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Child Language and Autism Diagnosis Impact Hierarchical Temporal Structure of Parent-Child Vocal Interactions in Early Childhood

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Lay Summary

Successful interactions involve conversational partners' flexibly adapting the timing of their behaviors. We measured the temporal patterns of vocalizations in parent-child interactions of typically developing (TD) and autistic infants/toddlers. While language growth made vocal interaction timing more flexible for TD child-parent dyads, it did not for autistic child-parent dyads who exhibited increased clustering of vocal interactions. Both language and social reciprocity play a role in the timing structure and flexibility of smooth interactions.

Abstract

Timing is critical to successful social interactions. The temporal structure of dyadic vocal interactions emerges from the rhythm, timing, and frequency of each individuals' vocalizations and reflects how the dyad dynamically organizes and adapts during an interaction. This study investigated the temporal structure of vocal interactions longitudinally in parent-child dyads of typically developing (TD) infants ($n=49$; 9-18 months; 48% male) and toddlers with ASD ($n=23$; 27.2 ± 5.0 months; 91.3% male) to identify how developing language and social skills impact the temporal dynamics of the interaction. Acoustic hierarchical temporal structure (HTS), a measure of the nested clustering of acoustic events across multiple timescales, was measured in free play interactions using Allan Factor. HTS reflects a signal's temporal complexity and variability, with greater HTS indicating reduced flexibility of the dyadic system. Child expressive language significantly predicted HTS ($\beta=-0.2$) longitudinally across TD infants, with greater dyadic HTS associated with lower child language skills. ASD dyads exhibited greater HTS (i.e., more rigid temporal structure) than nonverbal matched ($d=0.41$) and expressive language matched TD dyads ($d=0.28$). Increased HTS in ASD dyads occurred at timescales > 1 second, suggesting greater structuring of pragmatic aspects of interaction. Results provide a new window into how language development and social reciprocity serve as constraints to shape parent-child interaction dynamics and showcase a novel automated approach to characterizing vocal interactions across multiple timescales during early childhood.

Keywords: Parent-child interaction, autism spectrum disorder, Hierarchical Temporal Structure, interaction dynamics, language development, social reciprocity.

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The terminology used throughout this paper reflects both identity-first (i.e. “autistic children”) and person-first (i.e. “individuals with autism”) language, in line with preferences expressed by autistic self-advocates, caregivers, and professionals (Botha et al., 2021; Lei et al., 2021) and APA guidelines regarding language and disability (APA, 2020).

Introduction

Timing is essential to successful caregiver-infant social interactions and has downstream effects on subsequent interactions and infant development (Feldman, 2007). Acoustic temporal structure (i.e., the patterns and organization of acoustic information) emerges from the rhythm, timing, and frequency of each individuals’ vocalizations (e.g., individual prosody, volubility, intrapersonal pauses) and the relative timing of vocalizations between individuals (e.g., interpersonal turn-taking). The temporal structure across a dyadic interaction is more than just the sum of two individuals’ vocalizations. It reflects the coordination of two complex systems (i.e., caregiver and child) that through the interaction become interdependent and create patterns that extend beyond their individual actions, defining the dyad as a system of its own (cf. Fusaroli et al., 2014). Dyadic vocal temporal structure reflects each individual’s vocalizations *as constrained by the dyadic unit that emerges from and for the interaction* (cf. Dale et al., 2013). That is, it offers a window into the way that caregiver and child vocalizations reorganize, adapt, and respond to each other’s skills and needs, as well as to the shared interactional and contextual constraints, to make the dyadic interaction possible (Kelso, 2009a).

In the present study, we quantified Hierarchical Temporal Structure (HTS), a measure of multiscale nested clustering that reflects a system’s structure and flexibility, in audio-recordings of caregiver-infant dyads engaged in free play as a way of measuring their interactional

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dynamics. We investigated how children's language and social development serve as intra and interpersonal constraints on the temporal dynamics of the parent-child system by examining changes in HTS in typically developing (TD) infant-caregiver dyads over time and contrasting their HTS with that of parent-child dyads of toddlers with autism spectrum disorder (ASD).

Contributors to the Temporal Structure of Caregiver-Infant Vocal Interactions

Caregiver prosody (i.e., speech stress, rhythm, and intonation), is one prominent contributor to the temporal structure of caregiver-infant vocal interactions. When engaging with infants, caregivers naturally use the distinctive speaking style of infant-directed speech (IDS), characterized by acoustic features of heightened pitch, exaggerated pitch contours, slower tempo, increased rhythmicity, and increased temporal and pitch variability compared to adult-directed speech (Falk & Kello, 2017; Ferguson, 1964; Fernald, 1991; Katz et al., 1996; Papoušek, 1992; Stern et al., 1982; Trehub et al., 1993; Wang et al., 2018). These features of IDS capture and modulate infant attention and arousal to facilitate social interaction and learning (e.g., such as by using duration, intensity, and pitch accents to accentuate important linguistic information) (Räsänen et al., 2018; Senju & Csibra, 2008; Singh et al., 2009; Thiessen et al., 2005; Woolard et al., 2021).

Infants' own vocalizations are also important contributors to the temporal structure of caregiver-infant dyadic interactions. Infants' vocalizations become increasingly speechlike over the first year of life as they shift from primarily producing reflexive vocalizations to short vocalic sounds to longer sustained sounds to rhythmic canonical babbling and variegated babbling with first words emerging around 12-months of age (Oller, 1978; Stark, 1980). Infants' vocal skills interplay with caregiver-infant turn-taking dynamics: caregivers are more likely to respond to infants' speechlike vocalizations, which then promotes continued infant speech-

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related vocalizing in a social feedback loop (Hirsh-Pasek et al., 2015; Ritwika et al., 2020; Warlaumont et al., 2014). This transactional back-and-forth between caregiver and infant is an additional component of the temporal structure of vocal interaction. Infants and caregivers coordinate the timing of their vocalizations to each other, including latency between turns and relative duration of vocal turns (Abney et al., 2017; Jaffe et al., 2001; Jasnow & Feldstein, 1986; Northrup et al. 2015; Pretzer et al., 2019; Smith & McMurray, 2018).

Temporal characteristics of caregiver-infant vocal interactions change over the first years of life as children's speech and language skills develop. Caregivers reduce their use of the exaggerated acoustic features of IDS as their children get older (e.g., decreasing fundamental frequency, repetitiveness, and intensity) (Quigley et al., 2016; Tal et al., 2021). Caregivers also increase utterance length and decrease their repetitiveness and lexical redundancy resulting in changes in the broader prosodic structure of the dyadic interaction (Broen, 1972; Kaye et al., 1980; Snow, 1972; Stern et al., 1983; Tal et al., 2021). Turn-taking patterns between caregivers and infants become more refined with reduced overlap in vocalizations and shorter pauses by both the adult and child with increasing child age (Harder et al., 2015; Hilbrink et al., 2015).

Vocal Interaction Characteristics in Children with ASD

The temporal characteristics of parent-child vocal interactions differ when children exhibit impairments in their language and social communication skills such as for autistic children (Cohen et al., 2013; Droucker et al., 2013; Northrup & Iverson, 2015; Quigley et al., 2016; Seidl et al., 2018). This divergence in parent-child vocal interactions, including their acoustic-prosodic features, may involve both a child's direct language and communication skills (e.g., child's frequency and prosody of vocalizations), and adaptations made by parents based on their experiences with their child (e.g., communicative strategies used by parents to engage their

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child). For instance, caregivers of infants who are later diagnosed with ASD don't wane their use of IDS as quickly as parents of TD infants (Cohen et al., 2013), suggesting parents continue to use this exaggerated prosodic style of speech to engage and regulate interactions. At the same time, infants at elevated risk for ASD demonstrate reduced attention to IDS compared to their peers (Droucker et al., 2013; Quigley et al., 2016; Watson et al., 2012; Woolard et al., 2021).

Reduced interpersonal vocal coordination is also observed in interactions of children with or at elevated likelihood of ASD, particularly with regard to temporal characteristics. Frequency of child vocalizations and conversational turns differentiated children with and without later social-communicative concerns (Seidl et al., 2018). Coordination of vocal interpersonal turn durations predicted later language outcomes in infants at elevated likelihood of ASD (Northrup & Iverson 2015).

Hierarchical Temporal Structure of Vocal Interactions: A Complex Systems Approach

The temporal organization of vocal interactions provides a critical lens into developmental processes in both typical and atypical development. Acoustic-prosodic dynamics in parent-child interactions have increasingly been explored as an early clinical marker for ASD (Bedoya et al., 2020; Oller et al., 2010). Studies traditionally use time- and labor-intensive measures that require manually coding vocalization onsets and offsets and annotating vocalization types or linguistic information for each timescale of behavior (e.g., syllable rate, duration between turns).

An alternative approach is to examine the acoustic dynamics of the parent-infant interaction as a *complex system* that simultaneously *integrates across both individuals* in the interaction and the *multiple timescales* over which their vocalizations (and their vocal coordination) unfold. Such an approach presents a few characteristics that can complement more

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traditional measures: First, the complex system literature offers an array of methods to quantify temporal dynamics at various timescales of behavior using a common metric, which facilitates the measurement of relationships across timescales and highlights global systemic patterns that extend beyond local behaviors at any particular scale (see Richardson et al., 2014 for a review). Measuring temporal structure across timescales in this way can be informative of the flexibility of a system to changing constraints, its robustness to perturbation, and its behavioral consistency over time (Kelso, 2009b), and can also uncover differences and similarities across behavioral signals that are not apparent from their physical properties at a particular scale (see Kello et al., 2017 for extensive examples). Second, methods from the complex systems literature can meaningfully characterize temporal dynamics using inexpensive automated measures of behavior, which facilitates both the analysis of larger datasets, and the reproduction and replication of results. Third, integrating across the dyad, as opposed to just characterizing or comparing individual behavior, can reveal emergent interactional patterns that would be missed otherwise and are not dependent on a given individual producing a specific vocal form (e.g., linguistic vocalizations). This is particularly useful for parent-child interactions in which the vocal contributions are unbalanced, but are still a reflection of both interlocutors' behaviors.

One measure from the complex system literature that has recently been applied to (adult) conversational and infant-directed speech is Allan Factor (AF) analysis (Allan, 1996; Abney et al., 2014; Falk & Kello, 2017; Kello et al., 2017; Ramirez Aristizabal et al., 2018). This measure quantifies the HTS (or nested clustering of variability) of acoustic events (defined by amplitude peaks) within a timescale, and then measures their nestedness across multiple timescales in the signal at once by fitting a linear slope to the relationship between timescale and variability of event clustering (see Figure 1 for an illustration of the method) (Abney et al., 2014; Luque et al.,

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2015). For signals in which events are randomly distributed, as is the case in white noise, variability in event clustering doesn't increase with timescale, and the relationship between clustering variability and timescale is flat (see Figure 1, bottom-right, gray-line). Conversely, bursty signals such as speech have acoustic events that are nested across timescales, and variability grows exponentially with timescale (see Figure 1, bottom-right, blue line): phonemic variations (20–100 ms) are nested within syllables (100–200 ms), nested within words (200–500 ms), nested within phrases (500–4000 ms), which are nested within sentence-length utterances (1000–6000 ms) (Falk & Kello, 2017; Leong & Goswami, 2015). And at the interactional level (over 1000–2000 ms), all these timescales are also nested within turns and emergent interactional routines, which include starting and stopping patterns of vocalizations both within and between individuals at multiple timescales. At this level, interactions with stricter turn-taking, such as argumentative conversations or knock-knock jokes, for example, would create more nested clustering at the longer timescales of the interaction and have higher HTS (see Abney et al., 2014 for an analysis of argumentative conversations), while interactions with more flexible turn-taking patterns, such as friendly unstructured conversations (Abney et al, 2014), would have less nested clustering at the longer timescales and lower HTS.

When AF functions are measured for individual speakers they are sensitive to communicative skill and context. Infant-directed speech exhibits higher HTS (steeper AF slopes; see Methods below) than adult-directed speech reflecting increased multiscale nested clustering of infant-directed communication, and also indicating that the increased variability of IDS within each timescale is also more structured across timescales (Falk & Kello, 2017). Similarly, both parents' and infants' individual AF slopes decrease over the first two years of life, but only parents adapt the degree of nested clustering in their speech to that of their infants' vocalizations

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(Abney et al. 2017). Degree of clustering is also impacted by the rapport of the interaction; in conversing adults, individuals' vocalizations exhibit higher AF slopes during argumentative versus affiliative conversations with a partner, mainly as a result of differences at the longer timescales reflective of interaction-level variables (e.g., turn-taking; Abney et al., 2014). Thus, AF slopes are modulated by the linguistic skill and social reciprocity of interacting partners.

Research utilizing AF analysis has focused on typically developing populations and on the temporal dynamics of single individuals participating in fairly balanced conversations, and within various interactive contexts. However, examining HTS at the level of the dyad would reflect the coordination of the dyadic system, which should be sensitive to the constraints imposed by the behaviors of each partner as they adapt to one another in a shared interaction, and might prove particularly useful to study interactions with unbalanced acoustic contributions (such as parent-child vocal interactions). In the current study, we investigate changes in HTS in parent-child interactions as a function of child language development and autism diagnosis. First, we assess developmental changes in HTS over time in TD parent-infant dyads, from 9 months (when children are prelinguistic but using some speech-like canonical babbling) to 12 months (first words) to 18 months (increasing vocabulary and communicative complexity), to examine the effects of language development on the parent-child dyadic interaction dynamics. We hypothesize that as the infant's language skills develop, increasing the complexity of the parent-child vocal exchange, dyadic HTS will decrease to reflect more mature and flexible vocal interaction patterns. We next assess developmental constraints on HTS by comparing parent-child dyads of autistic children to dyads of TD children matched for either nonverbal developmental or expressive language level. We consider two possible outcomes: If the vocal interactional and communication patterns in ASD dyads are primarily dependent on children's

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nonverbal developmental or language level, then their HTS should be similar to TD children with comparable skills. If, however, the temporal clustering reflects social reciprocity with the interactional partner (e.g., Abney et al., 2014), then dyads of children with ASD would be expected to exhibit greater HTS even when compared to children at similar stages of nonverbal or language development.

Method

Participants

TD Sample

49 infants and their parents participated in a longitudinal study of social and language development with visits at 9 (N = 47), 12 (N = 45), and 18 months (N = 33). A few visits could not be completed due to covid-19 (i.e., research lab closed) leading to lower participant numbers at the later time points. Participants could not have diagnosed genetic disorders (e.g., Down syndrome), major visual or hearing impairments, or a family history of autism. 81.6% of the child participants were White, and 18.4% more than one race; 4% were Hispanic/Latino. All infants were evaluated using the Mullen Scales of Early Learning (MSEL) at each time point to assess developmental level (Mullen, 1995). Receptive and expressive subtests of the MSEL demonstrate acceptable test-retest reliability, 0.82 and 0.85, respectively, in children ages 1-24 months (Mullen, 1995). Table 1 summarizes MSEL age-equivalence scores for visual reception, receptive language, and expressive language at each time point, as well as other demographic information. Families were recruited from multiple sources, including recruitment listservs, pediatrician offices, local day-cares, and community centers. The Institutional Review Board of

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Vanderbilt University provided ethical approval for this study. Written informed consent was obtained from all parents/guardians.

Table 1. *Demographic Characteristics of the TD Longitudinal Sample*

Time Point	N	Age (months)	Sex	Expressive Language Age Equivalence (months)	Receptive Language Age Equivalence (months)	Visual Reception Age Equivalence (months)*
		<i>M(SD)</i>	<i>(% Male)</i>	<i>M(SD)</i>	<i>M(SD)</i>	<i>M(SD)</i>
9	47	9.2 (0.5)	46.8	8.7 (1.8)	8.9 (1.5)	10.7 (1.2)
12	45	12.2 (0.6)	48.8	12.1 (2.2)	11.5 (1.5)	-
18	33	18.6 (0.9)	48.5	18.7 (3.1)	20.9 (4.3)	21.3 (4.3)

* The MSEL Visual Reception Scale was not administered at 12-months due to time constraints.

ASD Sample

23 toddlers with ASD and their parents also participated in the study. 65.2% of the children in this sample were White, 8.6% African American, and 26.2% more than one race; 8.6% were Hispanic/Latino. Children with ASD were also evaluated using the MSEL (Mullen, 1995). Additionally, they were administered the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2) (Lord et al., 2012) by research reliable clinicians to confirm autism diagnosis and assess symptomatology. All participants in the ASD cohort met criteria for ASD diagnosis via clinical best estimate including ADOS-2 total scores that exceeded the cut-off for ASD. Participant characteristics, including MSEL scores and ADOS-2 subscale scores for the autistic participants, are provided in Table 2. Families were recruited from the community and the autism clinic at the university medical center. Written informed consent was obtained from all parents/guardians.

Nonverbal and Language Age-Matched TD samples

To compare the acoustic temporal structure of parent-child interactions across toddlers with and without ASD, a nonverbal age-matched (NVM) sample of 23 TD toddlers and an expressive language age-matched (ELM) sample of 23 infants and toddlers from the longitudinal sample were created (see Table 2 for demographic information for each matched sample). The TD children included in the NVM and ELM samples were selected (without replacement) to generally match the distributions of scores of the autistic toddlers on the MSEL visual reception and expressive language scales, respectively.

Table 2. Demographic Characteristics of the ASD and the Matched Samples

Group	N	Age (months)	Sex	Expressive Language Age Equivalence (months)	Visual Reception Age Equivalence (months)	ADOS-2	
		<i>M(SD)</i>	<i>(% Male)</i>	<i>M(SD)</i>	<i>M(SD)</i>	Social Affect <i>M(SD)</i>	Repetitive Behaviors <i>M(SD)</i>
ASD	23	27.2 (5.0)	91.3	14.7 (5.5)	20.6 (4.0)	14.9 (4.6)	5.4 (1.7)
NVM	23	18.7 (1.0)	52.2	-	20.5 (4.1)	-	-
ELM	23	13.9 (4.2)	52.2	14.6 (5.2)	-	-	-

Note: NVM = Non-Verbal Matched; ELM = Expressive Language Matched. ADOS-2 = Autism Diagnostic Observation Schedule, 2nd edition.

Procedure

Infants/toddlers and their parents were audio- and video-recorded during a free-play session in a child-friendly assessment room. At 9 and 12 months, infants were positioned in a highchair with their parents sitting directly across. At 18 months, children and their caregivers played on the floor. At each time point, dyads were given a standard set of quiet toys and were instructed to play and talk with each other like they do at home for 10 minutes. Sessions were

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recorded with three video cameras in different corners of the room and a condenser microphone on a platform adjacent to the dyad.

Acoustic Analyses

Audio files were first filtered using the Noise Reduction effect in Audacity (Audacity Team, 2021) to eliminate constant high-frequency background noise (e.g., from air-conditioning system) in the recording. Audio recordings for each dyad were analyzed using the methods described in Kello et al. (2017). The recordings were down-sampled from 44.1 KHz to 11 KHz and the analyses were conducted on sliding 4-minute segments with 75% overlap that covered from minutes two to nine of the recording. The first two minutes were not included to allow dyads time to acclimate to the activity; the last minute was not included due to some children becoming fussy toward the end of the activity (particularly at 9 months). For each segment, the Hilbert envelope (i.e., amplitude envelope with only positive frequency components following Hilbert transform) was computed, and a time series of acoustic events was obtained. Acoustic events were defined as peaks in the amplitude envelope that were both locally and globally maximal. First, local maximization was achieved by choosing amplitude peaks that were maximal within a 5 ms window. Then, global maximization was achieved by setting an amplitude threshold H for each recording that would select roughly 1 peak per 200 samples on average. These steps created time series that were sufficiently sparse to evaluate clustering, but also had enough events to achieve robust statistical analyses. These steps also served as a built in high-frequency filter that removed spurious peaks, and as a normalization procedure to select roughly the same number of peaks per time unit across recordings independently of volubility of vocalizations.

The clustering of peak acoustic events over time was calculated for different timescales of observation using Allan Factor variance (Allan, 1966; See Figure 1): For each timescale of window size T , the number of peak acoustic events N within each window were counted, and the difference in total peak counts between adjacent windows was obtained. The average of the squared differences was then divided by twice the mean event count (N) for window size T to obtain a normalized estimate of AF variance ($A(T)$) for that timescale. $A(T) \sim 1$ indicates events are randomly or periodically distributed (i.e., not clustered), while $A(T) > 1$ indicates they are clustered above chance. We calculated the $A(T)$ for 12 logarithmically spaced timescales (T) (i.e., timescale increased as a power of 2, doubling the length of the previous one) ranging between 30 ms and 30 s, and fitted a line to the relationship between timescale (T) and $A(T)$ variance in log-log coordinates to quantify the nestedness of the clustering across timescales (i.e., hierarchical temporal structure (HTS)). If clusters of events are hierarchically nested (i.e., clusters at the shortest timescales build up into bigger clusters at the longer timescales), $A(T)$ will grow exponentially with T , and the slope of the best fitting line describing their relationship will be positive. If they do not scale up across timescales, the slope describing the relationship between $A(T)$ and T will be near zero. If the events are hierarchically nested at shorter timescales but stop being nested after a certain timescale, the relationship between $A(T)$ and T will curve and flatten at the longer timescales.

As has been observed before in speech signals (Falk & Kello, 2017; Kello et al., 2017; Schneider et al., 2020), the AF functions of our parent-child interactions showed flattening at the longer timescales (see Figure 3, right-side panels, for an example). We fit a second order polynomial to each dyad's AF functions to account for such curvature (mean $R^2 = .90$); statistical

analyses were then conducted on the linear component consistent with previous studies (Kello et al, 2017).

Figure 1. Modified from Kello et al. (2017). Illustration of Allan factor analysis for a speech waveform (top – blue) from a TED talk. The Hilbert envelope (amplitude envelope computed via Hilbert transform) is shown under the waveform in cyan, followed by the peak acoustic events shown in red. Event counts (N) for 3 timescales (T_7 , T_6 and T_5 , also highlighted in the figure on the bottom right) are shown in the bins under the peak events. The bottom left shows the equation for the AF variance ($A(T)$), and the bottom right, a figure showcasing the relationship between $A(T)$ and timescale T for the speech waveform (blue solid line). This relationship is also plotted for waveforms of thunderstorms (gold dotted line) and white noise (grey dashed line) as a reference of signals with very high and very low HTS, respectively. For a given signal, the AF slope corresponds to the slope of the line that would best describe the relationship between $A(T)$ and timescale (T) when in log-log coordinates. In log-log coordinates, each unitary increment (x) in the axes represents an increment of $10x$ units in the data (e.g., the same distance in the x-axis represents a change from 0.1 s to 1 s in one increment, and from 1 s to 10 s in the next increment); each tick within the increments represents a 10th of such increment (e.g., each tick between 0.1 and 1 s represents a 0.1 s increment on the timescale duration, whereas each tick between 1 and 10 s represents a 1 s increment). In these coordinates, a positive linear relationship between T and $A(T)$ suggests the existence of a power law distribution, in which clusters of acoustic events grow proportionally and exponentially with each increase in timescale.

Analysis Plan

The degree of HTS was calculated for the audio recordings of the parent-child interactions. To examine how HTS in the dyadic interaction changed as children's expressive language developed in the TD sample, we conducted a linear mixed-effects model analysis predicting the AF linear slope with the expressive language (EL) age equivalence score from the MSEL. We included random intercepts per dyad to account for individual variability in the dyad's AF values. The models were run in R (R Core Team, 2021) using the *lme4* (Bates et al., 2015) and *lmetest* (Kuznetsova et al., 2017) packages. To examine the effects of ASD diagnosis on the HTS of the parent-child interactions, we compared the AF slopes of the ASD group to those of the ELM group and those of the NVM group using independent samples t-tests.

Results

Change in HTS as a Function of Language Development in TD Children

We first assessed the effects of child expressive language development on the HTS of parent-child dyadic interactions from 9 to 18-months of age. Expressive language scores significantly predicted the AF slope of the dyadic interaction ($\beta = -0.20$; $t = -2.26$; $p = .02$; Figure 2), which suggests that as TD children's expressive language skills develop, the nested clustering of the dyadic interaction decreases, becoming more similar to the clustering observed in adult interactions (Falk & Kello, 2017; Kello et al., 2017, Schneider et al., 2020).

Figure 2. Relationship between the MSEL expressive language age equivalence scores and the AF slope in TD parent-child dyads. The shaded region shows the 95% confidence interval around the mixed-effects model predictions.

HTS in Dyads of Children with ASD

We next compared the HTS in dyads of autistic children to that of TD dyads with children matched for non-verbal (NVM) or expressive language (ELM) functioning. Figure 3 shows the distributions of the AF slopes and average AF slopes for the ASD, ELM, and NVM groups. The ASD dyads had significantly steeper slopes (i.e., more nested clustering across timescales, but driven by differences at timescales longer than one second, as seen in Figure 3) than the NVM group ($M_{\text{ASD}} = 0.77$, $SD_{\text{ASD}} = 0.08$; $M_{\text{NVM}} = 0.66$, $SD_{\text{NVM}} = 0.07$; $t(44) = -5.03$; $p < .001$, $d = 0.41$; Figure 3A) and the ELM group ($M_{\text{ELM}} = 0.69$, $SD_{\text{ELM}} = 0.09$; $t(44) = -3.14$; $p = .002$; $d = 0.28$; Figure 3B), respectively. Neither the ELM nor the NVM groups were matched to the ASD group for sex due to sexual dimorphism in ASD prevalence. Epidemiological estimates

of autism prevalence suggest a 4:1 male-to-female sex ratio (Fombonne, 2003). However, we confirmed there were no sex differences in the AF slopes of TD children ($p = .17$) suggesting sex is not driving the differences observed between groups. In supplemental exploratory analyses, we also assessed individual differences in the ASD dyads: AF slopes in the ASD dyads were not significantly associated with child's EL skills (consistent with the group comparison results). AF slopes were also not associated with ADOS-2 Social Affect scores in the ASD dyads (see Figure S-1 and associated discussion in the Supporting Information).

Figure 3. The panels on the left show the distributions of AF slopes for (A) the ASD group (blue, left) and the non-verbal matched (NVM) group (magenta, right), and (B) the ASD group (blue, left) and the expressive language matched (ELM) group (orange, right). The blue diamonds in the violin plots show the mean slope for each group; *** $p < .001$, ** $p < .01$. The panels on the right depict the average AF functions in log-log coordinates for (A) the ASD and NVM groups, and (B) the ASD and ELM groups.

Discussion

HTS Changes in TD Infants Over Time

We first assessed whether HTS changed over time in TD parent-infant dyads. Based on previous research on parent-child vocal coordination (Abney et al., 2017; Harder et al., 2015; Pretzer et al., 2019) and infant-directed speech characteristics (Falk & Kello, 2017; Segal & Newman, 2015; Tal et al., 2021), we hypothesized that dyadic HTS would decrease as children's expressive language skills developed and became more sophisticated, a hypothesis that was born out in our data.

AF as a measure is agnostic to the specific mechanisms that are shifting the clustering of acoustic events. This in itself was an advantage that allowed us to extract meaningful dyadic dynamic patterns from unbalanced acoustic signals -- listening to our parent-infant free play recordings revealed that across all timepoints, parents vocalized more frequently and for longer durations than infants, consistent with prior studies (e.g., Abney et al., 2017; Northrup & Iverson, 2015). Yet, child expressive language development appears to be one important contributor to the shift toward more adult-like patterns in the temporal structure of dyadic vocal interaction, a finding that has been hinted at but not directly investigated in prior analyses of the temporal structure of single individuals' vocalizations (cf. Abney et al., 2017; Falk & Kello, 2017). Thus, child language growth may represent a change in the constraints of the dyadic system, contributing to less clustered and more flexible interactional dynamics that allow for smoother interactions. This interpretation is consistent with previous work on the bidirectional influence of parents and children during play (Hirsh-Pasek et al., 2015; Ritwika et al., 2020; Warlaumont et al., 2014).

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Previous findings in the literature offer clues to potential mechanisms by which child language development may shift the HTS at the level of the dyad by changing the nesting of the different timescales of the interaction. Although listed separately, the influence of all these potential mechanisms on the emergent interaction dynamics of the parent-child dyad is likely multiplicative and their effects not reducible to their individual contributions but the joint effects they have on the dyadic system's constraints. First, as infants shift from primarily prelinguistic communication to first words and then multiword communication, they may contribute more vocalizations to the “conversation” with their parent, creating a more reciprocal turn-taking pattern of interaction and thus reduced HTS (Hilbrink et al., 2015).

Second, parent's use of infant-directed speech characteristics typically wanes as children's language skills increase (see Wang et al., 2018 for review). The prosodic features of IDS such as its relatively slower speech rate and increased prosodic variability at phrase endings were associated with increased HTS during scripted storybook reading in an infant-directed compared to an adult-directed style (Falk & Kello, 2017), suggesting the current findings may also reflect parents' reducing their use of IDS as a function of their child's expressive language ability. Relatedly, children's increasing language skills might also trigger an increase in the lexical and syntactic complexity of the caregiver's speech to the child (Choi et al., 2020; Fusaroli et al., 2019). Third, as infant communication abilities develop, parents adjust their own hierarchical clustering to that of their infants (Abney et al., 2017), which might also contribute to the changes in HTS found at the level of the dyad.

Increased HTS in ASD Toddlers

We also characterized the HTS of parent-child dyads of children with ASD. HTS was significantly greater (steeper slope) in the parent-child dyads of autistic children compared with

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either non-verbal matched or expressive language matched parent-child dyads of TD children, suggesting that the interaction dynamics of the ASD parent-child dyads were more rigidly organized across timescales, particularly for longer timescales. That is, from a dynamical systems perspective, the dynamics of these dyads were more determined by the ongoing patterns of interaction already established within the dyad and less adaptive or flexible to changing interactional constraints (cf., Kelso, 2009a), consistent with impairments in the transactional social feedback loop in ASD (Swanson, et al., 2019; Warlaumont et al., 2014).

Additionally, while child expressive language served as a constraint to the interactional dynamics in TD dyads, it did not serve the same function in the parent-child dyads of toddlers with ASD (at least over the expressive language range of the current sample). The greater HTS in ASD dyads may reflect differences in reciprocal interaction between dyadic partners in the ASD sample regardless of child's language skills. For example, although the autistic toddlers may have developed certain language skills (as measured by the Mullen), they might not reliably and robustly use these skills during unstructured social interaction. This hypothesis is in line with the observation that the AF functions differed across the ASD and TD groups particularly at longer timescales of vocal behaviour (e.g., longer than one second, indicating phrase-, sentence-, and pragmatic-level timescales), which mostly reflect the effects of social communication and pragmatic constraints in the interaction (Abney et al., 2014; Schneider et al., 2020). Such pragmatic constraints may be influenced by many variables, including affect, language, social communication, temperament, mental health, context, etc; all which may affect the social reciprocity between two partners and be reflected in their conversational dynamics. In contrast, TD and ASD dyads demonstrated similar patterns in shorter timescales, likely reflecting the physics of the human vocal tract characteristics as well as the use of similar registers, for

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instance, IDS across dyads. This is consistent with previous work where conversational speech signals of contexts differing in rapport only diverged at longer timescales. For example, though a highly different context and population, HTS differed based on the reciprocity of fluently conversing adults, who exhibited greater individual HTS at longer timescales during argumentative versus affiliative conversations (Abney et al., 2014). Because HTS quantifies temporal organization across multiple levels of interaction, it is well suited to quantify the cumulative and cascading bidirectional effects in parent-child communication. Combining AF analysis with other qualitative measures, such as conversational analysis or global ratings of dyadic interaction, would provide further insight into how parents and their autistic children work together to create social action (Bottema-Beutel & Kim, 2020).

Methodological Considerations for the Characterization of HTS in the Dyadic System: Strengths, Limitations, and Future Directions

The current study builds upon previous work showing that AF analysis is a promising avenue for meaningfully characterizing global differences in interactional dynamics across a variety of communication contexts (Abney et al., 2017; Abney et al., 2014; Falk & Kello, 2017; Kello et al., 2017; Ramirez Aristizabal et al., 2018) and expands this work to a clinical population of children with ASD. Extending this work into parent-child dyads demonstrates the feasibility of measuring HTS in unbalanced dyadic signals without having to separate individual speakers, while still being able to interpret results in light of prior single-speaker findings since the majority of vocalizations in our data come from parents. Quantifying the temporal structure of the dyad as an interactive unit reflects the bidirectional influence that parents and children have on each other during vocal interaction and the shared constraints provided by individual,

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interactional, and contextual factors (Abney et al., 2017; Bottema-Beutel, 2017; Choi et al., 2020; Hilbrink et al., 2015; Rowe & Snow, 2020).

The AF analyses reflected changes in temporal structure as a result of expressive language growth, in the case of our TD longitudinal cohort, as well as child ASD diagnostic status. A strength of this approach is that it provides an automated and objective measure of interactional dynamics, particularly compared to traditional vocal analysis methods that typically involve manual segmentation and annotation, which are time- and resource-intensive. This data-driven approach also avoids the challenges associated with behavioral coding in the turn-taking of parent-child coordination literature, such as defining appropriate inter-turn latencies or operationalizing parent input (Bottema-Beutel & Kim, 2020). By capturing hierarchical organization across multiple timescales and individuals, the dyadic AF approach offers a global look at interactional dynamics that complements more traditional metrics that look only at one timescale or that conduct multiple analyses to iteratively examine different timescales and individuals. Relatedly, AF analysis, by definition, controls for the frequency of acoustic events, meaning that the distribution (clustering) of events across timescales is the primary driver of variability in HTS, even for signals that differ in density of vocalizations (e.g., dyads that vocalize a lot versus dyads that are relatively more silent); and when applied across the dyad, still meaningfully captures interactional dynamics of unbalanced signals such as parent-infant interactions in which one interlocutor (e.g., the parent) contributes more to the signal (e.g., Abney et al., 2017; Northrup & Iverson, 2015). These features suggest dyadic AF analysis may be particularly useful when investigating vocal temporal structure in populations such as young children, those with developmental differences, or when capturing changes in interaction dynamics over time.

A limitation of the current approach is that it does not clarify underlying mechanisms. Future research could combine dyadic AF analysis with traditional metrics of communication behaviors within and between individuals (e.g., prosodic stress markers like durational contrasts, turn-taking latency, etc.) to provide insight into theory-driven factors that can be tested as predictors of HTS (Harbison et al., 2018; Harder et al., 2015; Kellerman et al., 2019; Northrup & Iverson, 2015). Relatedly, other individual and environmental factors that may contribute to the dyadic interaction, such as parent stress, responsiveness, affect, and child temperament, should be explored in future research. At the same time, a strength of the AF approach is recognizing that these different communication and linguistic features do not occur in isolation – local and global prosodic features interact with each other, as do individual vocalizations with interpersonal responsiveness, to impact the multiscale temporal dynamics of the interaction (e.g., Falk & Kello, 2017; Ramirez-Aristizabal et al., 2018; Smith & McMurray, 2018; Warlaumont et al., 2014).

The current results are only directly generalizable to the interaction dynamics of parent-child dyads of TD infants and toddlers, and autistic toddlers, during a free-play scenario, as more structured tasks or situations might impose additional constraints on the interactional patterns of the dyad. While the bidirectional exchange between the parent and child is of primary interest, parent-child interaction is not a closed system, and future research could expand these results to different settings with different interactional demands (e.g., a more structured play or snack routine). One limitation of the current study is that environmental variables such as positioning (e.g., free play in a high chair vs. the floor) may impact or put additional constraints on the dyadic interaction (Schneider et al., 2021). Prior studies show promise with respect to stability of HTS measures within interactional contexts in TD individuals (Schneider et al., 2020). However,

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investigating the stability of HTS over short-term periods and across environmental configurations would provide invaluable information into the psychometric properties of HTS as a measure of interactional dynamics and its generalizability, including in ASD. Future studies could also evaluate HTS as a metric of interaction dynamics in children with other developmental disabilities as well as in older children with higher expressive language levels. For example, examining children with non-ASD developmental delay, or examining children/adults with and without ASD with fluent speech, could clarify the extent to which greater dyadic HTS reflects language skills versus social motivation or reciprocity at different developmental timepoints. Additionally, longitudinally studying changes in HTS across parent-infant dyads with children who later do or do not develop ASD could reveal when changes in these interactional dynamics emerge.

Summary

Examining HTS at the level of the dyad recognizes the dyad as its own system that is affected by constraints intrinsic to each member of the dyad, their interaction, and the external setting. In parent-infant dyads of TD infants, HTS decreased with increasing child expressive language skills consistent with the emergence of more mature and flexible interaction dynamics. In contrast, parent-toddler dyads of children with ASD exhibited significantly greater HTS, even when matched for child language level, reflecting interactional patterns more strongly driven by the existing internal dynamics of the dyad and potentially less sensitive to changes in constraints. The application of AF analysis to explore the temporal structure of parent-child interactions in various populations is a promising avenue for better understanding early childhood communication through an interactional lens.

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Supporting Information

Individual Differences in HTS of ASD Dyads

We correlated the AF slope for each ASD dyad with the child's MSEL expressive language score and ADOS-2 Social Affect score. AF slopes in the ASD dyads were not significantly associated with child's expressive language skills ($r = -.10$; $p = .66$; Figure S-1A) consistent with the group comparison results presented in the main text indicating significantly steeper AF slopes for ASD dyads than ELM dyads. AF slopes in the ASD dyads were also not associated with children's ADOS-2 Social Affect scores ($r = .19$; $p = .39$, Figure S-1B).

Figure S-1. Relationship between AF scores in the parent-child dyads of children with ASD with children's (A) MSEL expressive language age equivalence scores; and (B) ADOS-2 Social Affect scores. The shaded regions show the standard error.

It is possible that our ASD sample, small due to Covid-19, was underpowered to detect an effect of ADOS-2 Social Affect and this could be further investigated in future studies with larger samples. Additionally, differences in the interactive context of the ADOS-2 and the parent-child play session may have attenuated any relationship between these two measures. The ADOS-2 is conducted by a trained clinician, contains both free play and semi-structured play

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routines, and includes different toys and specific interaction bids compared with unstructured parent-child free play session. Moreover, the ADOS-2 scale quantifies the vocal and nonverbal behavior of only the child while the AF slope quantifies the vocal behavior of the parent-child dyad using acoustics from both partners. Future studies could employ direct measures of child's social engagement during the parent-child interaction itself, as well as parent social behaviors (e.g., parent responsiveness) and other factors that might affect interaction dynamics, such as parental anxiety and depression scores (e.g., Granat et al., 2017) to examine individual predictors of HTS in ASD parent-child dyads.

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