Identifying stable speech-language markers of autism in children: Preliminary evidence from a longitudinal telephony-based study

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Abstract

This study examined differences in linguistic features produced by autistic and neurotypical (NT) children during brief picture descriptions, and assessed feature stability over time. Weekly speech samples from well-characterized participants were collected using a telephony system designed to improve access for geographically isolated and historically marginalized communities. Results showed stable group differences in certain acoustic features, some of which may potentially serve as key outcome measures in future treatment studies. These results highlight the importance of eliciting semi-structured speech samples in a variety of contexts over time, and adds to a growing body of research showing that fine-grained naturalistic communication features hold promise for intervention research.

1 Introduction

Natural sampling is a rich approach to investigating speech and language in autistic children. Previous studies have shown that language behavior in autism differs from neurotypical (NT) patterns in a number of ways. For example, autistic children who are more severely impacted have been shown to produce less speech (Bone et al., 2014), slower speech (Parish-Morris et al., 2016; Bonneh et al., 2011), and speech with atypical voice quality compared to NT peers (Paul et al., 2005; Shriberg et al., 2001), including heightened jitter, increased jitter variability, but reduced harmonic-to-noise ratio (Bone et al., 2014). It has also been observed that autistic children's prosody differs from NT children, with qualitative observations ranging from "sing-songy" and exaggerated to monotonous, machine-like, or hollow (Bonneh et al., 2011;DePape et al., 2012; Lord et al., 1994; Wehrle et al., 2020; Fusaroli2017; Fusaroli2021). In the lexical domain, prior research has shown that autistic children use more nouns than NT peers when narrating a story from a picture, suggesting that the storytelling of children with autism is more object-focused (Boorse et al., 2019). Also, children with autism use fewer filler words during clinical assessments than NT children (Parish-Morris et al., 2017), and they talk less about social topics during get-to-know-you conversations compared to NT children (Song et al., 2021). It is also observed that children with autism have difficulties in using words in non-literal ways (Bara et al., 1999; Rutherford et al., 2012). Research in this domain continues to emerge, but samples remain small and results occasionally conflict, as in the description of prosody being either "sing-songy" or monotonous, or fail to replicate (See Fusaroli et al., 2017 for a meta-analysis of previous findings).

Prior studies of natural language in autism used a variety of data collection and analysis methods that could critically affect results and may have led to conflicting findings. For example, the presence of an unfamiliar adult during in-person or remote elicitations could adversely impact the behavior of autistic children, thus reducing the quality and informativeness of their language samples (Barokova and Tager-Flusberg, 2020). Also, children's linguistic behavior might differ depending on the specifics of the elicitation task in a given study, i.e., whether natural conversations or semi-structured speech tasks are used, and the characteristics of certain elicitation stimuli.

In order to develop scalable, cost-effective, reliable intervention progress monitoring systems of autistic symptoms using speech as a primary target, it is necessary to understand how contextual and testing factors affect children's behavior. Then, it will be possible to identify robust features that reliably index autism symptoms across heterogeneous testing conditions. Toward this goal, we developed a telephony protocol to examine how various factors affect speech performance in autistic children and adolescents. Telephony has particular potential to address service and monitoring gaps for

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autistic and NT children from historically marginalized and/or low-resource communities(Omer et al., 2022), and is a useful alternative to in-person data collection during the COVID-19 pandemic. The final battery of our protocol consisted of seven versions of seven tasks that a parent or legal guardian could independently facilitate. In this preliminary report from an on-going study, we assessed children's speech and language features during one of the seven tasks (picture descriptions) collected in the first and second phone sessions. Our goals were to (1) identify diagnostic group differences in automated speech and language features that are stable over time, and (2) examine potential effects of staff vs. parent administration in each diagnostic group.

	Autism (n=13)	NT (n=16)	p-value
Age (years)	9.8 (2.5)	9.6 (2.6)	0.767
Sex (%)	10 boys (76.9%)	6 boys (37.5%)	0.015
Full scale IQ	115.1 (15.4)	119.1 (13.7)	0.469
Race	4 non-whites	5 non-whites	0.69
SCQ (total)	17 (6.6)	1.2 (1.1)	<0.001
SRS-2 (total)	70.5 (7)	42.1 (3.5)	<0.001
CCC-2 (speech)	9.2 (2.5)	11.8 (0.8)	<0.001
CCC-2 (non-speech)	5.5 (2.2)	11.8 (1.3)	<0.001

Table 1: Demographic and clinical characteristics of the participants. Groups were compared with *t*-tests, except the sex ratio, where a chi-square test was used. SCQ: Social communication questionnaire (Rutter et al., 2003), SRS: Social responsiveness scale (Constantino, 2011), CCC: Children's communication checklist (Bishop, 2006).

2 Methods

2.1 Participants

Study inclusion and exclusion criteria are included in the Appendix. In this report, we analyzed data from 29 children who successfully completed two sessions. Participant groups were matched on age, full-scale IQ, and self-reported race. Groups were not matched on sex (p=0.015), which is expected due to the prevalence of ASD in boys (Baio et al., 2018), and we are currently addressing with targeted recruitment. One autistic participant identified as non-binary. Autism and NT groups differed in several clinical ratings (Table 1).

2.2 Data collection and annotation

We developed a telephony platform to support single and dual speaker modes. This platform consisted of a high-availability server, voice over internet protocol (VoIP) service by Vonage, telephony software framework (Asterisk 13.18.3), a relational database, and telephony applications.

The seven sessions included seven age-appropriate tasks, and the picture description task was included in all sessions. Children described different pictures in all seven sessions, and four sessions were administered by study staff and the other three sessions were proctored by children's caregivers. The data collection is on-going, and we only analyzed the first and second sessions in this study. Prior to the first official data collection call, study staff held an "informational call" with the participating parent to review standard elicitation methods to be utilized across sessions. During the first session with the child, study staff remained on the line and facilitated tasks with the parent and child. During the second session, children and parents independently completed all seven tasks on their own. The second session was collected approximately one week after the first session was completed. The study was reviewed by the institutional review board at the Children's Hospital of Philadelphia. Written informed consent was obtained from parents and children provided a verbal assent before study enrollment.

Recordings were transcribed by trained annotators using a web-based transcription tool with a built-in speech activity detector (SAD) function. Data were stored in secured HIPAA-compliant servers, and all annotators were trained to protect patients' identities and identifiable information. For dual speaker mode recordings, SAD ran on each channel separately. Annotators also corrected speech segment boundary errors.

2.3 Acoustic and text features

Words were automatically tagged for part-of-speech (POS) categories using spaCy (Honnibal and Johnson, 2015). POS categories, fillers, partial words, repetitions, and "hm" were counted separately and converted to counts per 100 words. Content words were rated for word frequency (Brysbaert and New, 2009), concreteness (Brysbaert et al., 2014), ambiguity (Hoffman et al., 2013), age of acquisition (AoA) (Brysbaert et al., 2018), and familiarity (Brysbaert et al., 2018). We also ran the Language Inquiry and Word Count program (Pennebaker et al., 2015) to calculate additional word-level measures found to be useful in clinical population.

For acoustic processing, stereo recordings were split into single channels for precise audio processing. We extracted low-level descriptors of pitch, jitter, shimmer, harmonic-to-noise ratio (HNR), and four spectral moments (1st order: centroid, 2nd order: standard deviation, 3rd order: skewness, 4th order: kurtosis) from participants' picture descriptions per 10 ms using openSMILE with the ComParE13 configuration file (Eyben et al., 2013). Pitch values in hertz were converted to semitones (st) using individuals' 10th percentiles to normalize physiological differences among participants (St = $\log_2$(f0 / 10th percentile) x 12). Since this method used each speaker's baseline (i.e., the 10th percentile of individual's pitch range) to convert raw hertz values to semitones, it allowed us to compare the groups directly despite the significant difference in sex ratio and the wide age range. Several durational measures were computed from SAD timestamps.

2.4 Statistical considerations

Preliminary analyses revealed that our variable residuals met the assumptions of parametric tests, so we employed analysis of covariance (ANCOVA) models. Speech/language features were included as dependent variables, with group, session, and the interaction of group and session as independent variables. Sex was covaried in all models. Since this was a first exploratory analysis, with findings that would be considered reliable only once the data collection is over, we did not currently correct p-values for multiple comparisons.

3 Results

3.1 Acoustic measures

Median shimmer and jitter values were higher for autistic children than NT children (shimmer: F(1,52)=4.17, *p*=0.046; jitter: F(1,52)=3.96, *p*=0.052, Figure 1A-B). Mean, standard deviation (SD), and interquartile range (IQR) of jitter and shimmer did not differ by group. Autistic children also had higher mean (skewness: F(1,52)=13.46, *p*<0.001; kurtosis: F(1,52)=12.98, *p*<0.001), median (skewness: F(1,52) =6.17, *p*=0.016; kurtosis: F(1,52)=4.7, *p*=0.035, Figure 1C-D), SD (skewness: F(1,52)=9.89, *p*=0.003; kurtosis: F(1,52)=13.86, *p*<0.001), and IQR values (skewness: F(1,52)=7, *p*=0.011; kurtosis: F(1,52)=8.26, *p*=0.006) of spectral skewness and kurtosis than NT children. Groups did not differ in pitch and HNR, and Session had no significant effect on any acoustic variables.

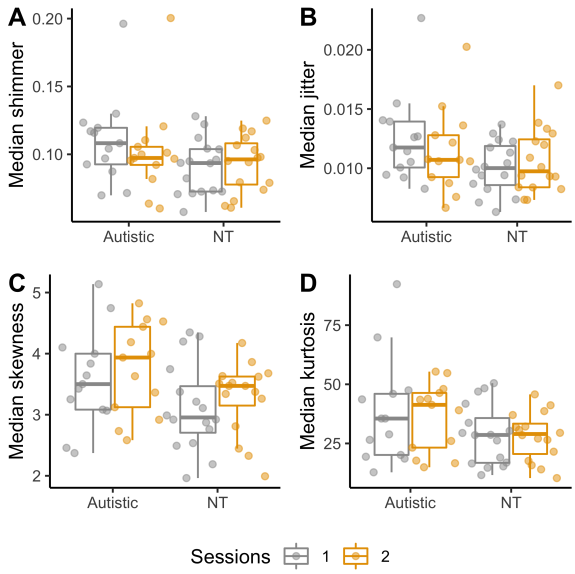

Figure 1: Acoustic features during picture description tasks. Shimmer refers to variability in signal amplitude, whereas jitter represents variability in signal frequency (A, B). Spectral skewness and kurtosis refers to the third and fourth order of spectral moments, which are known to characterize voice timber (C, D). Only median values are plotted for an illustration purpose.

3.2 Durational measures

Autistic children produced longer (F(1,52)=7.79, *p*=0.007) and more variable (F(1,52)=8.49, *p*=0.005) speech segment durations than NT children (Figure 2A-B). The difference in total speech duration between the first and second sessions was larger for autistic children than NT children (F(1,52)=4.34, *p*=0.042). Total pause duration was shorter in autistic participants than NT children (F(1,52)=5.14, *p*=0.028, Figure 2C-D), and children paused longer during the first session compared to the second (F(1,52)=4.82, *p*=0.033). Autistic children paused less frequently than NT children (F(1,52)=6.33, *p*=0.015).

3.3 Textual measures

Autistic participants produced fewer conjunctions (F(1,52)=5.06, *p*=0.029) and pronouns (F(1,52)=

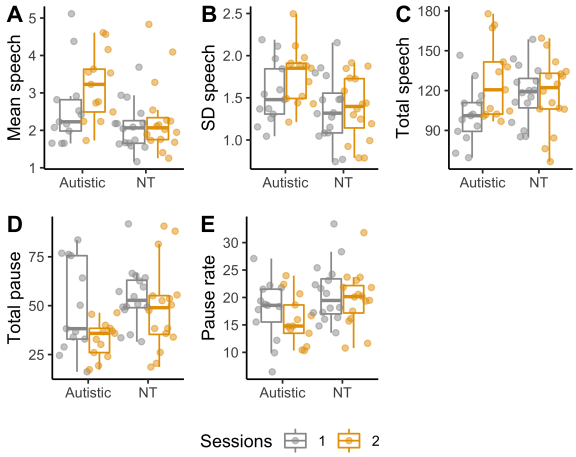

Figure 2: Durational measures during picture descriptions. The units of the y-axis are seconds, except the pause rate, where pause rate per minute was plotted.

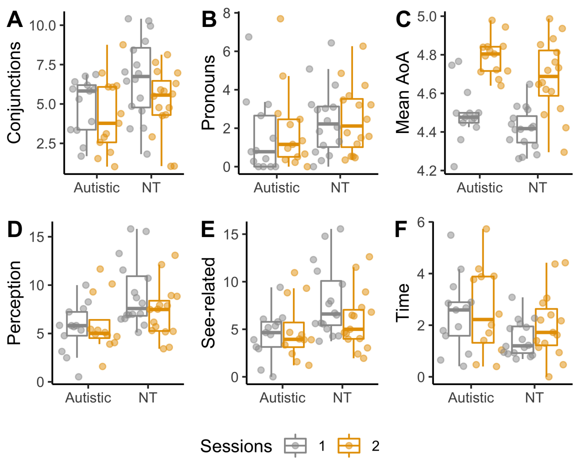

Figure 3: Lexical measures during picture description tasks. All POS counts are per 100 words, and the age of acquisition was averaged across all content words produced by each child. The counts of LIWC categories were also normalized.

4.75, p=0.034) than NT children, and their content words had a higher AoA than those of NT children (F(1,52)=6.35, p=0.015, Figure 3A-C). Also, autistic children produced fewer perception (F(1, 52)=9.17, p=0.004) and see-related words (F(1,52) =7.1, p=0.01) and more time-related words (F(1, 52)=4.79, p=0.033) than NT children (Figure 3).

Regardless of diagnostic status, children produced more adverbs (F(1,52)=9.08, p=0.003) and prepositions (F(1,52)=6.47, p=0.014) during the second session than the first (not shown in the figure). Children also produced content words that were more ambiguous (F(1,52)=10.82, p=0.002), later acquired (F(1,52)=54.9, p<0.001), and familiar (F(1,52)=14.85, p<0.001) during the second session than the first session. Finally, several LIWC categories, including anger (F(1,52) =4.69, p=0.035), difference (F(1,52)=5.55, p=0.023), feeling (F(1,52)=4.06, p=0.049), bio (F(1, 52)=4.99, p=0.03), and ingestion (F(1,52)=19, p<0.001), showed significant effects of Session.

4 Discussion

In this study, we elicited picture descriptions from autistic and NT children using a telephony platform, and tested for the presence of diagnostic group differences in a variety of acoustic and lexical features over two sessions. Results showed that autistic children produced greater local jitter, shimmer and the third and fourth orders of spectral moments, as well as shorter and less frequent pauses compared to NT children, across two sessions and with different stimuli. Autistic children produced more speech during the second session when parents administered the task without study staff, compared to the first session. In contrast, NT children's speech duration did not differ by session. Lexically, autistic children produced fewer conjunctions and pronouns than NT children, and used later-acquired content words compared to NT peers. Our results also showed that autistic children used fewer see- or perception-related words and more time-related words than NT children. However, many other lexical features differed by session without significant group differences, suggesting that the picture stimuli may have had more influence than diagnostic group on lexical production.

Given that the acoustic features described here remained stable from the first to the second telephony session, and also distinguished diagnostic groups, they might hold potential as reliable speech markers of autism. Higher jitter (variability in frequency) and shimmer (variability in amplitude) are perceived as harsh, hoarse, or breathy voice (Tsanas et al., 2011). The observation that autistic children's jitter and jitter variability were higher than NT peers is consistent with a previous study that also showed positive correlations between jitter and autism symptomology (ADOS scores; Bone et al., 2014). Yet, a recent meta-analysis study found that jitter was lower in autistic children than NT children in US and it did not differ in Denmark, so future study is needed to resolve this mixed finding (Fusaroli et al., 2022). Also, previous studies showed consistently lower HNR values for autistic children compared to NT peers, with mixed findings in shimmer (Fusaroli et al., 2022); this differs from our pattern of results, where we found no difference in HNR but higher shimmer in children with autism. Spectral moments in autism have rarely been studied, even though these measures are known to characterize individuals' voice timbre (Lerch, 2012). We plan to study these features further in a larger sample after completing the data collection, to explore whether they could serve as validated speech markers of autism.

Children on the autism spectrum spoke longer and paused less frequently during the second session than the first session, whereas TD children's duration measures did not differ by session. This finding is in line with prior research where fewer pauses were consistently observed in children with autism (Fusaroli et al., 2022). This finding has at least two potential explanations: First, autistic individuals experience social-communicative challenges which might have hindered their willingness to speak freely in the presence of unfamiliar study staff. In this case, they may have spoken longer in the second session because their parent administered the task. Thus, it is important to consider the presence or absence of study staff when interpreting studies of speech and language in autism. Alternatively, children's greater speaking duration in the second session could simply be due to task familiarity; by week 2, children knew what to expect and had already completed the picture description once.

Finally, our study also found that autistic children produced fewer conjunctions, pronouns, see- and perception-related words with high AoA than NT children. We also observed that many word-level features differed by session in both the autistic and NT groups, suggesting that picture selection has an outsized effect on lexical features. In this study, we selected seven different pictures to prevent boredom and practice effects across multiple sessions. However, since different pictures include unique objects that children are likely to list in their descriptions, this will result in significant session-based differences in word-level features. Picture selection and objects in pictures need to be carefully designed in future research, potentially with less weight placed on specific content words as stable outcome measures. As data collection continues in the current study, we will investigate whether group differences in more abstract lexical features (e.g., pronoun use) might remain stable over all seven sessions.

5 Conclusion

Telephony carries great potential as a low-cost and scalable platform for monitoring intervention responses from afar, as well as measuring longitudinal developmental changes in individual children. Acoustic features extracted from data collected using a telephony system, which delivered consistent, high-quality recordings, could be important tools for identifying speech markers of autism.

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A Inclusion and Exclusion Criteria

Inclusion criteria for participants were the following:

- Subjects age 6 – 17.99
- English is participant's first language
- Verbally fluent – language on grade level/consistent with chronological age
- Strongly suspected/confirmed diagnosis of autism or typical development
- Full-scale and verbal IQ > 75
- For autistic children, current SCQ score >= 11
- For the NT group, current SCQ scores < 11

Exclusion criteria for participants were the following:

- Known genetic condition that impacts neurodevelopment or vocal production/language
- History of persistent language deficits that are currently affecting child's language abilities such that it impacts their ability to have a conversation
- Extreme prematurity (<32 weeks)
- History of severe neurological injury likely to affect expressive language and communication behavior
- If NT, no first-degree family members with autism
- Plan to begin or change medication during study duration
- Plan to begin or change an intervention during study duration
- Diagnosis of hearing impairment or cochlear implant