Received: 15 December 2020 | Accepted: 14 April 2021
DOI: 10.1002/aur.2526

RESEARCH ARTICLE

A granular perspective on inclusion: Objectively measured interactions of preschoolers with and without autism

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Funding information
Institute for Educational Sciences, Grant/Award Number: R324A180203

Abstract
Children's preschool experiences have consequences for development. However, it is not clear how children's real-time interactions with peers affect their language development; nor is it clear whether these processes differ between children with autism spectrum disorder (ASD) and two other groups of children, those with general developmental delays (DD) and typically developing (TD) children. We used objective measures of movement and vocalizations to quantify children's real-time dyadic vocal interactions and quantify classroom social networks. Participants included 56 preschoolers (22 female; M = 50.14 months) in five inclusive classrooms for children with ASD or DD and their TD peers. Each class was observed monthly on two to five occasions. Overall, children vocalized more to peers who had vocalized more to them in the previous observation. These dyadic vocalization patterns were associated with group differences in social network analyses. Modularity, the cohesiveness of group ties, was lower among children with ASD than it was among TD children or children with DD. Individually, children with ASD exhibited lower total levels of vocalizations with peers (lower degree centrality) than TD children and children with DD. In an exploratory analysis with a subset of the participants, children's degree centrality was strongly associated with their end-of-year assessed language abilities, even when accounting for mean differences between groups. Findings highlight the impact peers and social networks play in real-time language use and in the developing language abilities of children with ASD in inclusion classrooms.

Lay Summary: This study objectively measured associations between children's peer vocal interactions and assessed language abilities in inclusion classrooms for children with autism spectrum disorder (ASD) and their peers. All children benefited from peers talking to them, but children with ASD were less central to classroom speech networks than were typically developing children. Children's centrality to social speech networks, regardless of ASD status, was associated with assessed language abilities.

KEYWORDS
autism spectrum disorder, developmental disabilities, language development, objective measurement, peer interactions, social networks

INTRODUCTION

Children's experiences in preschool have cascading effects on their social–emotional and language development (Goldfeld et al., 2016). Peers play a significant role in these developmental changes (Bulotsky-Shearer et al., 2012; Hanushek et al., 2003). The role of peers in language development is noteworthy (Justice et al., 2011). Children whose peers have relatively advanced expressive language abilities in the fall exhibit larger gains in their own receptive and expressive language abilities in the spring (Justice et al., 2014; Mashburn et al., 2009). However, it remains unclear whether peer *interactions* shape children's language abilities, and how this process differs for children with autism spectrum disorder (ASD), relative to peers with general developmental delays (DD) and typically developing (TD) peers. Here we use objectively measured indices of language and social interaction in inclusion classrooms for preschoolers with ASD together with TD peers or peers with DD to examine how peer interactions constitute classroom social networks and are associated with assessed language abilities.

Children with developmental disabilities

ASD is a pervasive neurodevelopmental disorder characterized by deficits in communication and social interaction (American Psychological Association, 2013). In this study, DD is defined as a delay in one or more developmental domains such as language and cognition, which can have consequences for social interactions (Florida Department of Education, 2020). Children with less advanced language abilities are often peripheral to social groups (Locke et al., 2013), isolated (Chen et al., 2020), and neglected by peers with more advanced language abilities (Chen et al., 2019, 2020; Locke et al., 2013). Both children with ASD and those with DD are likely to have general receptive and expressive language delays (Camargo et al., 2014; Charman et al., 2003; Delehanty et al., 2018; Merrell & Holland, 1997). However, children with ASD also exhibit additional, specific atypicalities in their social language usage and understanding, including repetitive speech (Tager-Flusberg et al., 2009), lower rates of sustained conversational turn taking (Laghi et al., 2018), and difficulties with the pragmatic aspects of language (Geurts & Embrechts, 2008), which could further increase difficulties in peer interaction (Brinton & Fujiki, 2017). Delays and speech atypicalities may result in reduced levels of social interaction between children with ASD, children with DD, and TD children. Similarly, the double empathy theory of ASD (Milton et al., 2018) would suggest that because children with and without ASD expect different social norms during social interactions, children with ASD may interact more with each other than with children in different eligibility groups. Reductions in interaction between these groups can be viewed through the lens of homophily, the tendency of similar peers to interact among themselves. Homophily is evident in preschoolers affiliation with respect to diagnoses and disabilities (Chen et al., 2020). Consequently, we expect children with ASD to interact less with TD peers, but do not have specific expectations with respect to potential differences between children with ASD and DD.

Inclusion classrooms and social development

Inclusion preschool classrooms—in which children with ASD are educated alongside children with other developmental disabilities (DD) and TD peers—are a national standard (Guralnick & Bruder, 2016). Emerging evidence suggests that exposure to peers with more advanced social and language abilities improves children's own social (Blazer, 2017) and language abilities (Bauminger-Zviely et al., 2017; Justice et al., 2014). It remains unclear, however, precisely how peer interaction might contribute to language development in inclusion classrooms.

Capturing individual experiences in the classroom

Preschool classrooms are dynamic environments where children engage in simultaneous interactions and have varied language and social experiences (Chaparro-Moreno et al., 2019; Justice et al., 2019; Perry et al., 2018). Previous research has focused on the influence of group- or classroom-level variables including child diagnosis (Danzig et al., 2013), language delay (Fujiki et al., 1999), the general quality of teacher language use (Dickinson & Porche, 2011), and the average peer language ability in a classroom (Mashburn et al., 2009). However, these approaches do not capture speech between individual children during interactions.

Automated measures: Language

Automated tools such as the Language ENvironment Analysis (LENA) system, allow for efficient, objective measurement of individual children's language experiences. LENA digital language processors (DLPs) are lightweight child-worn audio recorders. LENA software provides estimates of the number of child and adult vocalizations (Gilkerson & Richards, 2008), which are valid in both TD and atypical populations (Richards et al., 2017; Trembath et al., 2019). Multiple studies have employed LENA in preschool classrooms (Dykstra et al., 2013; Irvin et al., 2013; Soderstrom & Wittebolle, 2013), revealing for example, that children receiving high levels of peer vocal input have faster rates of vocabulary development over the school year (Perry et al., 2018). Although adoption of LENA in the classroom has characterized individual differences in vocal input, LENA cannot indicate who a child is interacting with—information critical to understanding the role of peer social interactions in language development.

Automated measures: Social interaction

Radio frequency identification (RFID) technology such as that embedded in child-worn Ubisense tags, allows for efficient tracking of each child's location and movement throughout the classroom indicating when pairs of children are in proximity (Irvin et al., 2018; Messinger et al., 2019). When children wear two tags (on the left and right side of the body), their relative orientation to other children (e.g., who is facing whom) can be measured (Altman et al., 2020). Here, we use objectively measured movement and orientation from preschoolers with ASD and DD to simultaneously measure all the dyadic interactions occurring in a class.

Classroom networks

Social network analysis is a tool for understanding the relative strength of ties between social partners, such as peers in preschool classrooms. To understand group and child level differences in classroom interactions, we consider two social network properties: modularity and degree centrality. Modularity indicates the cohesiveness of children's groups, that is, the relative strength of connections among children with ASD compared to the strength of connections among TD children. Degree centrality indicates the overall strength of a child's ties to all peers. Whereas modularity compares ties within and between groups, degree centrality compares a child's ties to each other child.

Chen et al. (2019, 2020) found that children with ASD and DD have weaker ties to their peers than TD peers (lower degree centrality). Despite yielding novel insights into classroom affiliation, this research is limited by its reliance on teacher reports of friendships (Chen et al., 2019, 2020). Recently validated technology can provide tools with which researchers can objectively measure children's positions to discern periods of social contact (via Ubisense) when children vocalize to one another (via LENA). Moreover, these objective measures of peer vocal interaction during social contact are associated with both teacher and child reports of affiliation typically used in classroom network analyses (Altman et al., 2020). In the current study, we used monthly LENA and RFID based observations to objectively characterize social networks in inclusive preschool classrooms.

The current study

This study longitudinally examined children's peer vocal interactions in three preschool inclusion classrooms for children with ASD and DD, as well as their TD peers. We employed objective measures to quantify children's real-time dyadic vocal interactions and classroom social networks. We first examined children's dyadic vocal interactions, hypothesizing that the number of vocalizations a child hears from a peer during one observation will predict that child's subsequent vocal output to that peer in the next observation. Using these vocalizations between peers to create classroom social networks, we ask if there are group differences in network properties, including modularity and degree centrality. We hypothesized that children with ASD will form less cohesive groups (lower modularity) with each other than will TD children. We also anticipate homophily effects such that modularity will be higher within than between groups (e.g., higher within the ASD group than between the ASD and TD groups. Additionally, we hypothesize that individual children with ASD will have weaker ties to peers overall (lower degree centrality) than TD children, indicating less vocal interaction with peers. In our final exploratory analysis, we hypothesize that a child's degree centrality will be positively associated with their end-of-year assessed language abilities, regardless of group.

METHODS

Participants

Participants were 56 preschoolers (22 girls) in five inclusion classes in which English was the primary language of instruction and communication (see Table S1). Two of the classes were half day AM/PM sessions ($\sim$2.5 h long) that occurred in a single classroom. In this classroom, TD children ($n = 8$) were enrolled in both sessions; children with ASD attended either the AM ($n = 4$) *or* PM session ($n = 3$). The third class was an AM only session ($\sim$2.5 h) with 1 TD child, three children with ASD, and seven children with DD. The fourth and fifth classes were full-day sessions ($\sim$5 h). The fourth class had two TD children, two children with ASD, and six children with DD. The fifth class had 10 TD children, four children with ASD, and six children with DD. Child mean age at study start was 50.14 months (SD = 7.06). Eligibility group (group hereafter) was determined by classroom (e.g., ASD inclusion classrooms) and children's individualized education programs (IEP) as supplemented by parent report (i.e., report of an ASD diagnosis). Sixteen preschoolers were in the ASD group, 19 were in the developmental delay (DD) group, and 21 were TD. Of the 56 preschoolers, 49 were Hispanic White, six were non-Hispanic White, one was Hispanic Black. Based on teacher or parent report, 27 of the children were monolingual English learners, 23 were bilingual English-Spanish learners, three were monolingual Spanish learners, and three were bilingual learners of English and a Romance language other than Spanish. We obtained informed consent from children's parents. All study protocols were approved by the University Institutional Review Board.

Data collection

Continuous RFID measurements of each child's location were collected using the Ubisense Dimension4 system. First-person audio was recorded using LENA DLPs (version H) worn by each child in the classroom. These recordings were collected in the classroom during monthly observations that lasted approximately the length of the school day (but excluded activities like outdoor play). The average length of children's recording was 2.25 h (SD = 0.93). Average recording time for children with ASD was 2.12 h (SD = 0.88) average recording time for children with DD was 2.52 h (SD = 1.08); average recording time for TD children was 2.19 h (SD = 0.86). Classes were observed on two to five occasions, with observation day coded 1–5 to account for the effect of earlier versus later observations.

Measures

Children's vocalizations

Each child in the classroom wore a LENA recorder in a specially designed vest. Audio files were analyzed using LENA Pro V3.4.0 pattern recognition software based on Gaussian mixture models, which distinguished children's own speech-like vocalizations from non-speech sounds (e.g., crying) and other speakers' vocalizations. Vocalization counts were derived from LENA's Interpretive Time Segment files, which contained the onset and offset of each vocalization made by the child wearing the recorder, and were calculated as a rate per hour.

LENA algorithms yield reliable estimates of the developmental age of children with varying language abilities and communication disorders, including children with ASD (Dykstra et al., 2013). LENA has been used to quantify speech in both English (Soderstrom & Wittebolle, 2013) and Spanish (Weisleder & Fernald, 2013). To assess the reliability of LENA classifications of speech as child or adult, two trained coders blind to LENA classifications re-coded approximately 5% of LENA-identified adult and child vocalizations (1500 total segments). These vocalizations were sampled across recordings made from 15 child-worn LENA recorders on 10 days. Percent agreement and Cohen's Kappa (K) for each child (each child's recorder) was averaged. There was 86% mean agreement (SD = 0.08) between human coders and LENA (mean K = 0.71, SD = 0.17), suggesting the reliability of LENA codes in the classroom setting. Reliability coding and calculations are available on Open Science Framework https://osf.io/84fwc/?view_only=306f65dcd1144d92b2bc87a185165c25.

Children's movement

The Ubisense system tracked children's location at 2–4 Hz to an accuracy of 15–30 cm (Phebey, 2010), and has previously been used in preschool classrooms (Irvin et al., 2018). The system consists of one sensor in each corner of the classroom (8.97 × 8.86 m, 8.76 × 8.93 m, 9.58 × 8.70 m, and 8.39 × 11.12 m), a dedicated server,

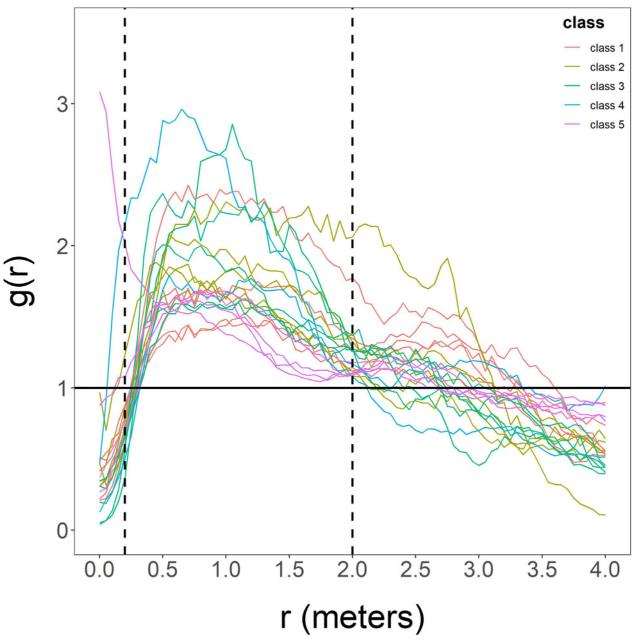

FIGURE 1 The radial distribution function g(r) indicates distances at which the probability of child–child and child-teacher pairs being in contact exceeds chance ($g(r) = 1$). The area between the vertical dashed lines (from 0.2 to 2 m) index the proximity criterion of social contact across observations for each of three classes

and active tags worn by children. Each child wore two tags (in the left and right pockets sewn into a vest housing the LENA recorder). The tags' ultra-wide-band RFID signals were used to calculate child location and orientation in three-dimensional space by means of triangulation and time differences in arrival. This information was used to determine social contact and index when children were speaking to one another.[1]

Social contact (proximity and orientation)
Ubisense measures of child position and orientation were used to detect instances of social contact based on children's proximity and mutual orientation with peers. Children were determined to be in social contact with one another based on proximity and orientation. The radial distribution function indicates distances at which pairs of children are closer than expected than chance ($g[r] > 1$). Chance refers to the likelihood of pairs of children being located at a particular distance given individual location preferences. The radial distribution function for all observations indicated that co-location between children was greater than chance between 0.2 and 2 m (Figure 1), an initial criterion of social contact. Within the 0.2–2 m range, we examined the relative orientation of each dyad. Relative orientation was calculated by

[1]Example visualizations of children's movement and vocalization epochs are available on Databrary for those with authorized researcher accounts (see visualizations at https://nyu.databrary.org/volume/987/slot/44021/) and two example visualizations are available on OSF at https://osf.io/84fwc/?view_only=306f65dcd1144d92b2bc87a185165c25.

measuring θ_1, the angle of Child A relative to Child B, and θ_2, the angle of Child B relative to Child A. We defined periods of social contact as instances in which children were oriented toward one another within $\pm 45°$ (approximately facing each other).

Data integration

The Ubisense signal was interpolated at 0.10 s intervals and synchronized with the audio recordings to determine when pairs of children vocalized during periods of social contact. Only vocalizations during social contact with peers were analyzed. We summed the number of vocalizations made by each child during periods of social contact with each of their peers to index which children were speaking to one other (e.g., how much Child A spoke to Child B, and how much B spoke to A). These sums were divided by the length of time both children in a dyad were simultaneously in the classroom to yield the rate of vocalizations per hour.

Social networks

To explore social ties, we constructed a social network for each of the three classes. In these networks, children (nodes) are connected to one another by ties. Ties have weights corresponding to the summed rate of child speech within a dyad while in social contact (i.e., Child A to Child B plus Child B to Child A). We used these networks to assess the modularity of groups (e.g., ASD vs. TD) and to assess individual children's degree centrality in the class network.

Modularity
Network modularity is a measure of group cohesion. Modularity indicates the degree to which the mean of the weighted ties connecting children (nodes) *within* a group is greater than the mean of the weighted ties connecting all children in the class. For example, the modularity of the ASD group is the mean weight of ties connecting children with ASD to other children with ASD divided by the mean weight of all ties in the class. By the same principle, between modularity, the modularity of ties connecting children in different groups, can be used to index intergroup speech in social contact. The modularity of ties connecting children with ASD to TD children and children with ASD to DD children is the mean weight of ties between children in these different groups divided by the mean weight of ties in the entire class (see Data S1). As our focus is how children with ASD may differ from other children, the between group modularity measure indexed only ASD-DD and ASD-TD ties.

Degree centrality
A child's degree centrality is the sum of the weights of the ties connecting the child to other children in the classroom. We calculated the weighted degree centrality for each child on each observation and averaged degree centrality over observations.

Standardized assessments of language abilities

Trained researchers administered the Preschool Language Scales, Fifth Edition (PLS-5, [Zimmerman et al., 2011] at the end of each school year to obtain a standardized measure of each child's receptive and expressive language abilities. A subset of 26 children (from three classes) were administered the PLS (10 ASD, 7 DD, 9 TD). Data collection for the other 30 children (in two classes) took place during the spring of 2020 when the COVID19 pandemic closed schools and paused in-person research, stopping data collection and preventing administration of an end-of-year PLS-5. Three children (one with ASD, one with DD, one TD) were administered the bilingual Spanish-English form of the PLS-5, based on teacher report of the child's language background (i.e., Spanish dominant bilingualism). There were no differences in PLS-5 scores administered using the bilingual or monolingual English form, $p > 0.39$.

Analytic plan

We use both multiple regression and mixed effects regression analyses to analyze the data using R (RStudio, 2018). In mixed effects models, conducted using the lme4 package (Bates et al., 2014), observations were nested within children. As eight children were enrolled in both the AM and PM sessions of one class, the design is more complex than simply nesting children within classes with classes in three-level design. Instead, the design is crossed and includes a random class intercept at level 2. Continuous variables (e.g., children's vocalizations to and from peers) were mean centered within subject. ASD was the reference group for contrasts with DD and TD. Significance of fixed effects was determined using the *lmertest* function, which provides summaries via Satterthwaite's degrees of freedom (Kuznetsova et al., 2017). Significance of random effects was determined using chi-square tests of model comparison. In multiple regression analyses predicting PLS-5 scores, predictor variables such as degree centrality were averaged over monthly observations for each child. In the Data S1 (Figures S2–S4) we report tests of model assumptions of homogeneity of variance and normality of residuals. R code and datasets are available on OSF at https://osf.io/84fwc/?view_only=306f65dcd1144d92b2bc87a185165c25.

TABLE 1 Predicting target child vocalizations to peers at observation t + 1

Parameter	Fixed effects *B*	*Se*	*t*	95% CI	*p*	*d*
Peer vocalizations to target at observation *t*	0.024	0.01	2.39	0.004, 0.044	0.017	0.13
Target vocalizations to peer at observation *t*	−0.002	0.01	−0.44	−0.014, 0.009	0.662	−0.02
Group						
ASD versus DD contrast	0.093	0.10	0.92	−0.115, 0.287	0.363	0.24
ASD versus TD contrast	0.108	0.09	1.25	0.062, 0.279	0.217	0.37
Interaction between group and partner input						
ASD versus DD contrast	−0.025	0.01	−2.04	−0.048, −0.001	0.042	−0.11
ASD versus TD contrast	−0.012	0.01	−1.06	−0.034, 0.010	0.291	−0.06

	Random effects		Chi-square test of model fit		
	Variance	SD	X^2	*df*	*p*
Subject intercept	0.036	0.19	33.84	1	<0.001
Class intercept	0.050	0.73	22.43	1	<0.001

Note: This analysis used a log10 ($x + 0.001$) model; a log transformation was implemented because assumptions were not originally met. The log transformation was applied to the target child's vocalization variable, which is the outcome variable in this analysis. Results show that previous peer input is associated with future vocalizations to that same peer.
Abbreviations: ASD, autism spectrum disorder; DD, developmental delays; TD, typically developing.

RESULTS

Our order of operation was to predict children's dyadic vocalizations, use patterns of dyadic vocalizations to investigate group modularity and individual child centrality in classroom networks, and, in a pilot analysis, to investigate the association between centrality and children's assessed language abilities. In these analyses, we assessed group differences between children with ASD and their TD peers and peers with DD.

Dyadic vocal peer interactions

We first investigated whether children vocalized more to peers who had vocalized more to them, and if, in addition, children with ASD engaged in fewer vocalizations to peers. A lead–lag analysis was implemented through a linear mixed effects model. Each child was simultaneously treated as a target whose vocalizations were being predicted, and as a peer whose vocalizations were a predictor of the target child's vocalizations. The model predicts the target child's rate of vocalizations to each of their peers at observation $t + 1$ from their rate of vocalizations *from* those peers at observation t, where t and $t + 1$ are consecutive monthly observations. All vocalizations occurred in social contact. We log transformed (log10 [$x + 0.001$]) the outcome variable to meet the homogeneity of variance assumption (see Data S1). Fixed effects in the model included previous vocal input from each peer to the target at observation t, previous target vocalizations to each peer at observation t (an auto-regression control), target eligibility group, and the interaction between peer input and target group. The model included random intercepts of subject and class.[2]

The rate of vocalizations from peers in the previous observation predicted the rate of target child vocalizations to partners, although the effect was small $p = 0.017$, $d = 0.13$ (Table 1). That is, greater exposure to peer speech in social contact, predicted greater subsequent speech in social contact to those same partners. There were no group effects. That is, children with ASD did not significantly differ from TD children, $p = 0.217$, or children with DD, $p = 0.363$, in their rate of vocalizations to peers. For the sample as a whole, then, peer input was associated with vocalizations to peers. The interaction between peer input and group was not significant for the ASD-TD group contrast, $p = 0.291$, suggesting that the effect of peer input did not vary between the ASD and TD groups. However, there was a small, but significant interaction between peer input and group for the ASD-DD group contrast, $p = 0.042$, $d = -0.11$, such that children with ASD showed a stronger effect of peer input than their DD peers.

Associations between group and social network properties

Social network analyses assessed differences in group cohesiveness (modularity) and children's individual

[2]An exploratory analysis indicated that children's vocalizations to peers did not vary by child age, $X^2(1) = 0.67$, $p = 0.473$, and age was not included in subsequent models.

centrality in class networks (degree centrality). The unit of analysis in these networks is the individual. The variables of interest are derived from the sum of each child's ties to their peers (rate of vocalizations to and from those peers) during social contact. Each classroom network (averaged over observations and pruned for visualization purposes to only show edges greater than the mean edge weight) is depicted in Figure 2. Analyses included all edge weights (see Figure S1, for visualizations of unpruned networks).

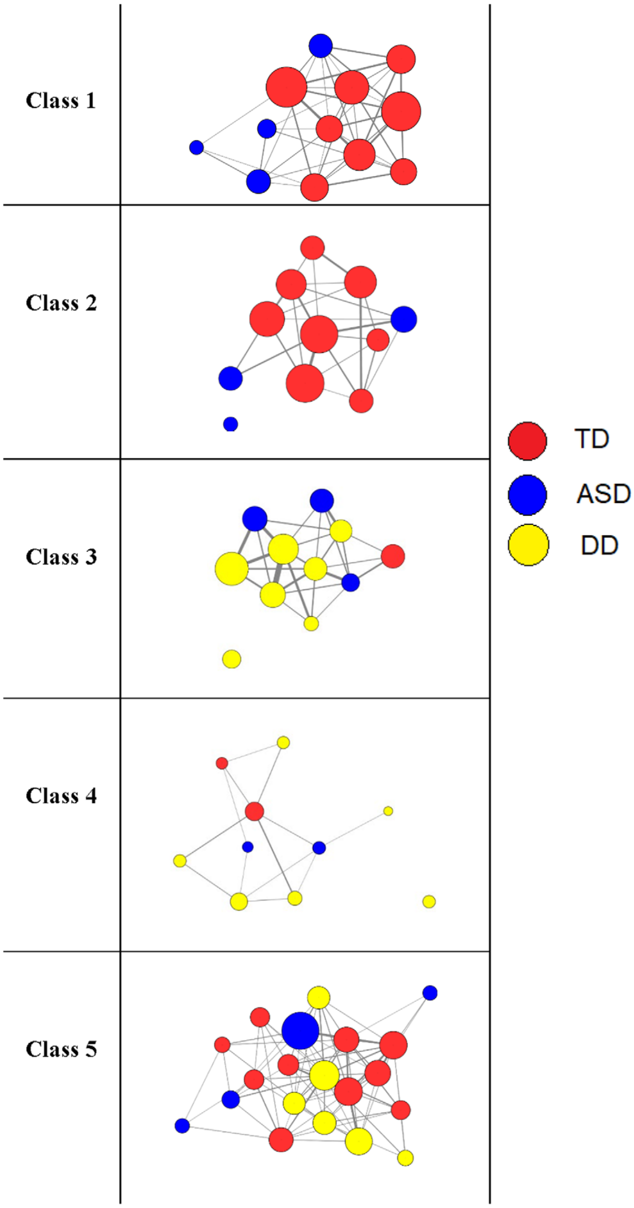

FIGURE 2 Tie width indexes the vocalization rate between two children in social contact. For visualization purposes, the network was pruned such that only ties of greater than mean weight (both per observation and overall) are displayed. Node (circle) size is proportional to total vocalization rate (input and output) in social contact with all peers. Children typically vocalized in social contact with all their peers during observations, and all ties were included in analyses

Group differences in network modularity

We investigated ASD within group modularity and the modularity between the ASD group and other groups (Figure 3). Mixed effects regression models in which observations were nested within groups with a random intercept of class indicated that the ASD group was less modular than both the TD, $p = 0.002$, $d = 0.82$, and DD groups, $p = 0.008$, $d = 0.69$, with large and medium effect sizes respectively. ASD within group modularity did not differ from between group modularity, $p = 0.743$ (Table 2). Overall speech in social contact was depressed for children with ASD both with respect to ties to other children with ASD and other children without ASD.

Group differences in network centrality and language abilities

Finally, we investigated whether children with ASD had lower classroom network centrality than other children, and whether children's classroom network centrality was associated with their end-of-year language abilities. We used mixed effects models with observations nested in children to compare group differences in children's degree centrality. Children with ASD ($M = 101.04$, $SD = 46.42$) had significantly lower degree centrality than TD children ($M = 147.75$, $SD = 62.54$), $p < 0.001$, $d = 1.04$, a large effect, but did not significantly differ from children with DD ($M = 106.69$, $SD = 50.35$), $p = 0.058$. There was also a small, but significant, effect

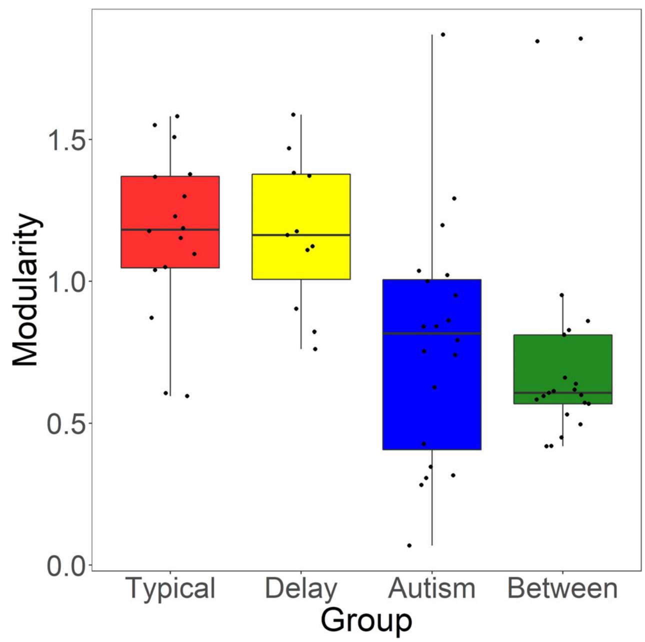

FIGURE 3 Average modularity over observations. Typical—TD; delay—DD; autism—ASD. Between—Modularity between the ASD and combined TD/DD groups

TABLE 2 Modularity of ASD-ASD connections compared to all other groups

	Fixed effects					
Parameters	***B***	***Se***	***t***	**95% CI**	***p***	***d***
ASD-ASD versus TD-TD	0.39	0.12	3.25	0.16, 0.63	0.002	0.82
ASD-ASD versus DD-DD	0.38	0.14	2.75	0.18, 0.65	0.008	0.69
ASD-ASD versus Between groups	−0.04	0.11	−0.33	−0.26, 0.18	0.743	−0.09

	Random effects		Chi-square test of model fit		
	Variance	**SD**	X^2	***df***	***p***
Class intercept	0.010	0.101	0.13	1	0.723

Note: ASD-ASD modularity was the intercept against the modularity values of the groups indicated in the first three rows were compared. Between groups refers to the modularity of ASD-TD and ASD-DD ties.
Abbreviations: ASD, autism spectrum disorder; DD, developmental delays; TD, typically developing.

of time, such that centrality was higher in later than earlier observation days, $p = 0.018$, $d = 0.34$.

Using separate multiple regression models, we predicted children's end-of-year language abilities (PLS-5 standard receptive and expressive scores) on the basis of child group and child degree centrality (Figure 4). These exploratory analyses were conducted only for the children in Classes 1–3, for whom we had end-of-year PLS-5 scores.[3] In separate regression models, children's degree centrality was positively associated with both receptive, $p = 0.006$, and expressive, $p = 0.025$, language abilities. Children with ASD ($M = 85.30$, $SD = 21.70$) had significantly lower receptive scores than TD children, a very large effect ($M = 120.22$, $SD = 14.40$; $p = 0.014$, $d = -2.14$), but did not differ from children with DD ($M = 97.57$, $SD = 16.32$; $p = 0.091$; Table 3). The same pattern was evident for expressive language scores, such that children with ASD had significantly lower receptive scores than TD children, $M_{\text{ASD}} = 82.30$, $SD_{\text{ASD}} = 18.82$, $M_{\text{TD}} = 120.78$, $SD_{\text{TD}} = 19.94$, $p = 0.007$, $d = -2.13$, a very large effect, but did not differ from children with DD, $M_{\text{DD}} = 91.86$, $SD_{\text{DD}} = 17.11$, $p = 0.148$.

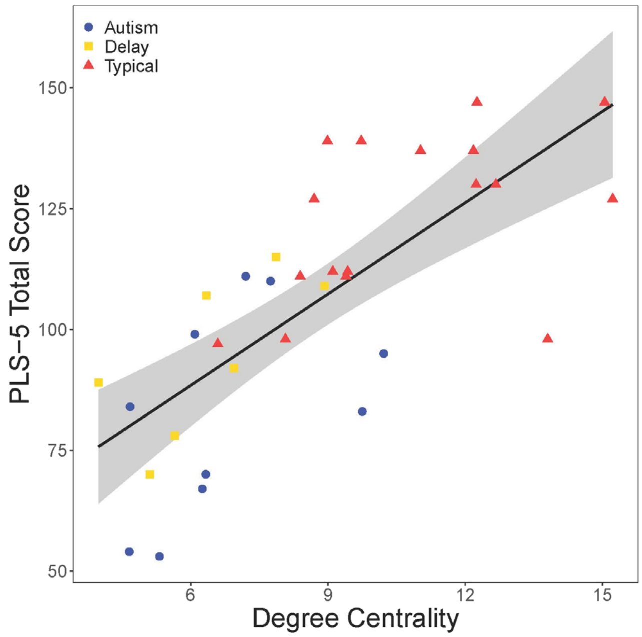

FIGURE 4 Degree centrality is expressed as the rate per hour of vocalizations to all peers and vocalizations from all peers in social contact. Language abilities are PLS-5 Total score, which integrates the auditory comprehension and expressive communication subscales. Typical—TD; delay—DD; autism—ASD. Findings include Classes 1–3, for whom assessment data were available

DISCUSSION

Preschool classrooms are a key context for communication with peers. Inclusion classrooms, in which children with ASD and other developmental disabilities are educated with TD children, are a national standard. Little, however, was previously known about children's real-time dyadic vocalizations with peers in these classrooms. Using automated measures of location and vocalization, we found that vocalizations from each of a child's peers during periods of social contact predicted their subsequent vocalizations to those peers, a pattern that did not vary by eligibility group. Modularity results indicated that children with ASD had less cohesive ties with each other and with other groups of children than TD children and children with DD. Further, children with ASD were less central to their classroom social networks than TD children, and this measure of centrality was associated with children's end-of-year assessed language abilities.

The importance of peer vocal interactions

By simultaneously tracking all children's interactions, we characterized both group and individual differences in children's peer vocal interactions. Partner speech input

[3]Data collection for Classes 4 and 5 was stopped in the middle of the 2020–2021 school year by the COVID-19 pandemic, which forced schools to close. We were not able to administer end-of-year language tests to these children.

TABLE 3 Peer speech and centrality (network degree centrality) predict PLS-5

Outcome variables and model parameters	Predictor	*B*	*Se*	*t*	*p*	*d*
Receptive language $F(3,25) = 13.35$, Adj. $R^2 = 0.57$, $p < 0.001$	Centrality	1.77	0.59	3.00	0.006	___
	ASD versus TD	25.18	9.28	2.71	0.014	−2.14
	ASD versus DD	14.66	8.17	1.79	0.091	−0.62
Expressive language $F(3,25) = 12.47$, Adj. $R^2 = 0.55$, $p < 0.001$	Centrality	1.48	0.62	2.39	0.025	___
	ASD versus TD	29.48	9.62	3.07	0.007	−2.13
	ASD versus DD	11.57	7.64	1.52	0.148	−0.53

Abbreviations: ASD, autism spectrum disorder; DD, developmental delays; TD, typically developing.

during periods of social contact predicted speech to those partners during social contact in the next monthly observation. This suggests a reciprocal process of peer vocal interactions across time. Higher (or lower) levels of Child A's speech to Child B were associated with higher (or lower) levels of subsequent speech of B to A. Thus, classroom speech was characterized by reciprocal patterns of dyadic speech, supporting the construct validity of this peer-to-peer vocalization variable. In predicting speech to peers, there was no main effect of group; however was there an interaction between partner input and the DD group, suggesting that children with ASD may benefit more from peer input than their peers with DD. Previous studies have characterized peers as contributing language resources that support children's language abilities (Chen et al., 2020). Here, we show that this provision of language resources occurs via vocal interactions during periods of social contact, which support the language abilities of children with disabilities in inclusion classrooms.

Modularity differences in cohesiveness within and between groups

This is the first study of classroom social networks based on objectively measured behavior observed over monthly observations. At an individual level, children with ASD had lower degree centrality than TD children, which accords with previous findings that children with disabilities tend to be isolated from peers and form smaller social groups (Chen et al., 2019, 2020). Thus, objective measures of peer vocal interaction in a sample of children with ASD appear to corroborate teacher reports of interaction proclivity. The current novel application of group modularity analyses contextualized these individual differences. Higher TD and DD than ASD within group modularity indicated lower levels of social interaction *between* children with ASD. However, there was no difference in within-group ASD modularity versus between modularity. Inclusive classrooms are intended to foster interaction between children with disabilities and their TD peers (Guralnick & Bruder, 2016). The current results suggest that, within these classrooms, the degree to which children from different eligibility groups interact may be relatively limited.

Two of the observed classes employed a Learning Experiences and Alternative Program curriculum designed to promote social interactions between children with ASD and their TD peers with a 1/2 ASD to TD ratio (Boyd et al., 2013); the third and fourth classes employed a Reverse Mainstream format with higher ratios of children with disabilities to TD children, and the fifth class employed a general inclusion format with a 1/1 ratio of TD children and children with disabilities. In all three formats, teachers purposefully pair children with disabilities with TD peers to promote interaction across groups. However, children also choose their own interaction partners during activities such as free-play. Future research comparing social network modularity across groups during more open-ended, child-led activities (e.g., outdoor play) versus structured, teacher-led activities (e.g., circle time) could yield insights into the role of intentional inclusivity practices in fostering play and interactions across groups.

The association of network centrality and language abilities

We examined degree centrality in networks formed by rates of peer-to-peer vocalizing during social contact. Degree centrality was positively associated with children's assessed receptive and expressive language abilities, even when accounting for eligibility group. Although this analysis included only a subset of the participants, the finding suggests that the use of vocalizations to coordinate dyadic interactions provides children with linguistic experiences that strengthen their receptive and expressive language skills. The finding is consistent with recent evidence on the importance of social interaction with TD children for children with ASD in inclusive settings (Watkins et al., 2015), and the importance of children's own language use for their language development (Ribot et al., 2018).

Children with ASD exhibited lower group modularity and individual degree centrality than TD children and children with DD. Children with ASD also had lower

PLS-5 indexed language abilities than TD children, but did not significantly differ from DD children on this measure. Null effects should be interpreted with caution as larger sample sizes might render observed differences significant. Nevertheless, this pattern of results is consonant with the possibility that ASD-specific difficulties are especially associated with decrements in the strength of children's vocalization-based interactions.

Limitations and future directions

The current study is not without limitations. The current longitudinal design extends previous research that utilized one to two classroom observations (e.g., Li & Griffin, 2013). However, the two- to five-month periods in which data were collected was not long enough to assess how speech in social contact, social networks, and children's language abilities changed over the course of the full school year, a topic for future research. Future research would benefit from the inclusion of an initial assessment of language abilities to help untangle potential bidirectional associations between children's language abilities and vocal interactions with peers. Additionally, our sample is limited by the small number of participating classrooms, and the class-group confound, as some TD children were in attendance in two class sessions, but their classmates with ASD were present in only one of those sessions. This created differences in the cumulative time children had to interact with each other. Nevertheless, reported group-level and individual-level effects emerged from analyses that account for class-level differences in outcome variables.

Although automated measures may reduce some sources of human error, objective measures are not immune to error. For example, LENA algorithms can confuse child speech and female adult speech vocalizations that were identified by human coders (Cristia et al., 2020). In the classroom context, however, human coders blind to LENA classifications exhibited high agreement with LENA as to whether vocalizations were uttered by a child or adult. Thus, synchronized LENA and Ubisense measures allowed for the quantification of the simultaneous vocal interactions of entire classrooms without relying on video recording and human coding.

CONCLUSIONS

Here we utilized longitudinal, objectively-measured behavioral data collected in inclusion classrooms to understand how patterns of dyadic speech among children with ASD and DD are associated with assessed language abilities. We found that children with ASD may be especially at risk for isolation. Their rates of vocal interaction were low both with other children with ASD and with children in other groups. Nevertheless, when children with ASD did engage in vocal interactions, there were benefits for both their vocalizations to peers and their assessed language abilities. The results suggest the importance of classroom social networks to the developing language abilities of children with and without ASD.

ACKNOWLEDGMENTS

This research was funded by a grant from the Institute for Educational Sciences #R324A180203 awarded to D.S.M. We thank the students, teachers, and administrators of the PRIDE and Tropical Preschools for their participation and assistance, and Aurora Adams and Stevie Custode for assistance with data collection. Portions of the data were collected for R.M.F.'s master's thesis.

CONFLICT OF INTEREST

The authors have no conflicts of interest.

AUTHOR CONTRIBUTIONS

Regina M. Fasano, Lynn K. Perry, and Daniel S. Messinger designed the study. Regina M. Fasano and Laura Vitale collected and coded the data. Regina M. Fasano, Laura Vitale, and Yi Zhang processed the data. Regina M. Fasano, Yi Zhang, Jue Wang, and Lynn K. Perry analyzed the data. Regina M. Fasano and Lynn K. Perry wrote the first draft of the manuscript. Regina M. Fasano, Lynn K. Perry, Yi Zhang, Chaoming Song, and Daniel S. Messinger edited the manuscript.

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How to cite this article: Fasano, R. M., Perry, L. K., Zhang, Y., Vitale, L., Wang, J., Song, C., & Messinger, D. S. (2021). A granular perspective on inclusion: Objectively measured interactions of preschoolers with and without autism. *Autism Research*, 1–12. https://doi.org/10.1002/aur.2526