure 2

Canonical babbling by Age, Risk, and Vocal Play. Canonical babbling ratios (CBRs) of infants at high risk (HR) and low risk (LR) for autism in segments with low vs high vocal play (VP) across three age ranges, 6.5-8.49 (7.5 months), 8.5-10.49 (9.5 months), and 10.5-13 (12 months) months. In this model, there was a significant effect of Age for both 7.5 to 9.5 months ($p = .023$, $b = .03$) and 9.5 to 12 months ($p = .001$, $b = .05$). A significant interaction occurred between Risk and VP level ($p = .021$, $b = -.03$) and Age and VP level at 7.5 to 9.5 months ($p < .001$, $b = -.06$), with the interaction approaching significance for ages 9.5 to 12 months ($p = .059$). The three-way interaction among VP level, Age, and Risk was significant for ages 9.5 to 12 months ($p = .039$, $b = .06$), and approached significance for 7.5 to 9.5 months ($p = .063$). As in the case of Figure 1, the values presented here were computed from the raw data with means and SEs weighted for the number of infants who contributed data in each Risk group at each Age. Standard error (SE) bars are shown.

Canonical babbling of HR and LR infants across three age groups

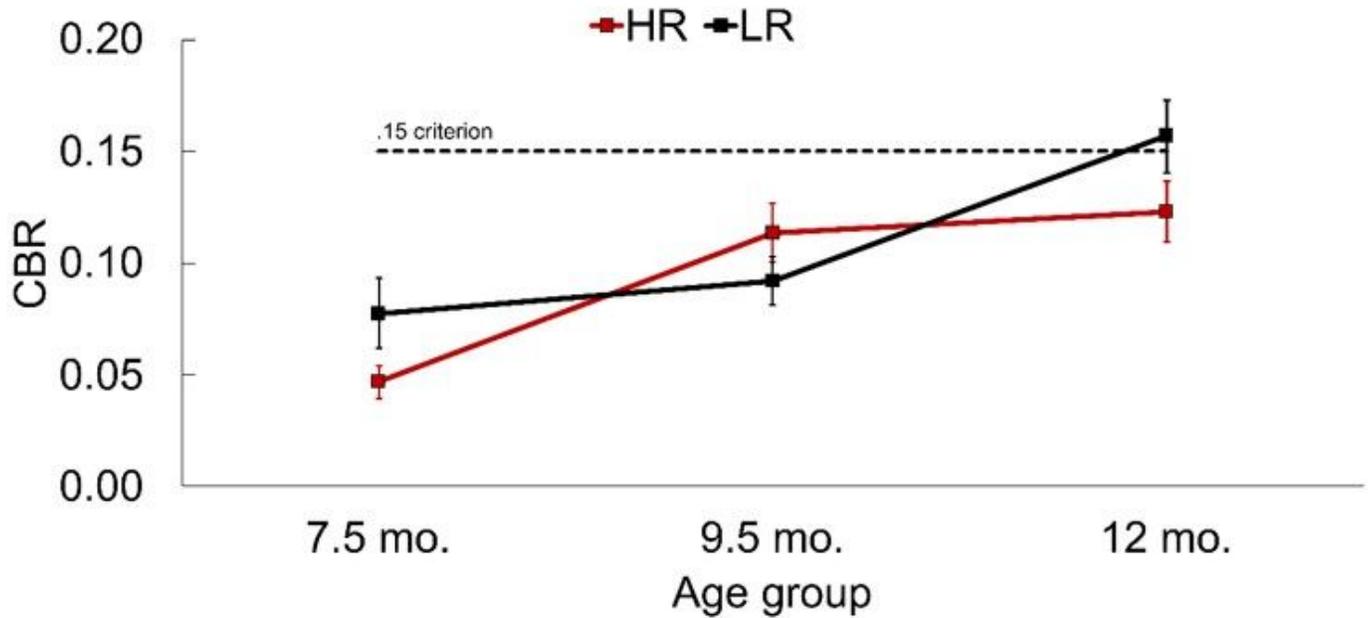


Figure 3

Canonical babbling ratios by Age and Risk. Canonical babbling ratios of infants at high-risk (HR) and low-risk (LR) for autism across three age ranges, 6.5-8.49 (7.5 mo.), 8.5-10.49 (9.5 mo.), and 10.5-13 (12 mo.). Overall, we found a significant interaction of Risk by Age for the first interval (7.5 to 9.5 months, $p = .017$), with CBRs rising much faster for HR infants than LR infants. The pattern was reversed, but not significantly in the second interval. Standard error (SE) bars shown.

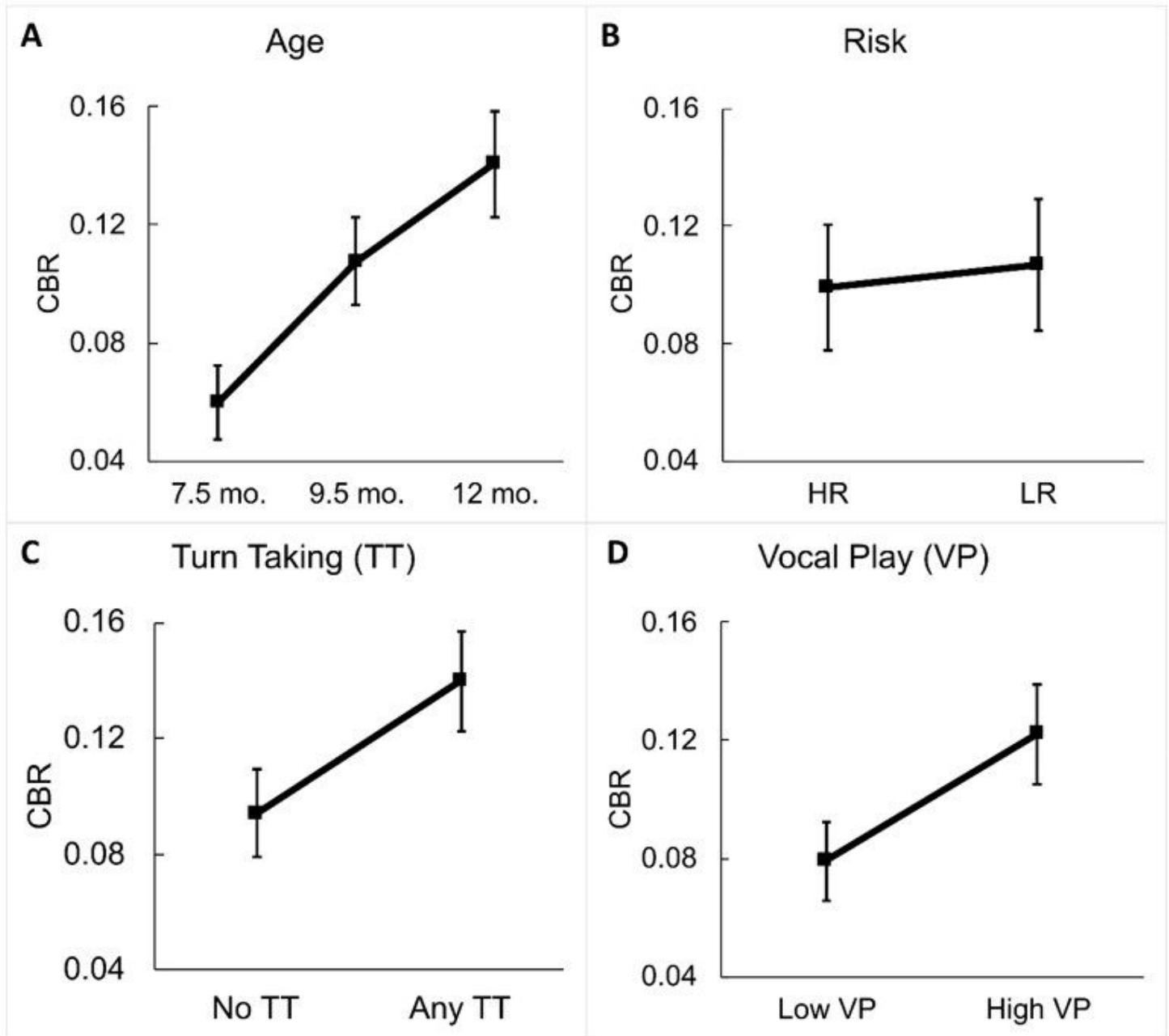


Figure 4

Main effects for Age, Risk, Turn Taking, and Vocal Play. Figure 4A illustrates the significant main effects of Age between 7.5 and 9.5 months ($p < .001$, $b = .04$) and 9.5 and 12 months ($p < .001$, $b = .04$). 4B shows the non-significant main effect of Risk group ($p = .742$). 4C presents the significant main effect of Turn Taking, with higher CBRs during segments rated as having any TT compared to those rated as having no TT ($p < .001$, $b = .04$). Finally, 4D shows the significant main effect of Vocal Play, with higher CBRs present during segments with high VP compared to segments with low VP ($p < .001$, $b = .06$). Standard error (SE) bars are shown.

Supplementary Files

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