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PAPER

Objectively measured teacher and preschooler vocalizations: Phonemic diversity is associated with language abilities

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Abstract

Over half of US children are enrolled in preschools, where the quantity and quality of language input from teachers are likely to affect children's language development. Leveraging repeated objective measurements, we examined the rate per minute and phonemic diversity of child and teacher speech-related vocalizations in preschool classrooms and their association with children's end-of-year receptive and expressive language abilities measured with the Preschool Language Scales (PLS-5). Phonemic diversity was computed as the number of unique consonants and vowels in a speech-related vocalization. We observed three successive cohorts of 2.5–3.5-year-old children enrolled in an oral language classroom that included children with and without hearing loss ($N = 29$, 16 girls, 14 Hispanic). Vocalization data were collected using child-worn audio recorders over 34 observations spanning three successive school years, yielding 21.53 mean hours of audio recording per child. The rate of teacher vocalizations positively predicted the rate of children's speech-related vocalizations while the phonemic diversity of teacher vocalizations positively predicted the phonemic diversity of children's speech-related vocalizations. The phonemic diversity of children's speech-related vocalizations was a stronger predictor of end-of-year language abilities than the rate of children's speech-related vocalizations. Mediation analyses indicated that the phonemic diversity of teacher vocalizations was associated with children's receptive and expressive language abilities to the extent that it influenced the phonemic diversity of children's own speech-related vocalizations. The results suggest that qualitatively richer language input expands the phonemic diversity of children's speech, which in turn is associated with language abilities.

KEYWORDS
language development, language quantity, objective measurement, phonemic diversity, preschool children, vocalizations

1 | INTRODUCTION

Individual variation in the quantity and quality of children's early language input and production predicts future language development and academic performance (Gilkerson et al., 2018; Hoff, 2013). The quantity and quality of children's language experiences are frequently studied during play with caregivers and laboratory-based tasks (Hirsh-Pasek et al., 2015; Woynaroski et al., 2017). Much less is known about the quantity and quality of children's language experiences in the preschool classroom where 54% of American children below age five

are enrolled (McFarland et al., 2018). In this study we employed objective measurement systems to characterize the quantity (rate) and quality (phonemic diversity) of children's language input and production in a preschool classroom including children with hearing loss and their typically hearing peers. This is a scientifically propitious setting because variation in the language abilities of children in these classrooms may be associated with variation in input from teachers, with cascading consequences for language development (DesJardin et al., 2014; Gilkerson & Richards, 2009).

RESEARCH HIGHLIGHTS

- We examined the rate and phonemic diversity of teachers' and children's speech-related vocalizations in children with and without hearing loss from child-specific audio recordings.
- The phonemic diversity of children's speech-related vocalizations uniquely predicted both receptive and expressive language abilities above and beyond the quantity of their vocalizations.
- Greater phonemic diversity of teacher vocalizations was associated with greater language abilities, insofar as it was associated with greater phonemic diversity of children's speech-related vocalizations.
- Objective measurements of children's vocal interactions with teachers have the potential to reveal patterns of classroom language experiences associated with children's language outcomes.

2 | QUANTITY AND QUALITY OF LANGUAGE AND THEIR ASSOCIATIONS WITH OUTCOMES

A robust body of work has highlighted the quantity of children's early language input and production as important predictors of future language proficiency, school readiness, and academic achievement (Hart & Risley, 1995; Rowe, 2012; Weisleder & Fernald, 2013). Language quantity is typically indexed by the number of speech-related vocalizations (e.g., words, utterances, conversational turns) per unit of time (e.g., words per minute, conversational turns per hour; Hirsh-Pasek et al., 2015; Weisleder & Fernald, 2013). Children who are exposed to larger quantities of adult speech in early childhood talk more themselves, have larger vocabularies and higher intelligence scores, and exhibit more efficient language processing capabilities (Gilkerson & Richards, 2009; Hart & Risley, 1995; Rowe, 2012; Weisleder & Fernald, 2013). Importantly, the quantity of vocalizations produced by children is associated with their expressive and receptive language abilities (Gilkerson & Richards, 2009).

The quality of young children's language input and production is another key indicator of children's future language capabilities (Hirsh-Pasek et al., 2015). Features of high quality language experiences, including diversity of input, conversational turn-taking, and parental responsiveness to children's vocalizations, are associated with more favorable language outcomes (Pan et al., 2005; Romeo et al., 2018; Rowe, 2012; Tamis-LeMonda et al., 2014). In the current investigation, we focused on a fine-grained measure of the developmental complexity of spoken language, phonemic diversity, to index language quality. Phonemic diversity is a measure of the number of unique consonant and vowel sounds in speech-related vocalizations (Moeller, et al., 2007; Woynaroski et al., 2017; Xu et al., 2014). Overall, variation in children's phonemic diversity is an index of their phonological development, the mastery of a language's sound system (Faes & Gillis, 2016; Gierut, 2007). Phonemes serve as the basic building blocks of language and children who produce more recognizable phonemes have more building blocks from which to produce words (Stoel-Gammon, 2011).

Individual differences in the phonemic diversity of children's speech-related vocalizations are associated with future language abilities, and distinguish children at risk for language delays from their typically developing peers (Wetherby et al., 2007; Woynaroski et al., 2017). More broadly, there appear to be bidirectional associations between the phonemic diversity of children's vocalizations and the diversity of their lexicons (Stoel-Gammon, 2011). Early observational and empirical studies indicated that children selectively, and more readily, learn words that contain phonemes they are able to produce (Ferguson & Farwell, 1975; Leonard et al., 1981; Schwartz & Leonard, 1982; Stoel-Gammon & Cooper, 1984). In contrast, recent work employing computational models highlight the role of higher-level lexical knowledge in guiding children's acquisition of phonetic categories by providing informative cues about sounds that occur together in words (Feldman et al., 2013; Swingley, 2019; Swingley & Alarcon, 2018). Preschool children's perception of the phonological make-up of words, which is supported by the phonemic diversity of their own speech, is a strong predictor of long-range literacy outcomes, including reading skill (Wagner et al., 1997).

3 | DIVERGENT LANGUAGE EXPERIENCES IN CHILDREN WITH HEARING LOSS

Hearing loss poses a sensory barrier to auditory input, which typically impairs the oral language development of affected children (Niparko et al., 2010; Walker & McGregor, 2013). Before hearing loss is identified, children's auditory sensory deficits make oral language perception challenging. When hearing loss is identified and hearing is aided, device limitations contribute to heterogeneity in children's aural access to speech. Hearing aids amplify the volume of children's residual hearing but can reduce access to high-frequency speech sounds (Stelmachowicz et al., 2001, 2002). Cochlear implants, which require surgical insertion, allow auditory input to be transmitted directly to the auditory nerve. Cochlear implant users typically have difficulty with frequency discrimination, particularly for sounds in the high frequency region, which can impact speech perception and comprehension (Macherey & Carlyon, 2014).

Research investigating the quantity of oral language input in children with hearing loss has produced mixed results. Some studies report decreased language directed toward children with hearing loss (Goldin-Meadow & Saltzman, 2000) and others report rates of input commensurate with typically hearing children (Fagan et al., 2014). It is also unclear whether children with hearing loss do (Fagan et al., 2014) or do not (Iyer & Oller, 2008; Moeller, et al., 2007) produce fewer speech-related vocalizations than their typically hearing peers. Mixed findings between studies may be due to heterogeneity between children in the severity of their hearing loss, leading to diverse spoken language outcomes.

With respect to oral language quality, children with hearing loss are exposed to and produce language that is less complex and diverse than typically hearing children (Fagan et al., 2014; Goldin-Meadow & Saltzman, 2000). Utterances directed toward children with hearing loss are shorter in mean length and contain more directives and prohibitions than those directed toward children with typical hearing, factors which are associated with lower receptive and expressive language skills (DesJardin & Eisenberg, 2007; Holt et al., 2012). The quality of hearing devices, noise, and distance can lead to inconsistent and distorted access to the structural details of language resulting in difficulties acquiring phonemes for children with hearing loss (McGuckian & Henry, 2007).

4 | CLASSROOM LANGUAGE EXPERIENCES

Despite the robust connection between children's everyday language experiences and their language abilities, relatively little is known about the quantity and quality of children's input and production outside of the home and laboratory contexts. Participation in oral language education programs that emphasize auditory comprehension and spoken language skills, has positive outcomes for children with hearing loss (Moog, 2002). However, no study to date has compared indices of the quantity and quality of moment-to-moment classroom language experiences in classrooms including children with hearing loss and their typically hearing peers. Understanding which features of classroom language input and production are most strongly associated with developing language abilities will help to shed light on the mechanisms that support language learning for both sets of children.

Recent advances in objective measurement technologies, such as those implemented using Language ENvironment Analysis (LENA) audio recorders and processing software, allow for the unobtrusive measurement of children's language input and production over multi-hour timescales (Gilkerson et al., 2008; Xu et al., 2009). LENA audio recorders have been employed in preschool classrooms to assess the relationship between the quantity of language input from teachers and peers and the quantity of children's language production (Dykstra et al., 2013; Perry et al., 2018). Increased input from peers as well as increased conversational turn-taking with teachers were associated with increased child talking as well as higher receptive and expressive language abilities and vocabulary gains (Dykstra et al., 2013; Perry et al., 2018). While previous LENA-based studies have relied on the number of conversational turns between teachers and children to measure language quality, the current study takes a more detailed approach. Here, we measured the phonemic diversity of individual classroom vocalizations and assessed its association with children's performance on measures of receptive and expressive language. In the home, parents are more likely to respond to more phonemically complex infant vocalizations (Gros-Louis et al., 2006) and increased parental responsiveness is related both to increases in infant's phonemic production in the moment (Goldstein & Schwade, 2008) and to language gains (Velleman et al., 1989). These findings suggest the importance of examining associations between caregiver and child phonemic complexity beyond infancy and within understudied developmental contexts, like preschool classrooms.

5 | CURRENT STUDY

The current investigation measured the quantity (rate) and quality (phonemic diversity) of children's classroom language experiences to determine the extent to which these features are associated with children's later language proficiencies. This investigation was conducted among three cohorts of children enrolled in an oral language inclusion classroom where children with hearing loss were educated alongside typically hearing peers.

We first asked whether the rate of children's language input predicted the rate of their own language production and whether the phonemic diversity of children's language input predicted the phonemic diversity of their language production. Rate was defined as the number of speech-related vocalizations produced per minute. We predicted that the rate of children's language input from teachers would predict the rate of their own speech-related vocalizations. We likewise predicted that the phonemic diversity of children's language input from teachers would predict the phonemic diversity of their own speech-related vocalizations.

Second, we investigated the relative importance of the rate and phonemic diversity of children's language input and production to their performance on a standardized measure of receptive and expressive language abilities. We hypothesized that the phonemic diversity of classroom speech-related vocalizations would account for more variation in children's end-of-year receptive and expressive language scores than the quantity of classroom language.

Finally, we asked whether either the rate or phonemic diversity of children's own speech-related vocalizations mediated the relationship between their linguistic input and end-of-year language abilities. Previous research has highlighted the relative importance of children's own production of language—as opposed to language input alone—in predicting language outcomes (Ribot et al., 2018). Consequently, we hypothesized that children's language production would mediate the relationship between children's language input and their end-of-year language abilities.

6 | METHOD

6.1 | Participants

Three cohorts of children were observed over three successive academic years in a single preschool classroom for children with and

without hearing loss ranging in age from 2.5 to 3.5 years (M_{age} = 2.95 years, *SD* = 0.33 years; 13 boys). The preschool implemented an English dominant oral language approach. Twenty-nine total children participated, including 21 children with hearing loss (seven per cohort) who wore cochlear implants (CIs) or hearing aids (HAs) and eight children with typical hearing (Table S1 for additional details). The average time between hearing device activation and study onset was 17.93 months (*SD* = 5.41 months) for children with CIs and 22.58 months (*SD* = 3.26 months) for children with HAs (Table S1). Of the 29 participants, 14 were Hispanic (13 White, one multiracial) and 15 were non-Hispanic (eight White, five Black or African American, two Asian). Thirteen children qualified to receive free or reduced-price lunch based on household income. The Institutional Review Board for Human Subject Research at the University of Miami approved this study. We obtained parental informed consent for each child's participation and each teacher provided informed consent for their own participation. All children and all teaching staff in each cohort (100%) participated in the study.

6.2 | Classroom characteristics

The three cohorts of children that participated in this study were enrolled over three successive years in a single oral language inclusion classroom within a university-based preschool. The classroom is part of an Auditory Oral Education Program which provides individualized early education, listening and spoken language intervention, audiological management, and technical support for children with hearing loss and their families. The Auditory Oral curriculum targets listening and spoken language development through daily activities such as circle time and free-play. Both Cohort 1 and Cohort 2 had one primary teacher and two teaching assistants, while Cohort 3 had one primary teacher and one teaching assistant. Overall levels of activities were roughly identical across children. However, children frequently engaged in activities in a small group guided by a single teacher, highlighting the degree to which children's language input might vary within the classroom. The current study aimed to understand the associations between naturally occurring classroom speech from children and teachers and children's language abilities in an inclusive classroom environment. The sample includes all children enrolled in the oral language inclusion classroom over three years, which included a higher number of children with hearing loss than typically hearing children.

6.3 | Objective measurement of classroom speech-related vocalizations

6.3.1 | Data collection

Children and teachers' vocalizations were recorded using individual LENA recorders. All children and teachers in attendance on recording days were recorded. Children wore a vest with a front pocket that held the LENA recorder. LENA recordings were collected approximately once every 2 weeks (*M* = 16.81, *SD* = 11.94 days between recordings) between October and May. Recording sessions were scheduled based on classroom and team availability (e.g., avoiding holidays) and occurred on different days of the week. There was a mean of 11.33 recording sessions per cohort (*SD* = 1.53). During recording sessions, between seven and 10 children and between one and three teachers were in attendance. The mean duration of recording sessions was 3.14 h (*SD* = 0.40). Children were recorded across both structured (i.e., circle time) and unstructured (i.e., free-play) activities. Children contributed an average of 21.53 (*SD* = 4.39) recording hours to analyses.

6.3.2 | Rate and phonemic diversity of speech-related vocalizations

Audio files were analyzed using LENA Pro V3.4.0 software. LENA Pro software distinguishes between children's own speech-related vocalizations and adult vocalizations within each audio recording and provides a total count of each vocalization type (Gilkerson et al., 2008; Xu et al., 2009). LENA software identifies speech-related vocalizations, from children and adults, as any phonemic production (e.g., from babbles to full word production). For children, phonemic production can include pre-linguistic sounds, such as cooing (resonant vowels), babbling (consonant vowel combinations), or protophones (squeals, growls, raspberries). The minimum duration of LENA-classified child speech-related vocalizations is 600 ms. The mean duration of child speech-related vocalizations in our sample was 941.68 ms (*SD* = 39.85). A child speech-related vocalization is terminated if interrupted by the vocalizations of another speaker or by silence or noise of longer than 800 ms. LENA identifies adult speech when a vocalization of greater than 1000 ms is spoken by either a male or female adult within an approximate 6 foot radius of the child (Irvin et al., 2013). LENA estimates of adult speech do not distinguish between adult speech directed toward the child wearing the recorder and adult speech directed toward other individuals that occurs in close proximity to the child wearing the recorder. We refer to these as teacher vocalizations. The mean duration of teacher vocalizations was 1535.30 ms (*SD* = 75.36). LENA also distinguishes children's own speech-related vocalizations and adult vocalizations from a separate category of overlapping speech—which was not included in analyses—in which the voice of one interlocutor is accompanied by another voice or another sound source. Speech-related vocalizations and their respective timestamps are reported in the LENA Interpreted Time Segments (ITS) file (Xu et al., 2008). Using the ITS file, we summed each child's own speech-related vocalizations and the teacher vocalizations recorded on that child's LENA recorder. For each recording session, the rate of child speech-related vocalizations per minute was calculated as the total number of child speech-related vocalizations divided by the length of the recording in minutes. The rate of teacher vocalizations per minute was calculated in the same fashion.

LENA-identified child and teacher vocalizations were further processed using Sphinx software to identify the individual consonants and vowels present within each vocalization. While LENA software

differentiated and quantified child and adult vocalizations, Sphinx provided an estimate of the phonemic richness of each of the LENA-identified vocalizations (Lamere et al., 2003). Sphinx estimates the number of 39 possible phonemic units from the North American English language (24 consonants and 15 vowels, Figure S1). A Python script was developed to read LENA ITS files and generate audio clips from the raw audio files based on the onsets and offsets of each speech-related vocalization. The Python script submitted the individual audio clips as input to Sphinx. Using Sphinx's estimates of the consonants and vowels present within each speech-related vocalization, we calculated the phonemic diversity or number of unique consonants and vowels present within each vocalization. The vocalizations "wait," "chocolate," and "baby" are illustrative. While each vocalization represents one LENA-identified speech-related vocalization, they differ in their phonemic diversity ('wait' = /weɪt/, phonemic diversity = 3; 'chocolate' = /tʃɔ.kə.lət/, phonemic diversity = 7; 'baby' = /beɪ.bi/, phonemic diversity = 3); note that the "b" phoneme in baby is repeated). In each recording session, we then calculated the mean phonemic diversity of child speech-related vocalizations and teacher vocalizations.

6.3.3 | Reliability

A recent meta-analysis indicated that LENA estimates of children's speech-related vocalizations exhibit medium size associations with children's language skills (Wang et al., 2020). However, LENA estimates exhibit lower concordance with human raters when recordings are less than 1 h long (Xu et al., 2009) and when female adults engage in infant-directed speech (Lehet et al., 2021). Therefore, we conducted stringent reliability coding to assess LENA's classification of child relative to adult speech in the classroom. Four trained coders blind to LENA designations re-coded 3,260 speech-related vocalizations. This reliability sample constituted 0.617% of the total sample of 528,290 recorded speech-related vocalizations. The audio clips of individual speech-related vocalizations generated by the Python script were used to assess reliability between human coders and the LENA and Sphinx processing algorithms. Speech-related vocalizations were sampled equally from each recording session for 12 children in the three cohorts (seven with hearing loss and five with typical hearing). The reliability sample consisted of 43.80% adult and 56.19% of child speech-related vocalizations. The trained coders listened to each speech-related vocalization clip and classified the speaker as either a child or adult. Comparisons between LENA and human coders on whether a vocalization was a child or adult speech-related vocalization indicated 89% agreement (Cohen's Kappa = .77). Separately, a trained coder blind to Sphinx results then assessed the phonemic diversity of 1,000 child and adult speech-related vocalizations. The coder recorded the number of unique phonemes present in each speech-related vocalization, which was compared to the number of unique phonemes estimated by Sphinx. The absolute, single-measure intra-class correlation, 0.87, indexed the overall accuracy of phonemic diversity estimates. The absolute intra-class correlation was 0.75 for the phonemic diversity of children's speech-related vocalizations and 0.81 for teachers' vocalizations.

6.4 | Assessment of children's language abilities

Children's language abilities were assessed at the end of the school year by a Speech Language Pathologist (SLP) using the Preschool Language Scales, Fifth Edition (PLS-5) (Zimmerman et al., 2011). The PLS-5 served as a developmentally meaningful, broad measure of receptive and expressive language. The PLS-5 is a standardized measure of language ability that assesses receptive and expressive language abilities in domains including, attention, play, gesture, vocal development, social communication, semantics (e.g., vocabulary, quantitative concepts, spatial concepts), language structure (e.g., morphology, syntax), integrative language skills, and emergent literacy. The PLS-5 consists of the Auditory Comprehension (AC) and Expressive Communication (EC) subscales, which assess receptive and expressive language abilities, respectively. There were no concerns regarding the speech and language development of the sample's typically hearing children (Table 1 for means by hearing status). Administration of the PLS-5 to the typically hearing students was added to the research protocol at the outset of the second year of data collection. As a result, three typically hearing children from the first cohort were not administered the PLS-5 and were not included in relevant analyses.

6.5 | Analytic approach

Analyses were conducted in R version 3.6.0 and RStudio version 1.1.442 (RStudio Team, 2016). We conducted separate linear mixed effects models to examine associations between exposure to teacher speech and children's production within recording sessions. Mixed effects models were run through the *lmer* function in the "lme4" package of R (Bates et al., 2014). In these models, recording sessions (level 1) were nested within children (level 2). Each model included a random intercept of subject (child). Time since the start of the school year (in days) was included as a predictor at level 1 to account for linear changes in language input and production. Child hearing status and cohort membership were included as child level predictors at level 2. As the Cohort parameter had three levels, significance was determined using the *lmertest* function in the "lme4" package of R, which employs Satterthwaite's degrees of freedom for model comparisons. For all other parameters we report the results of the chi-square tests of model fit comparing nested models with and without predictors of interest.

Hierarchical and linear regression models predicting children's end-of-year language abilities were conducted using language input and production variables that exhibited significant bivariate associations with receptive and expressive language abilities (assessed via the PLS-5). Unlike the mixed effects models where both the predictor and outcome variables were measured in each recording session, children's language abilities were measured at a single time point. Predicting a single PLS-5 score from multiple time-varying language input and production variables may inflate observed associations between variables. Consequently, in the hierarchical and linear regression models

TABLE 1 Correlations between and child and teacher language measures

			1	2	3	4	5	6	*Total M (SD)*	*Hearing loss M (SD)*	*Typical hearing M (SD)*
Child speech	1	Rate	1.00	0.66**	0.09	0.40*	0.51**	0.49*	**4.06** (1.16)	**3.80** (1.19)	**4.74** (0.81)
	2	Phonemic diversity		1.00	0.15	0.62**	0.59**	0.59**	**4.20** (0.47)	**4.03** (0.40)	**4.63** (0.38)
Teacher speech	3	Rate			1.00	0.57**	-0.12	-0.10	**6.10** (0.73)	**6.11** (0.72)	**6.06** (0.81)
	4	Phonemic diversity				1.00	0.17	0.20	**9.97** (0.55)	**9.93** (0.58)	**10.09** (0.46)
Child language abilities	5	Receptive					1.00	0.96**	**92.04** (27.95)	**85.24** (26.58)	**120.60** (9.32)
	6	Expressive						1.00	**92.27** (23.44)	**85.95** (21.06)	**118.80** (11.30)

Note. Each participant contributed one value for each measure of interest, which was an average across all recording sessions ($N = 29$). Phonemic diversity, for example, reflects the mean number of unique phonemes across all vocalizations for each vocalization type (child and teacher) over all recording sessions.

$^{*}p < 0.05$.

$^{**}p < 0.01$.

predicting children's end-of-year language abilities, the rate and phonemic diversity of children's language input and production were averaged across recording sessions and used as predictors. Hierarchical regressions were performed using SPSS Statistics for Macintosh version 26.0 (*IBM SPSS Statistics for Macintosh*, 2019). Linear regression models were conducted using the *lm* function of the "stats" package in R (R Core Team, 2019).

Next, we asked whether children's own speech-related vocalizations mediated the relationship between measures of teachers' vocalizations and their end-of-year language abilities. Mediation analyses were conducted when two criteria were met: (1) there was a significant direct effect of the independent variable (teacher input) on the mediator (children's language production), and (2) there was a significant direct effect of the mediator (children's language production) on the dependent variable (children's end-of-year language abilities; MacKinnon et al., 2002; Rucker et al., 2011). Mediation analyses were conducted using the *mediate* function in the "psych" package of R (Revelle, 2018).

7 | RESULTS

7.1 | Preliminary results

Bivariate correlations between variables aggregated over recording sessions are reported in Table 1. The rate and phonemic diversity of children's speech-related vocalizations were associated, as were the rate and phonemic diversity of teachers' vocalizations. Time (in days) from the beginning of the school year was associated with both the rate and phonemic diversity of classroom speech-related vocalizations. The rate of children's speech-related vocalizations increased over the course of the school year (Figure S2A and Table 2). Conversely, the rate of teachers' vocalizations decreased over the course of the school year (Figure S2B and Table S2). The phonemic diversity of children's speech-related vocalizations increased over the course of the school year (Figure S2C and Table 2) whereas the phonemic diversity of teachers' vocalizations decreased over the course of the school year (Figure S2D and Table S2).

There was a significant effect of cohort on the rate and phonemic diversity of teachers' vocalizations (Table S2). There was also a significant cohort effect on the phonemic diversity of children's speech-related vocalizations (Table 2). Consequently, analyses examining the associations between children's language input and language production controlled for changes in vocalizations over the course of the school year and cohort effects.

7.2 | Children's language input and vocal production

The higher the rate of teacher vocalizations to which children were exposed, the higher the rate of children's own speech-related vocalizations (Table 2). Likewise, children exposed to more phonemically diverse vocalizations from teachers produced more phonemically

TABLE 2 Associations between children's language input and their language production

		Fixed effects				Random effect		Chi-square test of model fit with and without effect of interest		
Model outcome	Model parameter	*B*	*SE*	*t*-value	*p*	Variance	SD	χ^2	df	*p*
Child rate	Teacher rate	0.15	0.05	2.98				9.59	1	0.002
	Hearing status	1.30	0.76	1.70				5.78	1	0.016
	Time since start of school	0.002	0.0008	2.24				5.40	1	0.020
	Cohort 1 versus Cohort 2	0.60	0.49	1.19	0.245			5.50	2	0.064
	Cohort 1 versus Cohort 3	-0.51	0.47	-1.08	0.291					
	Interaction between teacher rate and hearing status	-0.05	0.10	-0.45				0.19	1	0.665
	Subject intercept					1.01	1.00	165.74	1	<0.00001
Child phonemic diversity	Teacher phonemic diversity	0.18	0.04	4.26				17.58	1	<0.001
	Hearing status	1.51	0.77	1.96				29.55	1	<0.00001
	Time since start of school	0.0004	0.0002	1.99				4.05	1	0.044
	Cohort 1 versus Cohort 2	0.15	0.11	1.37	0.179			27.68	2	<0.00001
	Cohort 1 versus Cohort 3	-0.46	0.11	-4.22	<0.001					
	Interaction between teacher phonemic diversity and hearing status	-0.09	0.08	-1.19				1.45	1	0.229
	Subject intercept					0.04	0.20	81.73	1	<0.00001

Note. The table reports linear mixed effects models employing chi-square tests comparing nested models with and without the predictors of interest to determine significance. Cohort 1 served as the reference in cohort contrasts (e.g., the phonemic diversity of children's speech-related vocalizations was higher in Cohort 1 than in Cohort 3). Time since start of school was measured in days and served as a cohort-specific, time-varying predictor of child speech.

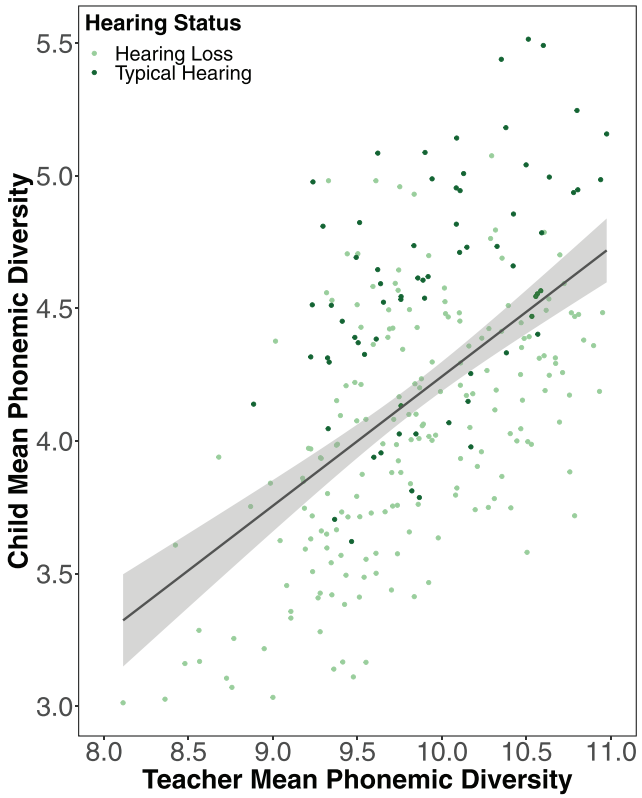

FIGURE 1 Each point represents one recording session for one child. For each recording session we calculated the mean number of unique phonemes (e.g., mean phonemic diversity) of children's and teachers' speech-related vocalizations. The mean phonemic diversity of children's speech-related vocalizations was then predicted from the mean phonemic diversity of teachers' vocalizations in a given recording session (Table 2). The mean phonemic diversity of teachers' speech was positively associated with the mean phonemic diversity of children's speech. That is children who were exposed to vocalizations containing a higher number of unique phonemes produced speech-related vocalizations with more unique phonemes

diverse speech-related vocalizations themselves (Table 2 and Figure 1). The rate and phonemic diversity of the teacher vocalizations that children were exposed to did not differ by children's hearing status (Table S2). However, children with hearing loss produced a lower rate of speech-related vocalizations and less phonemically diverse speech-related vocalizations than typically hearing children. There was no significant interaction between the rate of teachers' vocalizations and child hearing status in predicting the rate of children's speech-related vocalizations. Similarly, there was no significant interaction between the phonemic diversity of teachers' vocalizations and child hearing status in predicting the phonemic diversity of children's speech-related vocalizations.

The reported analyses parameterized hearing status categorically (hearing loss vs. typical hearing). Supplementary analyses parameterized hearing status continuously as age from cochlear implantation/hearing aid activation ("hearing age") and also included sex and free/reduced-price lunch eligibility status (as a proxy of socioeconomic status) as predictors. Those analyses yielded the same pattern of results—the rate and phonemic diversity of teacher vocalizations were associated with the rate and phonemic diversity of children's speech-related vocalizations—as those reported here (Table S3).

7.3 | Children's vocal production and language abilities

The rate and phonemic diversity of children's speech-related vocalizations were highly correlated ($r = 0.66$), and each measure was correlated with end-of-year receptive and expressive language abilities (Table 1).[1] To determine their relative importance, we conducted hierarchical regression analyses in which the rate and phonemic diversity of children's speech-related vocalizations were averaged across recording sessions and used as predictors of children's end-of-year language abilities. Hierarchical regression models indicate whether the addition of predictors of interest significantly improve model fit while controlling for other predictors. In predicting children's receptive language abilities, the addition of the rate of children's speech-related vocalizations as a predictor did not significantly improve model fit when controlling for the phonemic diversity of vocalizations (Table 3, Model 1A). By contrast, the entry of phonemic diversity significantly improved model fit while controlling for the rate of children's speech-related vocalizations (Table 3, Model 1B).

In predicting children's expressive language abilities, the addition of the rate of children's speech-related vocalizations as a predictor did not significantly improve model fit when controlling for the phonemic diversity of children's speech-related vocalizations (Table 3, Model 2A). The entry of phonemic diversity significantly improved the fit of the model when controlling for the rate of children's speech-related vocalizations. Taken together, phonemic diversity was a better predictor of children's language abilities above and beyond the effect of the rate per minute of children's speech-related vocalizations.

We next examined univariate associations between child hearing status and language abilities. Child hearing status significantly predicted children's receptive and expressive language abilities when hearing status was the sole predictor in these models. Children with hearing loss exhibited lower Auditory Comprehension ($M = 85.24$, $SD = 26.58$; $B = 35.36$, $SE = 12.22$, $t = 2.89$, $p = 0.008$) and Expressive Communication ($M = 85.95$, $SD = 21.06$; $B = 32.85$, $SE = 9.84$, $t = 3.34$, $p = 0.003$) standard scores than typically hearing children ($M_{AC} = 120.60$, $SD_{AC} = 9.32$; $M_{EC} = 118.80$, $SD_{EC} = 11.30$).

Given its unique role in predicting language abilities, we paired phonemic diversity with hearing status and cohort in final regression models (Table 4). Children who produced more phonemically diverse speech-related vocalizations exhibited higher receptive (Figure 2a) and expressive language abilities (Figure 2b) at the end of the school year. With the phonemic diversity of children's

[1] Since the rate and phonemic diversity variables were highly correlated, we assessed their collinearity using the variance inflation factor (VIF). The VIF between rate and phonemic diversity was 1.51 which falls below even the most conservative threshold for determining a problematic degree of collinearity (typically VIFs that exceed 5 or 10 are considered problematic; Chatterjee & Simonoff, 2012; James et al., 2013; O'brien, 2007).

TABLE 3 Changes in variance accounted for depending on the order in which quantity and quality of language use were added to models

	Model outcome	Step and predictor	R^2	ΔR^2	*df*	*p*
Model 1A	Receptive language ability	1. Child phonemic diversity	0.353	0.353	1, 24	0.001
		2. Child rate	0.395	0.042	1, 23	0.218
Model 1B	Receptive language ability	1. Child rate	0.263	0.263	1, 24	0.007
		2. Child phonemic diversity	0.395	0.132	1, 23	0.035
Model 2A	Expressive language ability	1. Child phonemic diversity	0.352	0.352	1, 24	0.001
		2. Child rate	0.383	0.031	1, 23	0.294
Model 2B	Expressive language ability	1. Child rate	0.239	0.239	1, 24	0.011
		2. Child phonemic diversity	0.383	0.144	1, 23	0.030

Note. Degrees of freedom and *p*-values correspond to the *F*-change test.

speech-related vocalizations included as a predictor, hearing status was no longer a significant predictor of children's end-of-year language abilities. This suggests that the phonemic diversity of children's speech was a better predictor of their language abilities than their hearing status. There was no significant interaction between child hearing status and the phonemic diversity of their speech on their language abilities. There was a significant effect of cohort on children's receptive language abilities. Supplementary analyses which included hearing age, child sex, free/reduced-price lunch eligibility status, and the phonemic diversity of children's speech-related vocalizations as predictors yielded the same associations between the phonemic diversity of children's speech-related vocalizations and PLS-5 scores reported here (Table S4).

7.4 | Mediating effect of the quality of children's vocalizations

The phonemic diversity of teachers' vocalizations was associated with the phonemic diversity of children's speech-related vocalizations, which, in turn, positively predicted children's end-of-year receptive and expressive language abilities. Consequently, we tested whether the phonemic diversity of children's speech-related vocalizations mediated the effect of teacher phonemic diversity on children's receptive and expressive language abilities (MacKinnon et al., 2002; Rucker et al., 2011). To meet the temporal precedence criterion for mediation, we calculated mean teacher phonemic diversity from the first half of the recording sessions—the first 5, 6, and 6 recording sessions, respectively, for the three successive cohorts—and mean child phonemic diversity from the second half of the recording sessions for each cohort—the last 5, 5, and 6 recording sessions, respectively (MacKinnon et al., 2013).

Mediation analyses indicated that the effect of the phonemic diversity of children's language input on receptive and expressive language abilities was explained by the phonemic diversity of children's own speech-related vocalizations (Figure 3). Specifically, exposure to teacher phonemic diversity was associated with children's language abilities to the extent that it influenced children's own phonemic diversity. As the rate of children's speech-related vocalizations was associated with the rate of teacher vocalizations, we conducted a parallel mediation analysis assessing the effect of the rate of vocalizations on children's PLS-5-indexed language abilities. The relationship between the rate of teacher vocalizations and children's end-of-year receptive ($B = 1.95$, $SE = 4.45$, 95% CI = [−6.66, 11.44]) and expressive ($B = 1.70$, $SE = 3.70$, 95% CI = [−5.40, 9.65]) language abilities was not mediated by the rate of children's speech-related vocalizations.

8 | DISCUSSION

The current study examined the relative contributions of the quantity (rate) and quality (phonemic diversity) of children's language experiences in the preschool classroom to their language abilities at the end of the school year. The phonemic diversity of children's

TABLE 4 Linear regression models of associations between children's phonemic diversity and language abilities

Model outcome	Model parameter	*B*	*SE*	*t*-value	*p*
Receptive language ability, adjusted $R^2 = 0.49$, $F(5, 20) = 5.72$, $p = 0.002$	Child phonemic diversity	74.47	19.42	3.83	0.001
	Hearing status	15.78	156.01	0.10	0.920
	Cohort 1 versus Cohort 2	6.07	10.59	0.57	0.573
	Cohort 1 versus Cohort 3	43.26	16.38	2.64	0.016
	Interaction between hearing status and child phonemic diversity	-5.40	34.83	-0.16	0.878
Expressive language ability, adjusted $R^2 = 0.43$, $F(5, 20) = 4.82$, $p = 0.005$	Child phonemic diversity	49.22	17.10	2.88	0.009
	Hearing status	-50.53	137.33	-0.37	0.717
	Cohort 1 versus Cohort 2	-0.65	9.31	-0.07	0.945
	Cohort 1 versus Cohort 3	23.78	14.42	1.65	0.115
	Interaction between hearing status and child phonemic diversity	12.58	30.66	0.41	0.686

Note. The table reports results from linear regression models. Receptive and expressive language abilities were indexed by standardized scores from the AC and EC subscales of the PLS-5. Cohort 1 served as the reference in cohort contrasts (e.g., the receptive language abilities of children in Cohort 1 were significantly lower than the receptive language abilities of children in Cohort 3).

speech-related vocalizations was a stronger predictor of children's end-of-year language abilities than the rate of their speech-related vocalizations. Moreover, children who were exposed to more phonemically diverse vocalizations from their teachers produced more diverse speech-related vocalizations themselves, which was in turn associated with higher end-of-year receptive and expressive language abilities.

8.1 | Vocalization quantity and quality and language abilities

In the current study, the quality of both teacher input and child production was operationalized as phonemic diversity, the number of unique phonemes in a speech-related vocalization. That is, the current results utilize a distinct measure of language quality related to the phonemic richness of individual vocalizations. Children and teachers who produced higher rates of speech-related vocalizations also exhibited increased phonemic diversity. When competing to explain children's end-of-year language abilities, the phonemic diversity of children's speech-related vocalizations was a stronger predictor of receptive and expressive language abilities than the rate of their speech-related vocalizations. It is possible that more phonemically diverse speech was reflected in children's use of a larger number of word types, longer word length, and/or more complex morphosyntactical structure (i.e., using more inflected morphemes). These processes, in turn, are associated with standardized assessments of children's receptive and expressive language abilities.

Evidence from parent-child interactions in the home indicates that measures of input quality at 2 years are robust predictors of child language outcomes when controlling for the quantity of parental speech (Hirsh-Pasek et al., 2015; Rowe et al., 2017). Indices of quality such as the fluency and connectedness of dyadic communication (Hirsh-Pasek et al., 2015), for example, and parental use of wh-questions (Rowe et al., 2017) account for more variance in language outcomes than the quantity of parental vocalizations. In parallel form, the current results suggest the importance of the quality of children's language experiences with respect to the phonemic diversity of both teacher input and children's own speech in predicting children's language abilities.

We found meaningful associations between children's exposure to teacher language input, children's subsequent language production, and their end-of-year language abilities. Children who received more phonemically diverse language input in the first half of the school year produced more phonemically diverse speech-related vocalizations during the second half of the school year, which was in turn associated with higher end-of-year receptive and expressive language abilities. The current study indicates that the diversity of children's language input was associated with children's language abilities to the extent that it increased the diversity of their own speech. The mediation effect highlights the importance of children's production of diverse speech (instantiated here as phonemes) in scaffolding their own developing language abilities.

Consistent with the current finding of mediation, research utilizing concurrently collected measures of children's language exposure and production have highlighted the unique contribution of children's language production to their developing language abilities. Using parent report, Ribot and colleagues (2018) found that when children's language production exceeded the input they received, they acquired expressive language skills at a faster rate than children showing the opposite pattern. Caregivers' responses to children's vocalizations facilitate children learning new vocalization patterns (Girolametto & Weitzman, 2002; Goldstein & Schwade, 2008). Talking, on the other hand, requires children to confront deficits in their own language knowledge in a way that listening alone does not. The process of verbalization requires children to address incompletely acquired linguistic forms in their own production and modify those productions to generate appropriate responses in the moment (Swain & Lapkin, 1995).

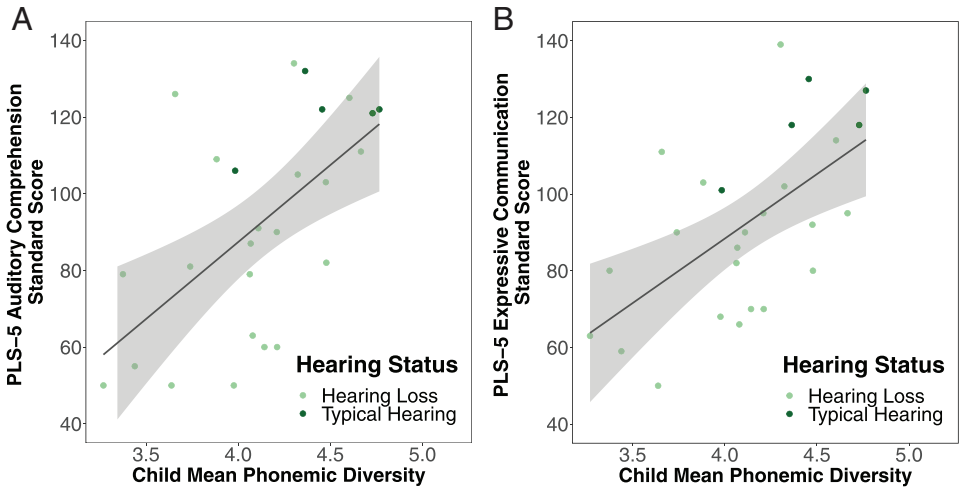

FIGURE 2 Each point represents the mean phonemic diversity of speech-related vocalizations across recording sessions for one child. The mean phonemic diversity of children's speech-related vocalizations positively predicted their end-of-year language abilities. Children who produced speech-related vocalizations with a higher number of unique phonemes scored higher on the **(A)** Auditory Comprehension and **(B)** Expressive Communication subscales of the PLS-5

Additionally, children's own talking allows them to practice the physiological aspects of speech (e.g., lingual articulation, somatosensory, and auditory feedback) that support spoken language development. Increasingly complex language builds on its earlier forms in that uses shared articulators (e.g., tongue, lips) and requires similar motor movements (Iverson, 2010; Stoel-Gammon, 2011). As such, children's practice with vocalizing allows them to build the physiological foundations needed to support expressive language development. Such processes may explain why the phonemic diversity of children's vocalizations mediated the relationship between the phonemic diversity of teachers' vocalizations and children's receptive and expressive language abilities. While the phonemic diversity of teachers' vocalizations served to increase the phonemic diversity of children's speech-related vocalizations, it was children's production of phonemically diverse speech-related vocalizations that was ultimately associated with higher overall language abilities.

Previous research indicates a robust association between the lexical diversity of children's speech and their language development (Malvern et al., 2004). In the current investigation, we examined the association between the phonemic diversity of children's speech and their language abilities. Children do not articulate isolated sounds; they communicate meanings, typically by speaking words. Consequently, there is a likely association between the phonemic diversity of children's speech and their lexical and morphosyntax development. In infancy and toddlerhood, lexicon size and phonetic inventories are commensurate such that precocious talkers are advanced in both domains whereas late talkers exhibit delays in both domains (Rescorla & Ratner, 1996; Smith & McGregor, 2002). Later in development, vocabulary knowledge and phonological abilities show a positive association such that school-age children—both those with and without hearing loss—who have higher levels of vocabulary knowledge also demonstrate enhanced phonological awareness skills (Dillon et al., 2012; Lund et al., 2015). Of particular import for children with hearing loss, who exhibit delays in developing sensitivity to phonological structure, is whether the acquisition of higher-level language constructs, including vocabulary and morphosyntax, can proceed independently of phonological development (Ingvalson et al., 2020). The current results suggest that the phonemic diversity of children's speech-related vocalizations can serve to index children's broader language abilities and that increasing the phonemic diversity of children's speech-related vocalizations can lead to higher receptive and expressive language abilities. However, future work is needed to examine the complex associations between the phonemic and lexical diversity of classroom speech in children with hearing loss and their typically hearing peers to understand the individual contributions of phonemic and lexical diversity to children's language abilities.

8.2 | Hearing status, phoneme production, and language abilities

Previous research has noted strong associations between children's *average* number of phonemes per vocalization (tokens) and their future spoken vocabulary (Woynaroski et al., 2017). We measured associations between the average number of *unique* phonemes (types) contained in children's language input and production and their end-of-year language abilities. Consistent with previous work, we found strong associations between the number of unique phonemes children produced and children's language abilities suggesting that the richness of children's phonemic production may serve as an index of their overall language ability. Individual differences in children's phonemic repertoires, the number of unique phonemes they have acquired overall, are potent predictors of literacy skills (Ingvalson et al., 2020; Wagner et al., 1997). Children with hearing loss exhibit smaller (Blamey et al., 2001; Moeller, et al., 2007; Serry & Blamey, 1999; Stoel-Gammon, 1988) and more variable (Yoshinaga-Itano et al., 2000) phonemic

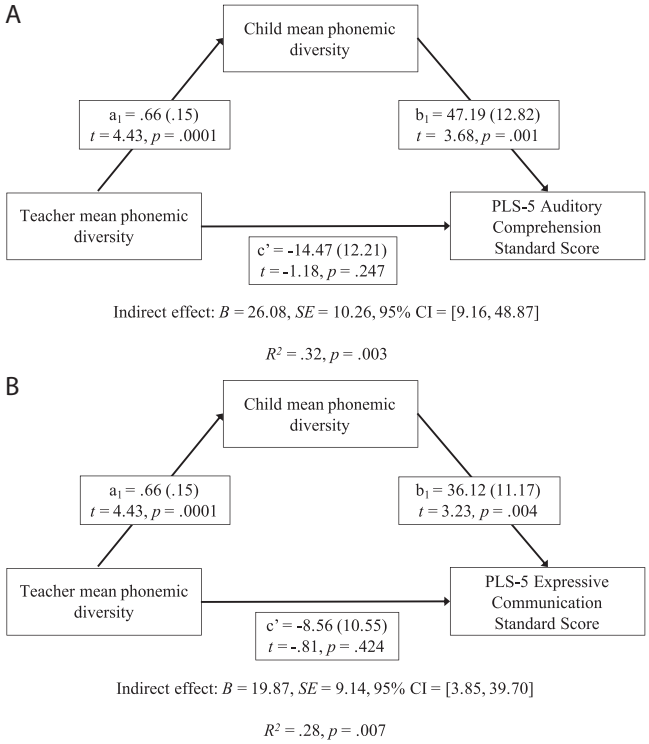

FIGURE 3 Modeling the mediating role of the mean phonemic diversity of children's speech-related vocalizations in the association between the mean phonemic diversity of teachers' vocalizations and children's (**A**) Auditory Comprehension and (**B**) Expressive Communication scores. The significance of indirect effects was determined by confidence intervals as bootstrapping does not yield *t* and *p* values

inventories than their typically hearing peers. Likewise, in the current study, children with hearing loss produced speech-related vocalizations that exhibited significantly less phonemic diversity than the speech-related vocalizations of their typically hearing peers. In addition to producing less phonemically diverse speech, children with hearing loss also produced fewer speech-related vocalizations per minute than their typically hearing peers, which is consistent with previous work documenting reduced verbal productions in children with hearing loss (Fagan et al., 2014; Moeller, et al., 2007). Taken together, the current results suggest delays in multiple aspects of expressive language development for children with hearing loss, and indicate that previously reported deficits in phonemic diversity are detectable in the vocalization-to-vocalization language production of children with hearing loss in the preschool classroom.

Although previous investigations indicate that children with hearing loss may receive caregiver input that is less complex and less diverse than children with typical hearing, we found no evidence of impoverished input for children with hearing loss in the classroom context (Fagan et al., 2014; Goldin-Meadow & Saltzman, 2000). There was an overall association between the phonemic diversity of children's language input and the phonemic diversity of their vocal productions, but no suggestion that the magnitude of the association differed by child hearing status. Likewise, treating hearing status as a continuous variable yielded no evidence of an interaction between hearing age and the phonemic diversity of vocal input in predicting the phonemic diversity of children's productions (Table S3). It is important to note that while LENA software estimates the amount of adult input children had the opportunity to listen to, it cannot determine whether that input was directed toward a given child. It is possible that the structure of preschool classrooms—a smaller number of teachers relative to the number of children—limited the variation in teacher input directed to individual children or limited our ability to detect those differences. It is also possible that in the Auditory Oral Education Program studied, which specifically targets listening and spoken language development, teachers provide similar language input to children with and without hearing loss. Finally, the small number of typically hearing children in this multiple cohort study ($N = 8$) indicates that these analyses which do not yield an effect of child hearing status on their language input should be interpreted cautiously.

Putting aside measures of classroom language production, children with hearing loss exhibited lower levels of receptive and expressive language abilities than typically hearing children. Importantly, including the phonemic diversity of children's speech-related vocalizations with child hearing status as predictors of children's receptive and expressive language abilities washed out the univariate effect of hearing status on PLS-5 scores. This suggests that the phonemic diversity of children's speech-related vocalizations is a stronger predictor of children's language abilities than hearing status. Together, these results suggest a potential avenue for improving the oral language outcomes of children with hearing loss via enriching language experiences in the preschool classroom. By providing children with hearing loss additional opportunities for exposure to phonemically diverse language input and opportunities to produce phonemically diverse speech, preschool teachers may play a role in supporting children's development of phonological skills. However, additional research is needed to determine whether mechanisms for supporting phonological development and ultimately higher-level language abilities is the same for children with hearing loss relative to typically hearing children. It is also important to note that the current findings may not generalize to classroom language experiences occurring outside of Auditory Oral Language Education Programs and that future work is needed to understand the role of the phonemic diversity of classroom language in improving children's language abilities in other types of educational programs.

8.3 | Limitations and future directions

The current study utilized dense behavioral data collected over 624 h of observation over the school year in three successive classroom-based cohorts of children. Although the sample size was modest ($N = 29$), each child contributed a mean of 21.53 ($SD = 4.39$) h of vocalization data to the analyses. This is commensurate with other computational and empirical studies utilizing small samples with high density data to understand children's everyday experiences (Chen et al., 2020; DeBolt et al., 2020; Perry et al., 2018). Nevertheless,

additional research is necessary to understand the degree to which phonemic diversity is a path to and index of language ability. This research would benefit from comparing multiple indices of language quality (e.g., phonemic diversity, lexical diversity, conversational turn-taking) in the prediction of children's language outcomes. Additionally, both the home and the preschool classroom are salient developmental contexts. Future investigations might examine both the quality of home language and classroom language to understand their relative contributions to children's language outcomes. Finally, future work would benefit from including a larger number of classroom cohorts in order to better assess the independence of data points through the inclusion of cohort as a random effect in multilevel models.

The current study's estimates of children's and teachers' speech-related vocalizations were derived from automated measurement technologies that are not without error. A recent report indicated that LENA algorithms can confuse children's speech-related vocalizations with the vocalizations of female adults, likely due to adults' use of infant-directed speech in the home (Lehet et al., 2021). However, the current study's reliability analyses indicated high levels of agreement between automated estimates and human raters. Another report indicated that LENA underestimates the speech-related vocalizations of the target child (the child wearing the audio recorder) by attributing a portion of target child vocalizations to other children (Cristia et al., 2021). To the extent that children's own speech-related vocalizations were mistakenly attributed to other children in the current investigation, associations between the phonemic diversity of children's own speech-related vocalizations and their language abilities may have been underestimated.

Phonemic diversity, the current measure of language quality, relied on speech recognition algorithms trained on adult speech. Nevertheless, strong associations between the phonemic diversity of children's speech and their end-of-year receptive and expressive language abilities replicate previous work in which Sphinx estimates of phoneme production were statistically indistinguishable from manually coded speech samples in predicting children's expressive vocabulary (Woynaroski et al., 2017). Associations between phonemic diversity (both automated and manual indices) and language outcomes highlight the potential of applying objective measures of language production to large speech samples, such as multi-day recordings of children in a classroom, where manual coding is not feasible.

As the PLS-5 measure of language ability was only administered at the end of the school year, we were unable to examine the effect of children's initial language ability on subsequent classroom language experiences. Prior research suggests a reciprocal interplay in which children with more advanced language abilities are exposed to more frequent and higher quality adult input, engage in more back and forth exchanges with conversational partners, and talk more (DesJardin et al., 2014; Gilkerson & Richards, 2009). Future work would benefit from using both beginning- and end-of-year language assessments to determine how children's initial language abilities influence their linguistic input and production. Additionally, future work would benefit from including a standardized assessment of children's speech production accuracy to understand how objective measurements of children's phoneme production in the classroom are associated with articulation accuracy.

9 | CONCLUSIONS

The current investigation utilized an unobtrusive automated measurement system to capture children's *moment-to-moment* language experiences. Results highlighted a specific feature of the classroom language environment, phonemic diversity, as a promising correlate of children's developing language capacities. The phonemic diversity of teachers' speech to children predicted the phonemic diversity of children's own speech. The phonemic diversity of children's own speech, in turn, predicted children's end-of-year receptive and expressive language abilities. These results highlight both the importance of phonemically diverse adult speech and the role of children's own production of phonemically diverse speech in children's language development.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on the Open Science Framework (https://osf.io/e3ujr/).

AUTHOR CONTRIBUTIONS

D.S.M. and L.K.P. designed the study. D.S.M., L.K.P., B.E.E., and N.F.J. obtained funding. S.G.M. collected the data. S.G.M. and Y.T. processed the data. S.G.M. analyzed the data. S.G.M. and D.S.M. wrote the manuscript. All authors edited the manuscript.

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