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Reciprocal patterns of peer speech in preschoolers with and without hearing loss

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ABSTRACT

Children with hearing loss often attend inclusive preschool classrooms aimed at improving their spoken language skills. Although preschool classrooms are fertile environments for vocal interaction with peers, little is known about the dyadic processes that influence children's speech to one another and foster their language abilities and how these processes may vary in children with hearing loss. We used new objective measurement approaches to identify and quantify children's vocalizations during social contact, as determined by children's proximity and mutual orientation. The contributions of peer vocalizations to children's future vocalizations and language abilities were examined in oral language inclusion classrooms containing children with hearing loss who use hearing aids or cochlear implants and their typically hearing peers. Across over 600 hours of recorded vocal interactions of 29 2.5–3.5 year olds (16 girls) in 3 cohorts of children in a classroom, we found that vocalizations from each peer on a given observation predicted a child's vocalizations to that same peer on the subsequent observation. Children who produced more vocalizations to their peers had higher receptive and expressive language abilities, as measured by a standardized end-of-year language assessment. In fact, vocalizations *from* peers had an indirect association with end-of-year language abilities as mediated by children's vocalizations *to* peers. These findings did not vary as a function of hearing status. Overall, then, the results demonstrate the importance of dyadic peer vocal interactions for children's language use and abilities.

Introduction

Children's preschool experiences can have long-lasting developmental impacts (Heckman & Raut, 2016; Schweinhart & Weikart, 1997). Children attending preschools that provide exposure to high quality language exhibit long-term gains in language development (Justice, Mashburn, Hamre, & Pianta, 2008) and later literacy abilities (Dickinson, 2011). Children with hearing loss (HL), who tend to have delays in their language (Niparko et al., 2010) and literacy development (Ingvalson, Grieco-Calub, Perry, & VanDam, 2020), often attend early intervention preschools featuring curricula focused on improving their oral language skills (Rice & Lenihan, 2005; Scheetz, 2012). However, we know of no research investigating the contribution of *peer input* on language outcomes in these programs. Further, although previous work indicates that the average language ability of a child's classroom peers in the fall was associated with their own spring language abilities, an effect that is stronger for children with disabilities (Justice, Logan, Lin, & Kaderavek, 2014; and see Chen, Justice, Tambyraja, & Sawyer, 2020), little is known about the role vocal interactions with peers play in this process. These dyadic interactions may be central to the previously-documented associations between peer abilities and children's language gains (Henry & Rickman, 2007; Justice et al., 2011, 2014; Mashburn et al., 2009). Here we model the influence of vocalizations from individual peers on children's vocalizations to their peers in inclusion classrooms for children with and without hearing loss.

1. The unique contributions of peers in scaffolding language abilities

As play becomes increasingly social during the preschool years, peers begin to take on a particularly important role in children's development (Bulotsky-Shearer, Bell, Romero, & Carter, 2012; Rubin, Watson, & Jambor, 1978). Children's exposure to

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peer language is associated with improvement in their own language abilities (Henry & Rickman, 2007; Justice et al., 2011, 2014; Mashburn et al., 2009) independent of the quality of teacher language in their classroom (Yeomans-Maldonado, Justice, & Logan, 2019). Furthermore, studies have found that peer effects are especially strong for children with delays or disabilities in inclusion classrooms (Chen et al., 2020; Justice et al., 2014). In particular, children with disabilities who have relatively poor language abilities benefit more from being in a class with a higher average peer language ability than do their classmates with relatively strong language abilities (Justice et al., 2014). Together these findings suggest an important role for peers in supporting children's language development.

Indeed several broad theories of development posit a central role for peers in language development. According to Vygotsky's socio-cultural theory, learning occurs in a social context. When a child interacts with a partner who has skills just exceeding his or her own abilities, the partner can help scaffold the child's own abilities, allowing for developmental change (Vygotsky, 1978). According to Bandura's social learning theory, children learn through observation and imitation of their social partners (Bandura, 1971). On both accounts, interacting with peers, especially more linguistically advanced peers, is important for language development because it provides children with opportunities to practice and improve their language skills. Indeed modern accounts of language development demonstrate that children's own language production is a stronger predictor of children's subsequent language development than their language input (e.g., Ribot, Hoff, & Burridge, 2018), suggesting perhaps that peer input only influences language development inasmuch as it increases children's language production.

However, the majority of research in this area has not addressed the mechanisms by which peer effects occur, instead showing associations between the mean of a child's classmates' abilities and the child's own development. A notable exception is Chen and colleagues' (2020) recent work. These researchers weighted the assessed language abilities of each of a child's peers using a teacher-reported index of how frequently the child played with that peer. The sum of these weightings for a child's peers formed an estimate of each individual child's "peer language resources." Children's peer language resources were positively associated with changes in their assessed language abilities (Chen et al., 2020). These findings indicate individual differences in children's levels of interaction with each of their classroom peers, and suggest those differences are meaningfully related to language abilities. However, as Chen et al. note, the results are limited in that that they rely on teacher reports of dyads' general levels of interaction over a period of several months. Consequently, it is unclear whether children's vocal interactions with peers affect their own vocalizations to peers, and whether these processes are associated with assessed language abilities. Additionally, peer vocal interaction may vary from day to day and from activity to activity, with less structured activities such as free-play allowing for more freedom amongst children to choose their social partners. We next describe how new measurement techniques can yield more precise insight into children's peer interactions.

1.1. Individual differences in children's language experiences

Preschool classrooms are dynamic settings, full of simultaneous language experiences that differ across individual children (Chaparro-Moreno, Justice, Logan, Purtell, & Lin, 2019). Historically, researchers have manually transcribed samples of vocalizations, but this approach cannot capture simultaneous classroom interactions. Advances such as the technologies incorporated in the Language ENvironment Analysis (LENA) system allow for efficient collection and automated analysis of audio from child-worn recorders. Investigators using LENA technology have been predominantly concerned with input from adults, especially from parents (Weisleder & Fernald, 2013). for example, Romeo et al., (2018) found that the number of LENA-estimated conversational turns children engage in with adults are associated with language abilities and language-related neural activity.

There has been little research utilizing LENA to investigate children's language experiences in classrooms, and almost nothing is known about children's classroom language interactions with peers. Typically, researchers who have deployed LENA in preschools have reported short-term observations encompassing 2 to 3 recording days and have focused only on teacher language input (Irvin, Hume, Boyd, McBee, & Odom, 2013; Soderstrom & Wittebolle, 2013). Those studies that do focus on peer interaction, including classroom network research, often do not have full participation of all children in a classroom limiting conclusions. In the single longitudinal LENA classroom study of which we are aware, researchers found that the number of vocalizations children heard from other children was associated with the quantity of their own vocalizations on a given day as well as their language development over a year (Perry et al., 2018). However, Perry et al. were constrained by LENA technology, which efficiently captures global estimates of peer vocalizations but cannot identify which peer is talking. Thus, it is unclear whether positive associations between global estimates of a child's peer vocal input and their language development, are driven by exposure to peer language in general, or whether they reflect a reciprocal process of interaction with individual peers. We turn next to research examining children's interactions with specific classroom peers as these dyadic interactions may facilitate children's classroom language learning.

*Who is Talking to Whom***?** Typically, classroom social interactions are identified by trained observers' manual coding of children's proximity and joint activity (Santos, Daniel, Fernandes, & Vaughn, 2015). However, an observer can only code one child at a time, while classrooms are rife with simultaneous interactions. This limitation may be superseded by new technology such as Ubisense tracking that uses Radio Frequency Identification (RFID) to provide objective measurement of a child's position in the classroom Irvin et al. (2018). validated the use of RFID in the classroom by comparing Ubisense position estimates of 2 children to the locations of classroom activity stations. Using Ubisense, Messinger et al. (2019) applied a data-driven index of physical proximity that indicates distances when children are in social contact at greater than chance levels. In the current project, we *combine* objective measurements of vocalizations from LENA with RFID movement and orientation data to determine when children are being spoken to by individual peers, and when they are speaking to those peers. Thus, the marriage of these technologies quantifies children's language-mediated social interactions with individual peers.

2. Conceptual framework

We propose a conceptual framework, depicted in Fig. 1, in which there is a reciprocal pattern of peer vocalization such that higher levels of Child A's speech to B are associated with higher levels of subsequent speech of B to A. On this account, hearing loss may decrease the number of vocalizations children produce and receive from peers (row A), but it will not affect the overall influence of peer input on subsequent output (row B). In this way, peer vocal input serves to increase a child's vocal output for both children with and without hearing loss. We then test whether peer vocalizations and children's own vocalizations are associated with end-of-year language abilities. We propose that children's vocalizations to peers will be associated with their assessed language abilities, and mediate an indirect association between peer input

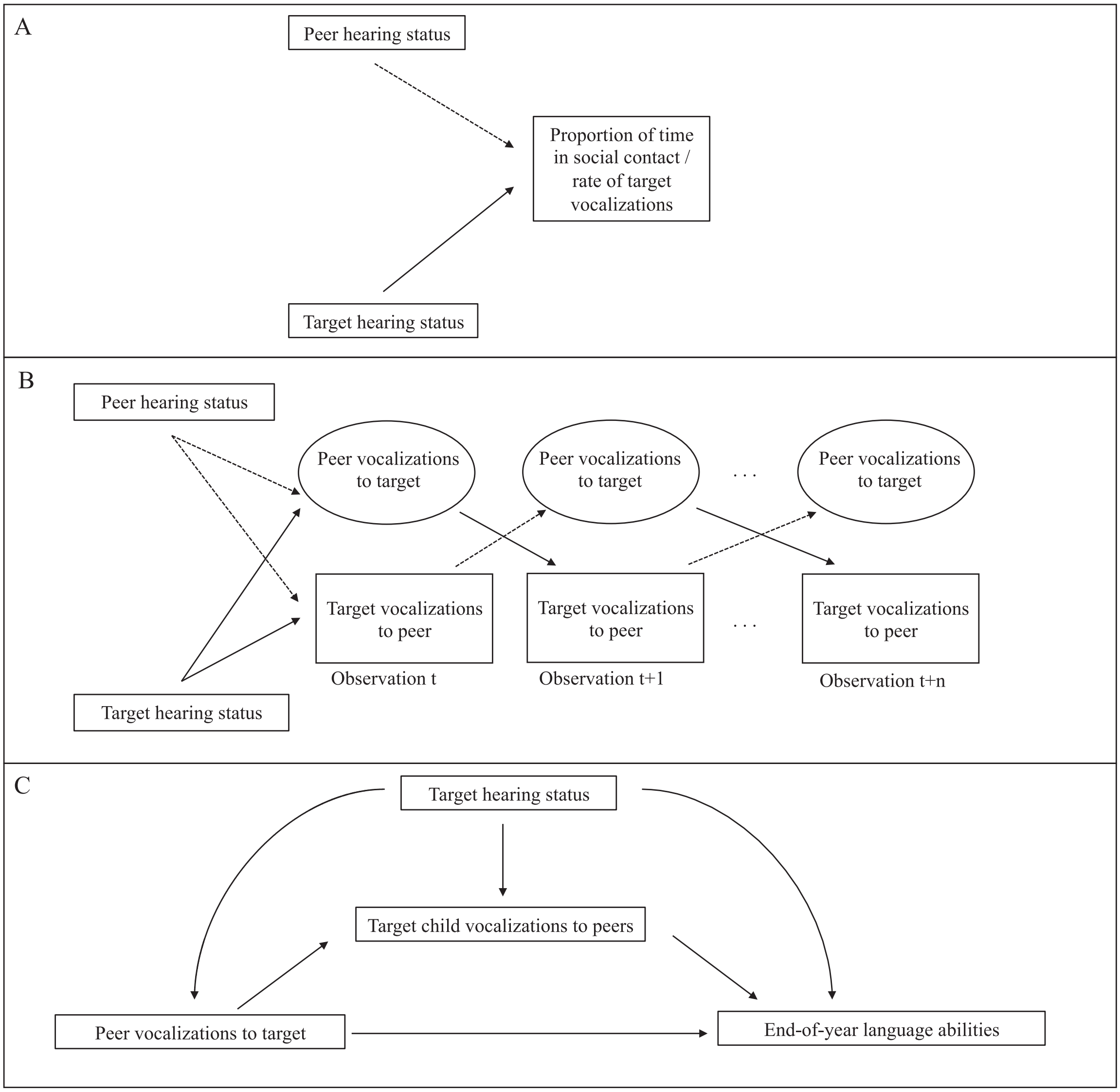

Fig. 1. Visual representation of the conceptual framework for exploring patterns of peer vocalization in children with and without hearing loss. (A) The top row depicts hypothesized influences of the target child and their peer's hearing status (hearing loss or typical hearing) on both the proportion of time they spend in social contact and the rate of vocalizations that the target child makes to the peer. (B) The middle row depicts hypothesized influences on the rate of vocalizations that the target child makes to the peer. Thus, the same associations are shown for peer vocalizations to highlight the reciprocal pattern of input and output over observations. (C) The bottom row depicts hypothesized influences of hearing status on assessed language abilities and the direct and indirect associations between peer vocalizations and language abilities, mediated through target output.

and language abilities (row C). Such a pattern would suggest that the mechanism by which peers affect language development is by providing children with opportunities to produce language. In the following sections we review relevant literature characterizing language development and peer interactions in children with hearing loss to motivate our conceptual framework and highlight how our innovative approach, combining automated measures of vocalization and location to measure children's peer interactions, can fill gaps in our current understanding of language development in children with hearing loss.

3. Hearing loss and language development

Children with hearing loss (HL) are heterogeneous with respect to their language development outcomes. Even with hearing aids or cochlear implants, many children with hearing loss exhibit delays in oral language development (Niparko et al., 2010; Stiles, McGregor, & Bentler, 2012; Walker & McGregor, 2013). These delays affect multiple aspects of their receptive and expressive development including speech perception and production (Blamey et al., 2001), vocabulary knowledge (Davidson, Geers, & Nicholas, 2014; Lund, 2016), morpho-syntax skills (Boons et al., 2013), narrative abilities (Crosson & Geers, 2001), and emerging literacy skills (Ingvalson et al., 2020).

Other researchers have targeted language-learning mechanisms by comparing the language of children with HL to both age- and language-matched children. Results indicate that children with HL generally perform similarly to younger, language-matched peers (Walker & McGregor, 2013). These results suggest delays rather than qualitative differences in children with HL. Additionally, despite older claims that children with HL might produce fewer pre-linguistic vocalizations than those with typical hearing (TH) (Fry, 1966), more contemporary studies quantifying vocalizations suggest this is not the case (Iyer & Oller, 2008), further highlighting similarities in the mechanisms of language learning. Furthermore, there is evidence that, similar to children with TH, children with

HL are receptive to enriched language environments such as exposure to high quality verbal input (Cruz et al., 2013). for example, children with HL receiving high levels of sensitive parent language input following cochlear implantation have faster rates of language development than their peers (Quittner et al., 2013). Overall, then, the evidence suggests that although children with HL have delays, high quality language input may facilitate their progress toward closing the gap in their language skills relative to those of TH children.

3.1. peer interactions and development in children with hearing loss

Children with HL can have difficulty in peer interactions, scoring lower in social competence and higher in behavior problems than children with TH (Hoffman, Quittner, & Cejas, 2015; Most et al., 2012). Additionally, children who are typically developing are more likely to play with peers who are also typically developing than they are peers with disabilities (Chen, Lin, Justice, & Sawyer, 2019), including those with HL (Antia, 1994). Children with HL are also tend to have lower group status and fewer friends than their TH peers (Wauters & Knoors, 2008). Notably, these differences in social competency in children with and without HL are driven by differences in children's language ability (Hoffman et al., 2015), suggesting a dynamic interplay between language and social development. However, although studies of school-age children reveal that peers positively influence the *social* development of children with HL (Lloyd et al., 2001; Martin et al., 2011), we know of no research investigating the influence of preschool peer interactions on language outcomes for children with HL.

Indeed, although research into the role of home language experiences on the language abilities of children with HL is increasing (Arora et al., 2020; VanDam, Ambrose, & Moeller, 2012), very little is known about children's language experiences with peers in preschools—a key intervention context for many children with HL. Children with HL often attend inclusive early intervention preschools featuring curricula focused on improving their oral language skills (Scheetz, 2012). Moreover, inclusive preschool classrooms give children opportunities to interact with peers with different language abilities, some of whom may have different language backgrounds (e.g., monolingual vs bilingual learners). for example, although studies comparing the assessed language abilities of monolingual and bilingual learners with HL do not consistently indicate differences (Bunta et al., 2016; de Diego-Lázaro, Andrea, & Adelaida, 2021; Robbins, Green, & Waltzman, 2004; Thomas, El-Kashlan, & Zwolan, 2008), it remains unclear whether factors like language background play a role in these children's peer interactions in diverse inclusive classrooms. Thus, inclusive classrooms are an ideal context to examine the role of children's dyadic vocal interactions with peers on their own vocalizations and assessed language abilities.

4. Aims of the current study

Here we investigate reciprocal patterns of peer vocalizations in inclusion classrooms for children with HL and children with TH testing the following research questions:

4.1. Research question 1: do social contact and vocalizations vary across peers and activities?

In our first question, using objective measures we explore whether children's hearing status or the hearing status of their peers are associated with differences in their time in social contact (the amount time spent in proximity with peers while facing them) and their peer vocalizations during social contact, and whether these effects vary by class activity. We hypothesize that children with HL will spend less time in social contact and produce fewer vocalizations than children with TH.

4.2. Research question 2: do peer vocalizations predict subsequent target child vocalizations?

In our second question, we test the hypothesis that when children are exposed to more vocalizations from individual peers during a given classroom observation, they vocalize more to those same peers during the following observation. Such a pattern, repeated over multiple observations, would reflect a reciprocal longitudinal process of language exchange within dyads. In this analysis we also explore whether, consistent with previous studies examining effects of peer language abilities (Chen et al., 2020; Justice et al., 2014), the effects of peer vocalizations vary with the child's and peer's hearing status.

4.3. Research question 3: are vocalizations to and from peers associated with language ability?

In our third question, we test hypotheses concerning the association between vocalizations from peers and assessed end-of-year language abilities. We first examine the direct associations between vocalizations from peers and vocalizations to peers on assessed language abilities. Here we also explore whether the effects of peer vocalizations vary with the child's hearing status. We then conduct a longitudinal mediation analysis to assess the direction of these associations. One possibility is that vocalizations from peers will be directly associated with assessed language abilities. Alternatively, vocalizations from peers could be associated with vocalizations *to* peers, which in turn will be associated with assessed language abilities. Either finding would suggest an association between objective measures of dyadic vocal interactions and standard assessments of children's language abilities.

5. Methods

5.1. Participants

We observed 29 2.5-3.5-year-olds (M = 36 months, SD = 4 months, at participation onset) in 3 successive cohorts of an oral language inclusion classroom. See Table 1 for overall and cohort level participant characteristics, and Tables S1 and S2 for each participant's characteristics. Of the 29 children, 14 were Hispanic (13 White, 1 multiracial) and 15 were non-Hispanic (8 White, 5 Black, and 2 Asian). Each cohort contained 7 children with HL who used hearing aids or cochlear implants and 2 to 3 typically hearing children (see Table 1). Children's HL ranged from mild to profound binaural HL, with the majority having severe to profound loss. All children with HL had sensorineural HL; 3 of the children also had auditory neuropathy. Based on teacher report, 14 of the children had some degree of bilingual English-Spanish exposure at home (see Table S1). We obtained informed consent from children's parents. One-hundred percent of all children enrolled in each cohort participated in the study.

5.1.1. Standardized assessments of language abilities

The school speech-language pathologist (SLP) administered the Preschool Language Scales, Fifth Edition (PLS-5 Zimmerman, Steiner, & Pond, 2011) at the end of each school year to obtain a standardized measure of each child's receptive and expressive language abilities (scores on the auditory comprehension and expressive communication subscales, respectively, of the PLS-5). Three typically hearing children were not administered the PLS-5 and were not included in relevant analyses. Receptive, M = 92, SD = 28, and expressive, M = 92, SD = 23, standard

Table 1
Participant characteristics by cohort.

Cohort	Number of observations	Mean (sd) days between observations	TH *n* / HL *n*	CI *n* / HA *n*	Female *n* / Male *n*	Bilingual *n* / Monolingual *n*	Mean (sd) Age*	Mean (sd) Age of CI/HA**	Mean (sd) Hearing Age***	Mean (sd) range PLS-5 AC scores	Mean (sd) range PLS-5 EC scores
1	10	9.34 (3.50)	3 / 7	5 / 2	8 / 2	4 / 6	37.48 (2.55)	15.86 (4.71)	26.37 (9.32)	85.38 (26.73) 60-134	89.93 (34.87) 66-139
2	11	20.40 (10.49)	2 / 7	5 / 2	5 / 4	4 / 5	33.20 (2.64)	14.89 (6.36)	21.62 (9.16)	99.28 (23.16) 50-125	97.04 (17.81) 68-127
3	13	19.42 (14.99)	3 / 7	3 / 4	4 / 6	6 / 4	35.38 (5.05)	17.14 (7.86)	23.38 (8.01)	90.81 (23.16) 50-132	89.89 (25.82) 50-130
Total	34	17.37 (13.45)	8 / 21	13 / 8	17 / 12	14 / 15	35.68 (3.95)	16.08 (6.23)	24.04 (8.81)	92.68 (27.76) 50-134	92.53 (23.13) 50-139

Note. TH = typical hearing; HL = hearing loss; CI = cochlear implant; HA = hearing aid. Ages in months. *Age of first observation. **Age of CI activation or HA fitting. ***Age with corrected (or typical) hearing. Auditory Comprehension (receptive language ability); EC: Expressive Communication (expressive language ability)

scores were within typical range (see Table 1 for cohort means). Children with HL had significantly lower scores (receptive: M = 85.24, SD = 26.58; expressive: 85.95, SD = 21.06) than children with TH (receptive: M = 120.60, SD = 9.32, t = 2.89, P = 0.008, d=1.78; expressive: 118.80, SD = 11.30, t = 3.34, P = 0.003, d = 1.94). There were no significant differences in the scores of the 14 children who had some degree of bilingual home exposure (receptive: M = 86.64, SD = 25.88; expressive: 85.43, SD = 19.35) and those who had monolingual home exposure (receptive: M = 98.33, SD = 30.05; expressive: 100.25, SD = 26.03), $ps > 0.10$. Four of these children were administered the bilingual Spanish-English form of the PLS-5, based on child preference and best practices. There were no differences in PLS-5 scores administered using the bilingual or monolingual English form, $ps > 0.10$.

5.1.2. Classroom characteristics

The oral language inclusion classroom observed in the study is part of a university-based preschool that includes an Auditory Oral program for children between 1-7 years old. The curriculum is designed to prepare children with HL to participate in general education classrooms and targets listening and spoken language development, communication, emergent literacy and STEM skills, and physical fitness as well as social-emotional development. The school follows federal recommendations that one third of class-time be occupied by free play (USDA, 2010). Classroom teachers are required to have the State Department of Education Professional Educator's Certificate with the Hearing-Impaired Endorsement and receive ongoing professional development through the school.

Although an English-language school, the school is located in a community with high levels of English-Spanish bilingualism, and approximately half of the participants came from bilingual homes (see Table 1, Table S1). To characterize classroom language, trained coders annotated 3 session-long recordings (~12 hours) revealing that 97% of children's vocalizations were in English and 3% were in Spanish.

5.2. Data collection

Continuous RFID measurements of each child's location were collected using the Ubisense Dimension4 system. First-person audio was recorded using LENA Digital Language Processors worn by each child in the classroom. These recordings were collected during multi-hour observations that spanned the entire school day (M = 3.62 hours, SD = 0.59 hours). Observations occurred approximately once every 2 weeks, with the time between observations varying based on classroom schedules (M = 16.80 days; SD = 11.94 days, range: 5-51 days). There was a mean of 11.33 observation occasions (SD = 1.53) per class. Due to absences, individual children contributed a mean of 9.83 recordings (SD = 1.83) recordings to analyses. The sample yielded 624 hours of recorded audio and movement data. During data collection, a team member, who was trained not to interact with the children, was present to verify that equipment was working and to note times in which the class engaged in free-play or when children left the room (for outdoor play or speech therapy sessions).

5.3. Measures

5.3.1. Children's movement

The RFID-based Ubisense system was used to track children's location at 2-4 times per second to an accuracy of 15 cm within the classroom (4.78 × 7.56 m). The system consists of one sensor in each corner of the classroom, a dedicated server, and active tags worn by children. Each child wore 2 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 3-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.

5.3.2. Social contact

Distance. The radial distribution function indicates distances at which pairs of children are closer than expected by chance ($g(r) > 1$). Chance refers to the likelihood of children being located at a particular distance given their overall physical distribution in the classroom (without regard to the location of others). The radial distribution function for the 34 observations indicated that co-location between children was greater than chance between 0.2 m and 1.5 m (Fig. 2A). We established a first criterion of social contact when pairs of children were within 1.5 m of each other.

Orientation. Within the 1.5 m range, we examined the mutual orientation of each dyad. Mutual orientation was calculated by measuring θ_1, the angle of child A relative to child B, and θ_2, the angle of B relative to child A (Fig. 2B). Children showed a tendency to be oriented towards one another. Consequently, we defined periods of social contact as instances where children were within 1.5 m of one another and oriented toward one another within ±45° degrees. Depending on orientation and distance a child could interact with 2 peers simultaneously. If child A, B, and C, were all located within 1.5 meters of each other and orientated such that they

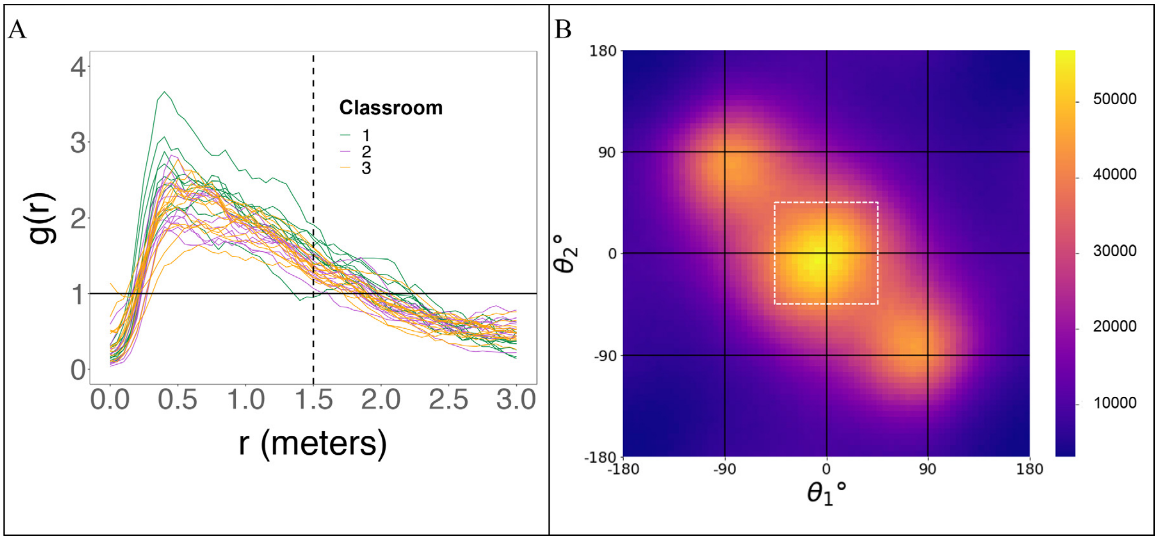

Fig. 2. Social contact determination. Social contact was determined using Ubisense measures of child-to-child proximity (A) and mutual orientation (B). **1A** depicts the radial distribution function, g(r), which indicates distances at which the probability of two children being in contact is higher than chance, g(r) = 1). Each line depicts one observation day for a given cohort 1B is a heat map indicating the angle of each child, $\theta_{1,}$ to all peers, θ_2, who are within 1.5 m. The color bar indicates number of tenth-of-a-second observations in 1000s. Children tend to be face-to-face ($|\theta_1°|$ & $|\theta_2°|$ within |45°| of 0°), which was used as the orientation criterion for social contact (white box).

were all approximately facing each other, this interaction would be coded as 3 dyadic interactions (A-B, A-C, and B-C). We calculated the proportion of time that each child was in social contact with *each individual* peer out of the total time in which both children in that dyad were in the classroom. This measure is referred to as proportion of social contact.

5.3.3. 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. Using Gaussian mixture models, the software segments audio recordings into categories distinguishing children's own speech-like vocalizations from non-speech sounds (e.g., crying) and other speakers' vocalizations. The LENA algorithm defines vocalizations as periods containing the voice of the child wearing the recorder of least 50 ms duration that do not include the vocalizations of adults or other children. If interrupted by silence or noise for more than 300 ms, a vocalization ends (Lynch, Oller, Stefens, & Buder, 1995; Oller, Niyogi, Gray, Richards, Gilkerson, Yapanel, & Warren, 2010). In the current sample, the mean duration of LENA-identified child vocalizations was 777 ms (SD = 439 ms). LENA provides reliable estimates of language input and language use among both typically developing children and children with language delays (Gilkerson & Richards, 2009; Warlaumont, Richards, Gilkerson, & Oller, 2014). Of special note for the current investigation, LENA algorithms accurately estimate the developmental age of children with and without HL (VanDam et al., 2015). LENA has been used to quantify speech in both English (Soderstrom & Wittebolle, 2013) and Spanish (Weisleder & Fernald, 2013), but does not distinguish between them.

5.3.4. Reliability

Vocalization counts were derived from LENA's Interpretive Time Segment files, which contain the onset and offset of each vocalization made by the child wearing the recorder. In analyses, a given child's vocalizations served as both target and peer vocalizations. Both vocalization types were tabulated from that child's own recorder. To assess the reliability of LENA classifications, 4 trained coders, blind to the LENA classifications, re-coded approximately 5% of adult and child vocalizations (using LENA's Female Adult Near/Male Adult Near [FAN/MAN] and Target Child Near/Target Child Far [CHN/CHF] vocalization segments respectively). The 3260 segments were sampled equally from each observation day for 12 children spread across the 3 cohorts (7 children with HL and 5 children with TH). LENA-identified child vocalizations (the measure used in the current study) from both children with and without HL were identified as such by coders with agreement in 88% of segments (Cohen's Kappa = 0.77), suggesting relatively high levels of reliability between trained coders and LENA algorithms in the classroom setting (Bakeman & Quera, 2011).

5.3.5. Data integration

Both Ubisense and LENA data were written to a hard drive with an accompanying time stamp. To account for potential drift in the time signature of individual LENA recorders, we synchronized the audio recordings for each observation. To do so, we conducted a Fast Fourier Transform, cross-correlated the audio signal in the frequency domain, and offset recordings to maximize the cross-correlated signal (Rhudy, 2014). The Ubisense signal was interpolated at 0.10 s intervals and synchronized with the previously synchronized audio recordings. The synchronized vocalization/location data were used to calculate when pairs of children vocalized during periods of social contact. We summed the number of vocalizations made by each child during periods of social contact with each peer to index *which* children were speaking to each other (e.g., how much child A spoke to child B and how much child B spoke to child A). These sums were divided by the length of time both children in a dyad were in the classroom at the same time to create a rate of vocal interaction per hour, that is the rate of vocalizations given the amount of time in which a dyad *could* have engaged in social contact[1].

[1] Here we focus on the overall rate of vocalizations children made to each peer on each observation, to allow us to characterize patterns of peer interaction across observations. As an alternate approach to characterizing peer interaction, we explored whether the number of vocalizations that children produced were in the context of multi-turn conversations (both members of a dyad vocalized during a social interaction) vs one-turn utterances (only one member of the dyad vocalized). We then averaged the number of members of each dyad that vocalized during each interaction across observation days. A mixed effects regression model revealed a

5.4. Analytic approach

Analyses were conducted in R (R Core Team, 2014). Linear mixed effects models were conducted through the *lmer* function in the "lme4" package using maximum likelihood estimation to account for missing data, making them ideal for data collection in a natural setting such as a preschool, where children are occasionally absent on data collection days (Bates, Maechler, Bolker, & Walker, 2015). In these mixed effects models, observations (level 1) were nested within children (level 2) who were nested within cohorts (level 3). All models included random intercepts of subjects and cohort to account for this nestedness. Categorical variables (hearing status) were contrast coded and centered (+/- 0.5) in all analyses. Continuous variables (e.g., vocalizations) were mean centered within subjects to assiduously distinguish level 1 and level 2 variance (Enders & Tofighi, 2007). We report coefficients and standard errors from final predictive models and the results of chi-square tests of model fit, comparing models with and without each of the predictors of interest.

6. Results

We first explored general characteristics of interactions in the classroom, comparing children with and without HL on (A) the proportion of time in social contact, and (B) the rate of target child vocalizations during social contact to peers with and without HL across unstructured free-play periods and more structured activity periods.[2] Then we examined the reciprocal influence of vocalizations to peers over time, testing the hypotheses that (1) the vocalizations children heard from individual peers predicted their subsequent vocalizations to those peers; (2) children's vocalizations to their peers are associated with their end-of-year language abilities; and (3) children's vocalizations to their peers mediate the association between vocalizations from peers and end-of-year language abilities.

6.1. Research question 1: do social contact and vocalizations vary across peers and activities?

6.1.1. Variation in social contact across peers and activities

Linear mixed effects models predicted children's proportion of time in social contact with peers from the number of days since study onset (time in study), activity type (free-play vs not), target child hearing status, peer hearing status, and the interaction between target and peer hearing status. Children spent an average of 52% of their day (SD = 10%) in social contact with a peer, with an average of 7% (SD = 1%) of their time in social contact with each of their individual peers. On average, children with HL spent a similar amount of overall time in social contact TH children, $M_{HL} = 0.06$ (SD = 0.002); $M_{TH} = 0.07$ (SD = 0.02), $P = 0.172$ (see Table 2). Social contact varied depending on the peer's hearing status as evidenced by a main effect of peer hearing status, $P = 0.0006$, and a significant interaction between target and peer hearing status, $P = 0.0006$. This interaction was driven by children with TH spending a higher proportion of time in social contact with peers with TH (M=.09, SD=.008) than peers with HL ($M = 0.06$, SD = 0.02). Additionally, children's time in social contact varied across activity type such that they spent a lower proportion of time in social contact with each peer during free-play ($M = 0.05$, SD = 0.01) than other activities ($M = 0.08$, SD = 0.004), $P < 0.00001$.

6.1.2. Variation in vocalizations across peers and activities

Linear mixed effects models predicted the rate of target child vocalizations to each of their peers from the number of days since study onset (time in study), activity type (free-play vs not), target child hearing status, peer hearing status, and the interaction between target and peer hearing status. Children vocalized at a mean rate of 19.75 vocalizations per hour during social contact with peers. This rate was significantly lower for children with HL (M_{HL} = 16.92 per hour, SD = 1.47) than those with TH (M_{TH} = 24.67 per hour, SD = 6.87), see Table 2. Additionally, the rate of children's vocalizations varied with peer hearing status as evidenced by a main effect of peer hearing status and significant interaction between target and peer hearing status. This interaction was driven by children with TH vocalizing at a higher rate to peers with TH (M = 29.5309, SD = 1.11) than to those with HL (M = 19.81, SD = 5.83). Children's rate of vocalizations also varied across activity type; as a group, children tended to vocalize less to each other during free-play (M = 17.59, SD = 7.64) than other activities (M = 24.00, SD = 3.31).

6.2. Research question 2: do peer vocalizations predict subsequent target child vocalizations?

A lead-lag analysis was implemented through a linear mixed effects model to predict the target child's rate of vocalizations per hour to each of their peers at observation $t+1$ from their rate of vocalizations from the same peers at observation t, where t and $t+1$ are consecutive classroom observations. Each child was simultaneously treated as a target child whose vocalizations were being predicted, and as a peer whose vocalizations were a predictor of each target child's vocalizations. All analyzed vocalizations occurred during periods of social contact. Covariates included the target child's rate of vocalizations per hour to each peer at observation t (an auto-regression control), target child hearing status, peer hearing status, the interaction between target and peer hearing status, and the interaction between peer vocalizations and target child hearing status.

There was a significant effect of peer vocalizations on children's vocalizations to those peers at observation t+1 (Table 3). The more vocalizations children heard from a specific peer, the more they subsequently vocalized to that peer. There was also a significant positive effect of the target child's own vocalizations at observation t, an autoregression control. We found no main effects of the target child's hearing status or peer hearing status, nor any interaction between target and peer hearing status, or between target child hearing status and the effect of peer vocalizations. The results indicate that a child's vocalizations to peers was predicted by those peers' previous vocalizations to the child—above and beyond any differences in children's vocalization associated with HL—and suggests a longitudinal process of dyadic language exchange.

6.3. Research question 3: are vocalizations to and from peers associated with language ability?

Next we tested the hypothesis that vocalizations to and from peers were associated with children's PLS-5 scores. We calculated the mean (over observations) of each target child's rate of vocalizations to peers and the mean rate of vocalizations heard from peers, both while in social contact. In parallel linear regression models of expressive and receptive language, mean vocalizations from peers, mean vocalizations to peers, hearing status, and the interaction between vocalizations from peers and hearing status were entered as simultaneous predictors (Table 4). Children's vocalizations to peers

significant positive association between this measure and the one reported in this paper, the rate of vocalizations to peers, $X^2(1) = 9.16$, $P = 0.002$.

[2] Analyses reported here examined hearing categorically. Additional analyses treating hearing continuously as age from cochlear implantation/hearing aid fitting yielded the same results as those reported here. We report separate analyses examining whether these variables differed with child-level characteristics: hearing device type, sex, bilingual status, and socioeconomic status, none of which were significant predictors of social contact or vocalizations, in Supplemental Materials.

Table 2
Results of linear mixed effects models predicting social contact with peers and vocalizations to peers.

Model Outcome	Model Parameter	Fixed effects B	SE	t	95% CI	Random effects Variance	SD	Chi-square test of model fit X^2	df	*P*
Proportion of time in social contact with individual peers	Target hearing status	0.01	0.004	2.30	0.001, .02	___	___	1.87	1	0.172
	Peer hearing status	0.01	0.002	4.76	0.007, .02	___	___	11.87	1	0.0006
	Activity type	-0.03	0.002	-18.31	-0.04, -0.03	___	___	321.31	1	<0.00001
	Interaction between target hearing status and peer hearing status	0.02	0.005	3.41	0.007, 0.03	___	___	11.63	1	0.0006
	Random subject intercept	___	___	___	___	0.00008	0.009	83.41	1	<0.00001
	Random cohort intercept	___	___	___	___	0.00007	.009	6.41	1	0.011
Target vocalizations	Target hearing status	7.06	2.49	2.84	2.10, 12.01	___	___	4.62	1	0.032
	Peer hearing status	5.34	.82	6.56	3.75, 6.94	___	___	28.79	1	<0.00001
	Activity type	-8.70	.60	-14.40	-9.89, -7.52	___	___	201.83	1	<0.00001
	Interaction between target and peer hearing status	6.10	1.63	3.74	2.91, 9.30	___	___	14.00	1	0.0002
	Random subject intercept	___	___	___	___	31.79	5.64	262.75	1	<0.00001
	Random cohort intercept	___	___	___	___	17.30	4.16	3.78	1	0.052

Note. Target child's and peer's hearing status were coded categorically as hearing loss vs typical hearing. Positive values indicate a typical hearing advantage. Activity type was coded as free-play vs other activities (negative values indicate a free-play disadvantage).

Table 3
Linear mixed effects model predicting target child's vocalizations to peers at observation t+1.

Parameter	Fixed effects *B*	SE	*t*	95% CI	Random effects Variance	SD	Chi-square test of model fit X^2	df	*P*
Peer vocalizations to target at observation *t*	0.22	0.06	3.93	0.11, 0.33	___	___	14.60	1	0.0001
Target vocalizations to peer at observation *t*	0.32	0.06	5.49	0.20, 0.43	___	___	29.37	1	<0.00001
Target hearing status	3.75	3.29	1.14	-2.83, 10.27	___	___	1.17	1	0.280
Peer hearing status	.82	1.10	.74	-1.34, 2.96			.35	1	.554
Interaction between target and peer hearing status	.97	2.19	.44	-3.32, 5.26	___	___	.20	1	.66
Interaction between target hearing status and peer vocalizations	.07	.05	1.48	-.08, .16	___	___	2.21	1	.138
Subject intercept	___	___	___	___	55.24	7.43	187.41	1	<.00001
Cohort intercept	___	___	___	___	25.99	5.10	3.10	1	.078

Note. The peer vocalization to target effect indexes a positive effect on vocalizations to those peers while the target vocalization effect is an auto-regression control. Positive values for hearing status indicate a typical hearing advantage with respect to hearing loss.

Table 4
Linear regressions predicting children's end of year PLS-5 scores

Model outcome	Parameter	*B*	SE	*t*	95% CI	*P*
Expressive language, adjusted $R^2 = 0.37$	Mean target vocalizations	2.59	1.11	2.32	.27, 4.90	0.030
	Mean peer vocalizations	-2.62	2.28	-1.215	-7.35, 2.12	0.263
	Target hearing status	32.30	70.06	0.65	-113.41, 178.00	0.650
	Interaction between mean peer vocalizations and target hearing status	-0.28	3.71	-0.08	-8.01, 7.44	0.940
Receptive language, adjusted $R^2 = 0.32$	Mean target vocalizations	3.31	1.37	2.42	.46, 6.16	0.025
	Mean peer vocalizations	-3.07	2.80	-1.10	-8.89, 2.76	0.286
	Target hearing status	23.55	86.18	0.27	-155.68, 202.78	0.787
	Interaction between mean peer vocalizations and target hearing status	0.23	4.57	0.05	-9.27, 9.73	0.960

were positively associated with end-of-year expressive and receptive language abilities. Notably, the effect of hearing status was no longer significant in this model, which included children's vocalizations as a predictor. Additionally, there was no significant effect of vocalizations from peers, nor was there an interaction between the target child's hearing status and vocalizations from peers.

6.3.1. Mediation of target child vocalizations on peer vocalizations

The previous analyses indicated that vocalizations from peers were associated with target child vocalizations to peers, which were, in turn, associated with end-of-year language abilities. We conducted a full longitudinal mediation analysis to assess whether target child vocalizations mediated the association between peer vocalizations and language abilities (MacKinnon et al., 2004; Rucker, Preacher, Tormala, & Petty, 2011). Both peer vocalizations and target child vocalizations were averaged over observations. To meet the temporal precedence requirement of mediation (MacKinnon et al., 2013), we separately calculated the mean rate of vocalizations for the first and second half of observations for each cohort. This constituted the first 5, 6, and 6 observations, respectively, for the 3 successive cohorts. We included a child's mean of peer vocalizations only from the first half of observations, and rates of target child vocalizations to peers only from the second half of observations. The mediation analyses were conducted in R

Table 5
Mediation analyses

Model outcome	Parameter	*B*	SE	*t*	95% CI	*P*
Receptive language	Direct effect of peer vocalizations	0.30	0.78	0.39	-1.23, 1.83	0.70
R^2=.21, P = 0.047	Direct effect of peer on target	0.80	0.13	6.10	.55, 1.05	<0.00001
	Direct effect of target vocalizations	2.67	1.03	2.59	.65, 4.59	0.015
	Indirect bootstrapped effect of peer vocalizations	2.07	0.82	___	.40, 3.64	___
Expressive language	Direct effect of peer vocalizations	0.19	0.65	0.29	-1.08, 1.46	0.775
R^2=.23, P = 0.036	Direct effect of peer on target	0.80	0.13	6.10	.55, 1.05	<0.00001
	Direct effect of target vocalizations	2.34	0.86	2.73	.65, 4.03	0.011
	Indirect bootstrapped effect of peer vocalizations	1.83	0.69	___	.55, 3.31	___

Note**.** Analyses test for an indirect effect of peer vocalizations on children's PLS-5 scores as mediated by target child vocalizations. The significance of indirect effects was determined by confidence intervals from the bootstrapping procedure

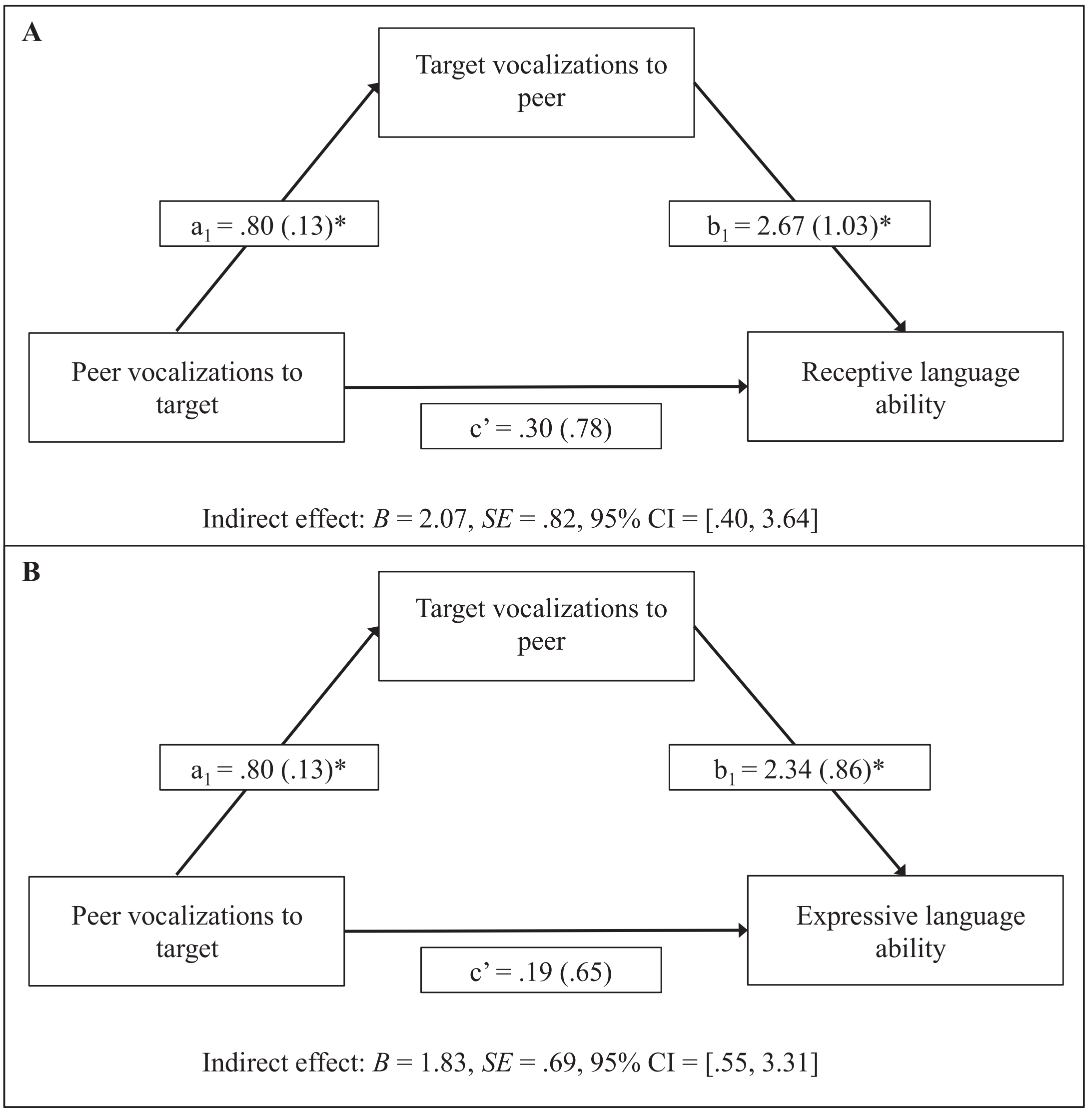

Fig. 3. Mediation models of the role of the children's vocalizations to peers in the relationship between vocalizations from peers to their assessed language abilities. (A) the dependent variable is receptive language abilities as measured by the PLS-5 and (B) the dependent variable is expressive language abilities as measured by the PLS-5. * Indicates $P < 0.05$. Models revealed an indirect association between peer vocal input and assessed language abilities, mediated through children's vocal output to peers.

using the "psych" package (Revelle, 2018) with the *mediate* function (Imai, Keele, & Tingley, 2010). Data were resampled with replacement with 5,000 bootstraps. The mediation analyses revealed significant indirect effects of peer vocalizations on children's receptive and expressive language abilities through their own vocalizations (Table 5 and Fig. 3). Greater vocalizations from peers were associated with greater vocalizations to peers, which were, in turn, associated with higher language abilities.

7. Discussion

Although preschool classrooms are fertile environments for children's peer communication, we know little about how children with HL talk to their peers. Moving beyond manual coding of sampled interactions, this study examined the dyadic interactions of *all* pairs of children in a classroom simultaneously. First, we found differences in the proportion of time in social contact and the rate of vocalizations children produced to peers based on hearing status. Namely, children with TH spent more time in social contact with and vocalizing to peers with TH than those with HL. However, we found that regardless of children's hearing status, vocalizations from peers during periods of social contact predicted subsequent vocalizations to those same peers, suggesting a reciprocal pattern of dyadic vocalization in the classroom. Children's vocalizations to peers were, in turn, associated with end-of-year expressive and receptive language abilities. Moreover, vocalizations to peers mediated the association between vocalizations *from* peers to assessed receptive and expressive language abilities. Thus, speech from peers, to the degree that it yields speech to those peers, influenced children's own language abilities. The results have implications for our understanding of the role of dyadic peer speech in facilitating language skills in both children with and without HL.

8. A novel measure of socially engaged peer-to-peer speech

Previous research using LENA recorders could not indicate which children were speaking to one another. To ascertain when individual pairs of children were talking, we assessed social contact based both on children's proximity and mutual orientation. Implementing these criteria indicated a 1.5 m social distance radius similar to that documented by Messinger et al. (2019). Within this radius, we examined the mutual orientation of each child with every other child. This orientation measure—the first bottom-up objective description of children's mutual orientation—indicated a tendency for children to be oriented face-to-face. Thus the study's determination of social contact suggests new approaches for investigating peer proxemics (McCall, 2017). Furthermore, by allowing for efficient simultaneous multi-hour observation of all children across a variety of activities, our method potentially increases the representativeness of observed behavior relative to previous labor-intensive human coding methods that are often limited to brief observations of specific activities (cf Bergelson, Amatuni, Dailey, Koorathota, & Tor, 2019.). Indeed, this novel measure allowed us to see that children engaged in less social contact and fewer vocalizations during periods of free play than during other activities. Although not the core focus of our investigation, this finding has implications for our understanding of the role that unstructured vs structured activities play in children's language development.

During periods of social contact, peer vocalizations predicted a target child's subsequent vocalizations to those individual peers. Results were independent of the target child's *previous* vocalizations to their peers, specifically implicating the role of partner vocalizations. Moreover, the predictive power of peer vocalizations did not vary based on the time elapsed between observations. This finding, together with the mediation analyses in which peer speech from the first half of observations predicted target speech in the second half, suggests relatively robust interactive patterns of dyadic speech over weeks and months. The results specifically reveal a pattern of reciprocal vocalization over time. Higher (or lower) levels of child A's speech to B were associated with higher (or lower) levels of subsequent speech of B to A, which were in turn associated with higher (or lower) levels of A's speech to B. Thus, classroom speech is characterized by reciprocal patterns of dyadic speech that vary over developmental time. Previous research on peer effects on child language indicated that average classroom language ability predicts children's language gains over the school year (Justice et al., 2011). By assessing children's vocal interactions with individual classmates, the current results suggest a mechanism for these peer effects. Specifically, within-dyad transmission of speech over the school year may lead to individual child language gains.

9. Peer-to-peer speech and language abilities

Higher overall levels of children's vocalizations to their peers were directly associated with higher expressive and receptive language scores, and mediated the indirect association between speech from peers and receptive and expressive language abilities. Vygotsky proposed that, "by giving our students practice in talking with others, we give them frames for thinking on their own" (1978, p. 19). Bearing out Vygotsky's insight, we found that children's talk to peers while in social contact may provide an opportunity to concretize the use of words and grammatical constructions related to both expressive and receptive language abilities. Speech from peers appears to be a vehicle for increasing children's subsequent vocalizations to their peers, which provides them with an opportunity to practice and consolidate their language competencies. The finding that children's own speech mediated the effects of peer speech on language abilities squares with previous observations that children's language production can predict language development over and beyond language input (Hirsh-Pasek et al., 2015; Ribot et al., 2018).

The consequences of the dyadic peer interactions that we observed may extend beyond children's language use and abilities. Conversations with friends are the primary context in which children hone conflict resolution skills and develop an appreciation of the principles of reciprocity and social exchange that guide relationships (Laursen et al., 1996). Thus, the patterns of reciprocal co-talking documented here may be a path to the development of social as well as language competencies. In fact, peer vocalizing during social contact in the second cohort of children investigated here was associated with teacher- and self-report of children's reciprocal friendships (Altman, Laursen, Messinger, & Perry, 2020).

Inclusion classrooms are the national educational standard of intervention for children with communication disorders (Guralnick & Bruder, 2016). The premise of inclusive practice is that children with communication disorders profit from social interactions with typically developing peers. Indeed, previous research indicates that children with disabilities have fewer opportunities for peer interaction with typically developing peers, but may nevertheless benefit more from peer language than typically developing children (Chen et al., 2020). Our initial findings that children with TH spend more time in social contact and vocalizing to other typically hearing peers is consistent with that previous work. However, we also found that the reciprocal process of peer input over time is a better indicator of children's future vocalizations and language abilities than their own hearing status. This suggests that inclusive settings that allow for peer vocal interaction can play a role in supporting positive language outcomes for children with HL. Future work could explore how the ratio of children with HL to TH influences their patterns of peer interaction and how teachers can facilitate TH-HL interactions during classroom activities.

We found significant differences in the end-of-year language assessment scores of children with and without HL—consistent with prior work showing language delays for children with HL. We note that in our sample, several of the children with TH had scores well above the typical range (i.e. above 115). However, these differences were not significant when accounting for the effects of vocalizations in the previous observation—both children's exposure to their peer's vocalizations and the children's own vocalizations to those peers. This pattern of results suggests that vocally mediated reciprocal interactions account for more unique variance in assessed language abilities than HL. This finding suggests that interventions targeting increasing vocal exchanges between peers might be appropriate for children with HL (e.g., Girolametto, Weitzman, & Greenberg, 2004).

10. Limitations

The present study is not without limitations as small samples may yield high correlations (Oakes, 2017). However, dense longitudinal data, like that presented here, including 624 hours of recording, may be necessary to decipher ongoing dyadic social communication processes that are repeated over time even with a relatively small number of participants (Perry et al., 2018; Roy, Frank, DeCamp, Miller, & Roy, 2015). Additionally, we had 100% participation in each cohort—a rarity in classroom-based research—allowing us a more complete picture of children's peer interactions. Nevertheless, the modest size of the current sample suggests the need for replication and ongoing exploration of group differences. Relatedly, although we found no differences in our measures related to children's bilingual status (see Supplemental Materials), our ability to address intersectional influences of hearing loss and bilingualism on social interaction and vocalization is limited by our sample size and will be an important direction for future research.

The findings underscore a potential role for dyadic conversation in supporting assessed language abilities. However, as only a single end-of-year language assessment was available for analysis, we cannot determine the directionality of the association between reciprocal peer vocalizations and language abilities. for example, children with higher language abilities may have been exposed to or engaged in richer classroom language use—or that use may have scaffolded the children's language abilities. A next step for researchers is to bookend repeated classroom observations with beginning-of-year as well as end-of-year assessments to determine whether dyadic communication lead to changes in language abilities over developmental time.

Notably, the determination of social contact here focused on the location and orientation of dyads. While a child might have interacted with 2 peers simultaneously, analyses focused on the vocalizations received from each peer and made to that peer. If triadic interactions resulted in a misspecification of dyadic interaction, this would bias against the research hypothesis of dyadic vocal prediction over observations, suggesting the strength of the current approach. Similarly, if for example, during circle time a child addressed the whole group from farther than 1.5 meters, these vocalizations would not have been captured by our analyses. If they were closer than 1.5 meters and face-to-face with some members of the group, their vocalizations to those members would be included. As can be seen in Fig. 2A-B, children were within 1.5 meters of each other more often than expected by chance, and when they were within 1.5 meters, they were most often face-to-face. Finally, a potential limitation of the current approach is that automated measurement technologies are not without error. A recent report indicated that LENA algorithms can confuse mother's speech for children's vocalizations perhaps because of the presence of infant directed speech in the home (Cristia et al., 2019). However, our own reliability analyses indicated high levels of agreement between human expert and objective coding in the preschool context.

11. Conclusions

We harnessed big behavioral data from automated measurements of peer interaction to identify patterns of dyadic speech during social contact over 3 years of observations in an inclusion classroom for children with hearing loss. Children in social contact dynamically affected each other's levels of dyadic speech in a reciprocal fashion over observations. Language from peers positively affected language to peers which was, in turn, associated with receptive and expressive language abilities. These effects did not vary between children with and without hearing loss. The results suggest that dyadic peer vocal interaction in classrooms is a potential mechanism for supporting language development.

Data Availability

The data that support the findings of this study are openly available on the Open Science Framework: https://osf.io/2c5g9.

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Disclosure

The authors have no conflicts of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecresq.2022.02.003.

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