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ORIGINAL ARTICLES

Language Exposure for Preterm Infants is Reduced Relative to Fetuses

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Objective To assess changes and deficits in language and auditory exposures consequent to preterm birth and neonatal intensive care unit stay compared with exposures *in utero* among typically developing fetuses.

Study design We analyzed over 23 000 hours of auditory exposure data in a cohort study of 27 typically-developing fetuses and 24 preterm infants. Extrauterine exposures for fetuses were captured by having pregnant women wear 24-hour audio recording devices. For preterm infants, recording devices were placed in the infant's crib. Multilevel linear regressions were conducted to test for group differences and effects of infant sex, maternal education, and mother' occupation. A linear mixed-effects model was used to test for an effect of speaker gender.

Results Fetuses were exposed to an estimated 2.6 ± 1.8 hours/day of nearby, predominantly female language, nearly 5 times greater than 32 ± 12 minutes/day estimated for preterm infants ($P < .001$). Preterm infants had greater daily exposure to electronic sounds (5.1 ± 2.5 vs 1.3 ± 0.6 hours; $P < .001$) and noise (4.4 ± 2.1 vs 2.9 ± 2.8 hours; $P < .05$), with 4.7 ± 3.9 hours/day of silence. Language and extrauterine sound exposure for fetuses showed a marked day/night cyclical pattern, with low exposure during nighttime hours, but preterm infants' exposures showed significantly less change across the 24-hour cycle ($P < .001$). Maternal occupation requiring frequent communication predicted greater language exposure ($P < .05$).

Conclusions Our findings provide the first comparison of preterm infant auditory exposures to typically-developing fetuses. Some preterm infants may incur deficits of over 150 hours of language exposure over the preterm period. Given known effects of prenatal/preterm language exposure on neurobehavioral outcomes, this magnitude of deficit is alarming. *(J Pediatr 2023;■:113344)*.

In the US, approximately 10% of newborns are born premature.[1] Because auditory function begins as early as 23 weeks' gestation,[2-5] preterm infants undergo a rapid and premature change in auditory experience as they transition from the intrauterine acoustic environment to the neonatal intensive care unit (NICU). The intrauterine environment is unique, with constant, primarily low-frequency sounds of mother's cardiovascular and digestive systems and voice transmitted to the fetal ear via amniotic fluid.[6-9] Also present are others' nearby vocalizations, music, and other airborne sounds that impinge on the abdomen of the mother.[8,10] Extrauterine sounds are modified by transmission through abdominal tissue, which provides some sound attenuation, possibly more pronounced at higher frequencies.[11,12] In contrast, NICU infants are exposed to high sound levels,[13,14] electronic and mechanical noises,[15] and periods of silence,[15,16] transmitted via air rather than fluid (**Table I**). Preterm infants suffer from a high incidence of neurodevelopmental problems,[17] many of which are linked with auditory function,[18-26] including widely reported speech/language deficits.[27-29] Neural mechanisms underlying these impairments are not clear, although structural abnormalities in cortical gray and white matter for preterm infants[30-32] are associated with poorer language abilities later in childhood.[32,33]

Extrauterine auditory exposures during gestation affect neurobehavioral outcomes. Full-term newborns exhibit behavioral and neurophysiological responses that distinguish familiar sounds (via exposure *in utero*) from unfamiliar sounds, including mother's voice, mother's native language, music, and oft-heard speech passages.[34-40] The result is a newborn brain primed for language acquisition.[38,41] It has been proposed that abnormal auditory exposures for NICU infants contribute to developmental deficits later in life.[42,43] However, one critical issue that has never been assessed is the extent to which NICU auditory exposures differ from typical exposures during the equivalent stage of neurodevelopment. Previous efforts to evaluate NICU auditory/language exposures,[15,16,44,45] while valuable, have been limited in the following ways: 1) few 16-hour audio recordings were analyzed per subject to estimate exposures over a multi-month period[15,16]; 2) no analysis of a typically-developing fetal group has been conducted; 3) the pattern of exposures across the 24-hour cycle has not been examined. Thus, although it is

LENA	Language ENvironment Analysis
NICU	Neonatal intensive care unit
PMA	Postmenstrual age
VPT	Very preterm

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Table I. Putative differences between regularity of intrauterine and NICU auditory exposures

Typical exposures	Womb (*via* fluid)	NICU (*via* air)
Heartbeat	Always	Never
Silence	Never	Often
Alarms	Rarely	Often
Biological sounds	Always	Never
Airborne noise	Sometimes	Often
Maternal voice (when speaking)	Always	Sometimes
Non-maternal voices (when speaking)	Often	Often
High sound levels	Unknown	Often

presumed that auditory exposures in the NICU differ from fetal exposures, the extent to which they differ is unknown. Consequently, interventions to modify auditory/language exposures in the NICU, although increasingly prevalent,[46] lack meaningful targets for healthy exposures. We addressed these gaps by analyzing auditory exposures for typically-developing fetuses and NICU infants. We tested 3 hypotheses: 1) language exposure is greater for fetuses than NICU infants; 2) exposure to electronic sounds and airborne noise is greater for NICU infants than fetuses; 3) auditory exposures for fetuses follow a 24-hour day/night pattern, whereas this pattern is diminished for NICU infants.

Methods

This prospective cohort study was approved by institutional review boards at the University of Illinois Urbana-Champaign and Carle Foundation Hospital. Mothers provided written informed consent. Recruitment and data collection occurred October 2018 through March 2020, and was discontinued when NICU visitation restrictions began due to the COVID-19 pandemic. For typically developing fetuses, pregnant participants were recruited through a university employee email listserv, online postings, and flyers posted at community maternity clinics. We recruited 28 pregnant female participants (age 27-36 year, mean = 31.4 year) and their fetuses. One participant carried twins. Inclusion criteria for pregnant participants were: ≥19 years of age, ≥20 weeks but ≤32 weeks pregnant, and no pregnancy complications. Participation was discontinued for 1 participant due to suspension of data collection consequent to the COVID-19 pandemic. Families of preterm infants were identified and approached by a nurse practitioner in the NICU. We initially recruited families of 37 neonates born very preterm (VPT; ≤32 weeks' gestation) from a level III, 48-bed, open layout NICU in Urbana, Illinois. The initial VPT group included 2 sets of triplets and 3 sets of twins. Inclusion criteria for VPT infants were maternal age ≥19 years and ≤32 weeks gestational age. Exclusion criteria for both groups included known or suspected congenital anomaly, infection, or prenatal brain lesion. All mothers completed a survey including demographic, social, and economic information. Mothers were asked to indicate whether their occupation involved frequent verbal communication with others ("Yes" or "No") as this could affect language exposure for their baby. Pregnant participants' occupations were diverse; aside from 4 university professors and 3 stay-at-home mothers, there was little overlap among participants' occupations. All participants were informed that the purpose of the study was to assess daily language and auditory exposures for their baby.

Exposure data collection

For fetal exposures, a Language ENvironment Analysis (LENA)[47,48] recorder was placed in a fabric pouch, attached to a necklace, and worn around the neck near the abdomen of the pregnant participant for a 24-hour period. All LENA devices were configured by the manufacturer to record 24 hours of audio. During sleep, the recorder was placed at the bedside. Recordings took place twice per week throughout the third trimester. Each week the participant chose 2 days to wear the recorder from a schedule that alternated weekly between Monday/Wednesday/Friday and Tuesday/Thursday/Saturday. The start time of recordings was determined by the participant, and differed across participants, but remained consistent within participant. Compliance was tracked via instant messaging. Any necessary removal of the device lasting more than 5 minutes (eg, to shower) was documented by the subject via instant message. Individual recordings were excluded from analysis if they were incomplete or if the participant did not keep the recorder on her person for at least 23 hours.

For NICU exposures, a LENA recorder was attached to the inside wall of the crib, near the infant's head. Although recordings were made inside infant incubators, only open crib recordings were used in the present analysis due to potential errors in automated labeling that would occur for sounds modified drastically by transmission through incubator walls.[49] Recordings were made 3 times per week throughout NICU stay on an alternating weekly schedule (Monday/Wednesday/Friday vs Tuesday/Thursday/Saturday). The start time of recordings was typically in the early morning, but scheduling issues sometimes necessitated starting recordings in the evenings. When the infant was removed from their crib for care, the caregiver removed the recorder and attached it to an adjacent armchair, near the infant's head. Individual recordings were excluded from analysis if the recorder did not capture a full 24 hours (ie, was accidentally stopped) or when the recorder was misplaced by the nurse or parent. Per institutional review board requirements, signage was placed throughout the NICU explaining that audio recordings were being made.

Exposure data analysis

Each recording was processed with the LENA automated classification algorithm, which segments the audio and assigns a category label to each segment, resulting in a duration for each category.[50,51] The algorithm classifies each segment of the audio as being silence or being from 1 of 7 sources: female adult, male adult, key child, other child, noise, electronic sound, or overlapping sources. Additionally, the algorithm classifies the sound as either "near" (representing sound that is near the model prediction and/or has an amplitude indicating it was produced near the recording device) or "far" (representing sound that is far from the model prediction and/or has an amplitude indicating it was not produced near the recording device).[48,52] Variables included in the present analysis are the duration of "near" segments labeled female adult (algorithm label: FAN), male adult (MAN), noise (NON), electronic sound (TVN), overlap (OLN), and silence (SIL), as well as 5 derived variables: adult language (calculated as the sum of near female adult and near male adult segments), child language (calculated as the sum of near key child [CHN] and near other child [CXN] segments), other (calculated as the sum of all the far segments from all 7 sources), total extrauterine sound exposure (sum of all near and far segments; ie, all segments except silence), and adult word count (which is calculated by the LENA software based on acoustic characteristics of the near female adult and near male adult categories). The noise variable (NON) is also referred to herein as "airborne noise" (ie, extrauterine noise) to distinguish it from biological noise and sounds to which fetuses are exposed. Mean daily exposures for each category for each subject were calculated by averaging across all recordings for that subject.

The LENA algorithm has been validated to show reasonable correlation with human raters.[48] Automated labeling of daylong recordings using LENA and other algorithms has been conducted by many groups,[16,42,53-55] but is subject to labeling error.[56,57] The following measures were undertaken to reduce the effect of labeling errors. Outlier values were initially identified for all variables of interest across all individual recordings. Following manual inspection of recordings that produced outlier values, recordings were excluded from the analysis when the outlying values were due to systematic errors in automated labeling. Daily averages were calculated for each subject by averaging across all recordings available for that subject. Following exclusion of recordings as described above, subjects were excluded from further analysis if they had less than six 24-hour recordings available for averaging, resulting in final group numbers of 27 pregnant women and 24 VPT infants. The final VPT group included 3 sets of twins.

To assess day/night patterns, we conducted a time-varying analysis of hourly adult language and total (extrauterine) sound exposure. For each subject, we first calculated the mean language exposure in minutes per hour for each hour of the day (eg, 1-2 PM, 2-3 PM, 3-4 PM, etc.) using all 24-hour recordings for that subject. A circadian exposure index was then calculated for each subject as follows. The 16-hour window containing the greatest amount of language exposure was determined for each subject. The index was calculated as the ratio of exposure amount occurring during the 16-hour window to the total amount of exposure over 24 hours. A value of 1.0 indicates all exposure came during a single 16-hour window, whereas a value of 0.67 indicates no pattern of exposure associated with any 16-hour window. For data visualization, we also calculated a grand average 24-hour exposure cycle for each group by averaging mean hourly exposures across subjects. This procedure was repeated for total sound exposure.

Statistical analyses

Between-group differences were assessed using multilevel linear regression, with a random intercept at level 2 for the nesting of twins. Separate multilevel linear regression models, adjusting for group, were used to assess the effects of infant sex, maternal education, and mother's occupation. The effect of speaker gender was tested using a linear mixed-effects model with a fixed factor of group and a random factor of talker gender. All analyses were conducted in R.[58]

Results

Over 23 000 hours of auditory exposure data were collected. For the fetal group, the mean duration of study participation was approximately 12 weeks (range: 6.5-15 weeks), resulting in an average of 24 days (576 hours) of exposure data per subject. Postmenstrual age (PMA) during data collection ranged from 22 weeks to 41 weeks PMA across fetal participants. For the VPT group, the mean duration of study participation was approximately 5 weeks (range: 2-10.7 weeks), resulting in an average of 13.4 days (321.6 hours) per subject. PMA during data collection ranged from 26 weeks to 44 weeks PMA across VPT participants. **Table II** shows group characteristics.

VPT infants differed from fetuses in daily exposures for several categories of sound (**Figures 1** and **2**, **Table II**). VPT infants received an estimated 0.53 hour/day (SD: ±0.2 hour/day) of exposure to adult language, nearly 5 times less than the 2.6 (±0.6) hour/day estimated for fetuses ($F (1.49) = 245.3$, $P < .001$). These exposures resulted in adult word count estimates of 7108 (±3091) words/day for VPT infants and 36 679 (±8873) words/day for fetuses. There was a main effect of speaker gender, with greater exposure to female adult language than male adult language ($F (1.49) = 131.4$, $P < .001$), and a significant interaction between speaker gender and group ($F (1.49) = 24.1$, $P < .001$). For fetuses, 69% (1.8 hour/day) of adult language exposure was female, whereas 88% (28 minutes/day) of adult language exposure was female for VPT infants. VPT infants received only 4 minutes/day of exposure to male speech, while fetuses received 12 times this exposure (48 minutes/day).

VPT infants had more exposure to electronic sounds (5.1 ± 2.5 vs 1.3 ± 0.6 hour/day; $F (1.49) = 56.9$, $P < .001$) and airborne noise (4.4 ± 2.1 vs 2.9 ± 2.8 hour/day; $F (1.49) = 4.6$, $P < .05$) than fetuses. Manual inspection revealed that NICU exposures that were classified as electronic sounds consisted largely of alarms from monitors and other medical equipment in the NICU. Finally, whereas fetuses never experience silence, owing to the presence of mother's heartbeat or other biological sounds *in utero*, VPT infants spent an estimated 4.7 (±3.9) hours/day in silence (**Figure 2**).

We observed substantial within-group variability in daily averages for both groups (**Figure 1**). For example, fetuses ranged between 1.3 and 3.8 hours/day of exposure to adult language—

Table II. Group comparisons

	VPT infants	Fetuses	*P*-value
Participant characteristics			
N	24	27	
Male, %	50%	56%	>.99
Singleton, %	71%	96%	.04
Birth gestational age, wk	28.6 ± 1.8	38.9 ± 1.6	<.001
Birth weight, g (N)	1227 ± 410	3393 ± 472 (26)	<.001
Length of NICU stay, d	80.5 ± 41.4	–	
Race, %			.54
White non-Hispanic	92%	74%	
Black non-Hispanic	4%	7%	
Hispanic	0%	0%	
Multiracial/other	4%	19%	
Maternal age, y	29 ± 5	31 ± 3	.03
Maternal marital status, married, %	54%	100%	.02
Maternal education, %			<.001
Some high school	13%	0%	
High school degree	17%	0%	
Some college	29%	0%	
Associate's degree	13%	4%	
Bachelor's degree	13%	30%	
Graduate degree	17%	67%	
Maternal occupation requires frequent communication, %	88%	89%	.75
Average daily exposures			
Adult language, h	0.53 ± 0.2	2.6 ± 0.6	<.001
Female adult language, h	0.46 ± 0.2	1.8 ± 0.5	<.001
Male adult language, h	0.07 ± 0.04	0.79 ± 0.3	<.001
Adult word count, words	7108 ± 3091	36 679 ± 8873	<.001
Electronic sound, h	5.1 ± 2.5	1.3 ± 0.6	<.001
Airborne noise, h	4.4 ± 2.1	2.9 ± 2.8	.04

NICU, neonatal intensive care unit; *VPT*, Very preterm.

a factor of nearly 3—while VPT infants ranged between 0.28 and 1.3 hour/day—a factor of approximately 4.6. After adjusting for group, maternal education did not predict adult language exposure ($P = .59$), nor did infant/fetus sex ($P = 41$). However, a maternal occupation involving frequent communication with others was associated with greater language exposure after adjusting for group ($P < .05$). For the fetal group, number of family members in the home was positively associated with exposure to child language ($P < .005$), but not adult language ($P = .54$).

Whereas language and total extrauterine sound exposure cycles for fetuses showed the expected marked day/night pattern, with low exposure during nighttime hours, VPT infants showed less change across the 24-hour cycle

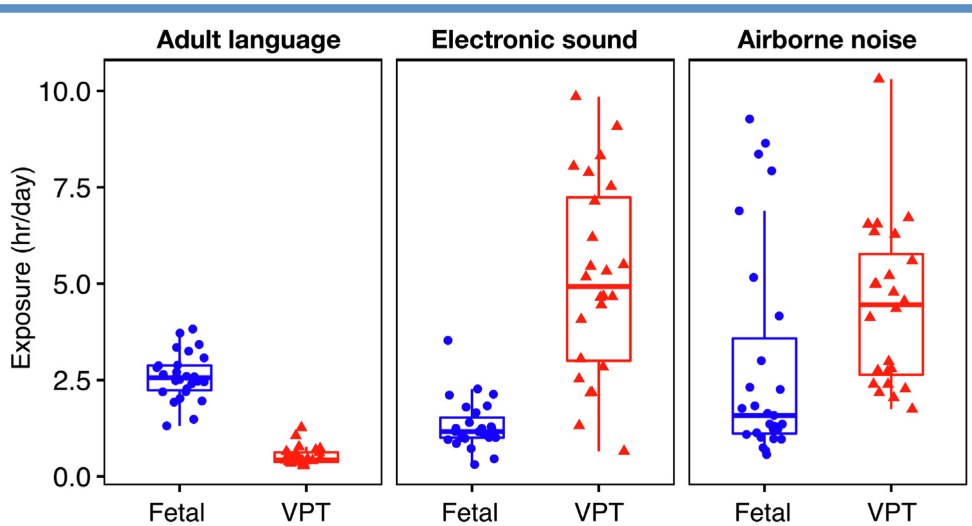

Figure 1. Daily auditory exposures for fetuses (*blue*) and VPT infants (*red*). Values for fetuses represent extrauterine exposures. Each data point represents a daily average for 1 participant. Some pregnant women reported using noise machines to sleep at night, which contributed to the high noise exposure for some fetuses.

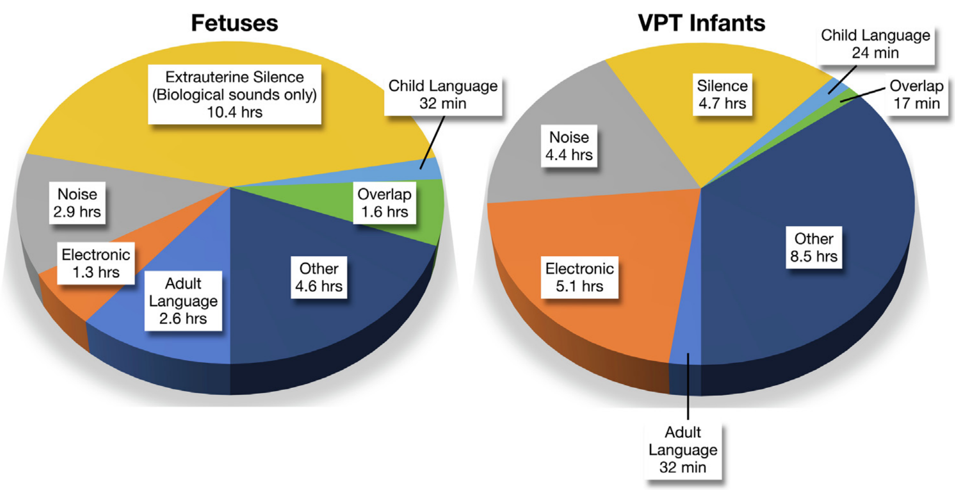

Figure 2. Mean daily auditory exposures for fetuses and VPT infants.

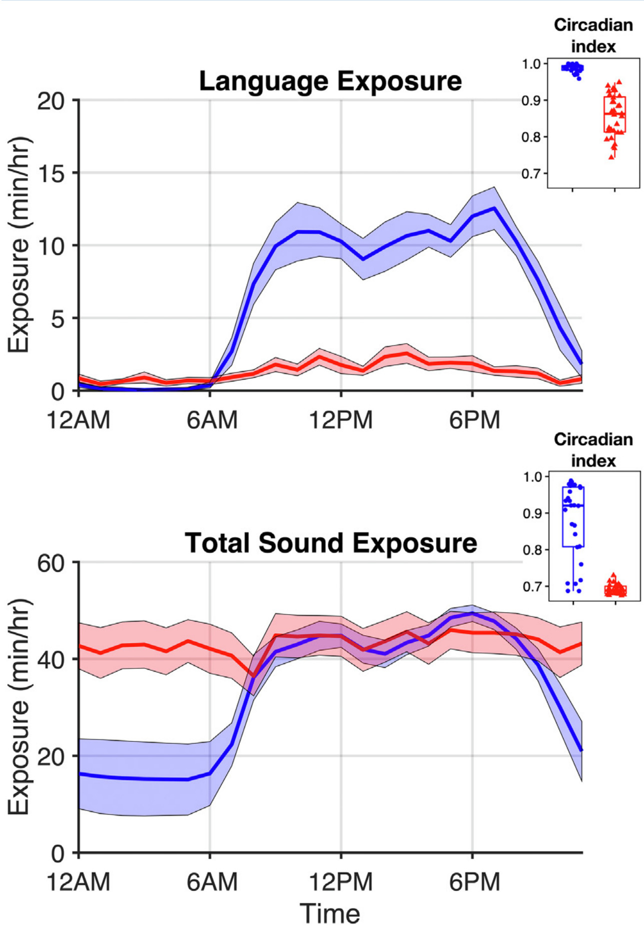

Figure 3. Grand average 24-hour exposure cycle for language and all extrauterine sound for fetuses (*blue*) and VPT infants (*red*). Circadian exposure indices are shown as insets. Shading represents 95% CI.

(**Figure 3**). Mean circadian exposure indices for VPT infants were less than those for fetuses for language (0.86 ± 0.06 vs 0.99 ± 0.01, F (1.56) = 131.1, $P < .001$) and total sound exposure (0.69 ± 0.01 vs 0.88 ± 0.1, F (1.56) = 98.2, $P < .001$).

Discussion

Our data indicate VPT infants may receive nearly 5 times less language exposure than fetuses. It is important to consider this difference over the course of the prenatal/preterm period. For example, 32 minutes/day of language for a VPT infant born at 24 weeks' gestation with an 11-week NICU stay results in approximately 41 total hours of language exposure. In contrast, exposure of 2.6 hours/day for a fetus results in approximately 200 hours of exposure over 11 weeks. Given previously demonstrated effects of prenatal language exposure on neurobehavioral outcomes, a potential deficit of over 150 hours of language is alarming. Additionally, as survival rates for infants born prior to 24 weeks of gestation continue to increase, the change in patient population may lead to increases in NICU length of stay that could introduce even greater deficits in exposures.

The primary source of language exposure was female adult speech, which was expected; however, the ratio of female adult speech to male adult speech differed between fetuses and VPT infants. The stark differences in female, male, and total adult language exposure may shed some light on language developmental delays and deficits that are widely reported for VPT infants.[27-29] Additionally, maternal occupation, specifically the mother's reported occupation-related communication habits, affected language exposure for her baby. The variability of language exposure durations for fetuses is striking and is worthy of further investigation to determine whether it is related to neurobehavioral outcomes later in life.

For VPT infants, intrauterine language exposure is traded for increased electronic sound and airborne noise exposure. The dominant sound sources for these exposures are essential life-saving medical equipment and other NICU machinery that produce mechanical noise and/or electronic alarms.[59] VPT infants also spend long periods in silence, a condition that never occurs *in utero*. It is possible that activity-dependent maturation of the auditory circuitry that occurs during early developmental stages[60] could be disrupted by this premature introduction to periods of silence, similar to how brief periods of hearing loss during early development result in abnormal neurodevelopment.[61,62]

Although visual (light/dark) day/night cycles have been studied in the NICU and have been shown to affect outcomes,[63-65] acoustic day/night cycles and their effects on NICU infants have not been examined. Language exposure for VPT infants followed a day/night pattern, but this pattern was diminished relative to fetuses. Total sound exposure for VPT infants showed no discernible day/night pattern. The differences in day/night-patterned exposures between VPT infants and fetuses are notable because, unlike fetuses, VPT infants no longer have access to maternal hormonal signals important for the fetal brain to develop a circadian rhythm during the third trimester of gestation.[66] In the absence of these signals, environmental stimuli such as light and sound are potentially useful compensatory sensory cues for entrainment to a circadian rhythm.[65]

One consideration in interpreting our data is whether fetuses have access to extrauterine language exposures we captured. Intrauterine recordings using animal models indicate extrauterine speech at conversational sound levels exceeds the endogenous noise floor and is available to the fetus.[8] A common misconception is that the intrauterine environment is devoid of any extrauterine high-frequency sounds (eg, some consonants) due to substantial high-frequency attenuation across the abdominal walls. To the contrary, human fetuses exhibit motor responses to extrauterine sounds at 3 kHz[4] and 5 kHz,[67] at least at later gestational ages. Both animal and synthetic models suggest that attenuation at high frequencies is not much greater than that for lower frequencies, with some higher frequencies attenuated very little.[68] Given these findings, by restricting the present analysis to language and sounds classified as "near and clear,"[52] the most reasonable assumption is that fetuses have access to the exposures we have reported.

A recent trend in hospitals worldwide is to reconstruct open layout, multibed NICU designs into private, single-patient rooms.[69] A consequence of this redesign is a substantial change to auditory input for NICU patients, with increased amounts of silence and decreased amounts of language, relative to the open layout.[15] We have demonstrated here an already marked reduction in language exposure for an open layout, multibed NICU. It has been proposed that reducing language and auditory exposures further with such reconstruction could lead to auditory deprivation, with consequences for the developing brain.[69] There would also likely be changes to day/night patterns of exposures for single-patient rooms compared to what we have measured here. Furthermore, the present data represent NICU infants in open cribs. Due to the attenuation of sound by NICU incubators,[49] it is possible that exposures will be further disrupted inside NICU incubators. However, to what extent neurodevelopmental and language deficits observed for preterm infants can be explained by abnormal auditory exposures, and whether differential effects of auditory input vs other biological and medical factors can be disentangled remain open and challenging questions.

Another factor that warrants further study is whether the intrauterine environment ought to be considered the optimal target for VPT infant auditory exposures. It is possible that the full-term newborn's postnatal (eg, in-home) auditory experience is a more suitable target.[45] For example, similar to full-term newborns, VPT newborns have an airborne acoustic pathway that does not alter sound characteristics like the fluid-filled intrauterine pathway. The presence of a newborn infant could lead to increased infant-directed speech—a distinctive type of vocalization thought to facilitate infant language acquisition.[70] However, full-term newborn brains differ substantially from VPT newborn brains due to the rapid maturation that occurs during the third trimester.[71,72] Given the dependence on extrinsic sensory activity to establish neural circuitry during development, it is likely that the VPT newborn brain lacks sufficiently mature basic auditory neural circuits to capitalize on potential benefits conferred by increased infant-directed speech or the aero-acoustic pathway. Thus, we speculate here that typical auditory exposures during the PMA-equivalent stage of neurodevelopment are the optimal inputs for VPT infants prior to full term.

This study was subject to limitations. First, the pregnant group had higher education level than the group of VPT mothers, which could have influenced language exposure for fetuses. The presence of twins in the NICU may have influenced results because; for example, nearby exposure to the mother's voice may have been reduced if the mother spent time separately with each infant. Our sample size was small and there may be limited generalizability of our findings. Additionally, because we discontinued data collection when the COVID-19 pandemic began, we cannot report on how the pandemic may have affected exposures for both populations. Although we did retain a hand-written NICU visitation log, several NICU participants were not compliant in completing the log, so it is uncertain how parental presence affected language exposure in our VPT data. It is also unknown whether adults' talking was directed toward the baby, another adult, or on the phone. Although we found an association between language exposure and mother's subjective response of whether her occupation required frequent talking, the subjective question may have been interpreted differently across participants. Finally, although intrauterine exposure appears to be important for brain development, it represents only a component of the language environment of the first 5 years of life important for brain and language development.

Our findings provide quantitative characterization of auditory exposures for typically-developing fetuses compared to NICU infants. As such, these data provide meaningful targets for interventions designed to optimize auditory exposures in NICU settings. Such efforts have included training programs for caregivers to increase language use while near infants,[73] reading programs,[74,75] playback of mother's voice recordings to the infant,[46] and noise reduction programs.[76-78] Our data offer additional insights for the development of future interventions. For example, if the intrauterine environment is taken as the optimal target for auditory exposures, a wholistic intervention would focus on replacing sounds that are overrepresented in the NICU (ie, noise, electronic sounds, silence) with sounds that are underrepresented (ie, language and biological sounds). ■

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