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# Assessment of Noise Exposure to Children: Considerations for the National Children's Study

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### Abstract

Evidence has been accruing to indicate that young children are vulnerable to noise in their physical environment. A literature review identified that, in addition to hearing loss, noise exposure is associated with negative birth outcomes, reduced cognitive function, inability to concentrate, increased psychosocial activation, nervousness, feeling of helplessness, and increased blood pressure in children. While increasing attention has been given to the health effects of noise in children, research about noise exposure is sparse and often the measure of exposure is simply proximity to a noise source. The U.S. National Children's Study (NCS) provides a unique opportunity to investigate noise exposures to pregnant women and children using a number of assessment modalities at different life stages. Measurement of noise levels in homes and other environments, personal dosimetry measurements made over a period of days, and questionnaires addressing sources of noise in the environment, annoyance to noise, perceived noise level, use of head phones and ear buds, noisy activity exposures, and occupational exposures, are planned for evaluation within the NCS Vanguard pilot study. We describe the NCS planned approach to addressing noise exposure assessment in study visits over a child's lifetime.

**Keywords:** Birth cohort; Noise; Children; Exposure assessment; National Children's Study

### Background

The National Children's Study (NCS) is a longitudinal, prospective cohort study to examine effects of the environment, broadly defined to include the biological, chemical, physical and psychosocial cultural environments, as they interact with genetic potential to impact growth, development, and health of children across the United States. Participants will be followed from before birth to 21 years of age. The goal of the Study is to improve the health and well-being of children by contributing to the understanding of the influence of multiple factors, both negative and positive, on health and disease (see nationalchildrensstudy.gov). While the NCS Main Study is still under development, an extensive and ongoing pilot phase, known as the Vanguard Study, began field work in January 2009 and has enrolled over 5000 participants. The goals of the Vanguard Study are to assess the feasibility, acceptability and cost of recruitment and retention, study visit data collection, and logistics. The Vanguard Study will continue for the next two decades as a separate study linked to and informing the Main Study.

Evidence has been accruing for over 30 years to indicate that young children are vulnerable to noise in their physical environment. Noise exposure has been associated with a number of adverse health effects, manifesting in the form of physiologic damage or psychological harm through a variety of mechanisms [1]. While increasing attention has been given to health effects of noise in children, research about noise exposure is sparse and often the measure of exposure is simply proximity to a noise source [2]. Noise exposures encountered by children include involuntary (environmental) and voluntary (school activities, listening to loud music) sources. Environmental noise includes transient noise intrusions from outdoors, such as airplanes, railways, motor vehicles, construction, industrial, or outdoor events, as well as indoor sources, such as television, music, appliances, and ventilation equipment. Some noise can arise from either outdoors or indoors, such as sounds made by neighbors, talk, laughter, slamming doors, and noise from barking dogs [3]. Internationally, urbanization, growing demand for motorized transport, and inefficient city planning and zoning are the main driving forces for increasing environmental noise exposure [4].

### Auditory Health Effects of Noise in Children

Chronic, elevated noise exposure [above 70 to 80 decibels, A-weighted (dBA) for 8 hours or more per day] can cause auditory effects including permanent hearing threshold shift and loss of hearing in specific frequency ranges. Almost 30 million adults [5] and 5.2 million children [6] in the US suffer from irreversible noise-induced hearing impairment and more than 20 million are exposed to dangerous levels of noise each day [7]. In studies of noise and children, the assumption is that hearing damage occurs at the same sound levels

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as in adults. However, no studies were identified which support this assumption.

The focus of recent auditory effects studies in children has been on voluntary exposures. Listening to loudly amplified music or video (personal electronic devices, playing electric or traditional musical instruments, concerts, etc.) can cause hearing damage of the same nature as caused by industrial noise. In studies of university students in music programs, 76% of UK subjects reported symptoms associated with hearing loss at mean exposures exceeding 98 dB equivalent continuous A-weighted sound pressure level (LA<sub>EQ</sub>) [8] and noise-induced hearing loss was identified in 45% of U.S. subjects [9]. In a study of UK students working in university entertainment establishments, mean exposures exceeded 90 dBA; although temporary threshold shifts associated with this exposure were moderate, 29% of subjects showed a permanent hearing loss of more than 30 dB [10]. Levey et al. [11] found 58% of New York College students were exposed above 85 dB LA<sub>EQ</sub> from listening to music.

There is special concern among hearing specialists about the effects of personal electronic devices (cell phones, MP3 players, tablets, etc.). Numerous studies have looked at the impact of the use of personal devices on teenagers and college students [11-13]. In 2006, 82% of U.S. high school students reported using a cell phone and 62% reported using another personal electronic device [14]. Since 2006, the use of these devices is likely increasingly more common.

The risk of hearing loss from any source of noise, including amplified music, is always a function of exposure intensity (volume) and duration. Hearing damage from headphones and ear buds is probably more common than from loudspeakers, because many people/children exploit the acoustic isolation by listening at higher volumes [13,15]. Moreover, the risk of hearing damage from headphones (or ear buds) may be higher than with loudspeakers due to the close coupling of the transducers to the ears and therefore higher levels at the tympanic membrane. Susceptible adults may sustain hearing ear damage if exposed to noise above 75 decibels (dB) for 8 hours or more per day [16]. In a study of noise exposure from portable stereos, listeners in a quiet laboratory setting were comfortable with headphones set at an average volume of 69 dB, but once outside where the mean noise level was 65 dB, the average volume went up to 82 dB, with some levels as high as 95 dB [15]. The study concluded that "some hearing loss risk would be expected when portable stereos are used in noisy conditions." Others have reported volumes of 115 dBA with ear buds [17].

A study of 1512 Dutch adolescents (age 12-19) showed that about half of the subjects were exposed above occupational noise exposure limits, about a third due solely to listening to MP3 players [18]. Some studies have reported differences in use of personal music devices, with Latino or Hispanic and Black or African/American students reporting longer duration of use than other racial groups [14,19]. United States (U.S.) males have generally reported louder use than females [19], but the prevalence of personal listening device use is increasing among U.S. females age 12-19 – from 19.8% in 1990 era to 34.8% in 2010 era [20].

High school students are more likely to turn the volume of personal devices to loud than adults [14].

### Non-auditory Health Effects in Children

While the most widely recognized health outcome of exposure to loud noise is hearing loss, outcomes arising from exposure to lower noise levels may include hypertension, tachycardia, myocardial infarction, and increased cortisol release and physiologic stress [1,21]. Stress can trigger production of certain hormones which may lead to a variety of intermediate effects, including increased blood pressure and hypertension [22,23]. Ambient noise is also reported to have disruptive effects on human sleep, although the few studies conducted have large differences in quality [3].

Chronic maternal exposure to airport noise during pregnancy has been shown to result in vasoconstriction which subsequently leads to decreased utero-placental blood flow, and possibly increased fetal hypoxia [24]. The stress of chronic elevated noise can lead to increased maternal blood pressure, greater secretion of maternal epinephrine and norepinephrine, and decreased human placental lactogen [24,25]. Exposure of pregnant women to airplane noise has been associated with a decrease in body weight of newborn babies; and the height of 3-year-old children was shown to be significantly decreased with higher noise levels [25]. Human fetal exposure to noise has been linked with decreased birth weight and length, and increased incidence of birth defects, specifically cleft lip, cleft palate, anencephaly and spinal bifida [24,26,27].

Elevated noise levels in neonatal intensive care units (NICUs) have received considerable attention. Technology to care for newborns has transformed NICUs into very noisy places. In a study of the acoustic environment in several mid-Atlantic region NICUs, the hourly mean sound levels ranged from 53.9 dBA to 60.6 dBA, well above the American Academy of Pediatrics (AAP) recommended 45 dBA mean level [28]. Nogueira et al. [29] pointed out issues with noise measurement in NICUs, including placement of the microphone in the incubator, continuous low frequency noise such as the incubator's motor, and intermittent middle frequency (human voice) and high frequency (alarms of equipment, telephones) noise. Situations such as opening and closing the hatches or the intensive care doors, moving the mattress tray, or putting objects on the dome may produce noise that varies from 78 to 93 dBA, exceeding the AAP-recommended impulse noise maximum of 65 dBA. Such noise can affect newborns, increasing their heart rate and respiratory frequency, dropping their oxygen saturation, diminishing the duration of their sleep state and hindering their ability to stay in a deep sleep state, and also causing alterations in their motor activity [29,30].

A large number of studies have looked at annoyance from noise and health effects among people living near an airport or highway. In one study, people living near a large metropolitan airport were exposed to noise levels as much as four times greater than those experienced by residents in a quiet, comparison home [31]. More than 55% of people living within the flight path were bothered by aircraft noise, and 63% by highway noise; these were significantly higher percentages than for residents in the non-flight area [31]. A study of 2,844 children age 9-11 around European airports examined annoyance and children's health and cognition [32]. In the Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health (RANCH) study, London air traffic noise was related to sleep disturbance and cognitive performance, in particular with respect to episodic memory [33,34]. In the Munich Study, 330 children were followed before and after a switchover of airports, with similar findings as the RANCH study [33].

Increasing attention has been given to non-auditory health effects of noise in children including reduced cognitive function, inability to concentrate, increased psychosocial activation, nervousness, and helplessness [23,26,35]. Living in crowded and noisy environments is associated with health risks for children including an increase in stress [36]. Studies of aircraft noise indicate a small but positive relationship between aircraft noise exposure and blood pressure in children, and studies on road-traffic noise show a stronger positive relationship with systolic blood pressure in children [37].

The effect of noise on performance in classrooms has been studied. A significant negative relationship has been found between noise levels and learning attainment, cognitive processing, reading, and to a lesser extent, numeracy tasks [38]. Noise has also been found to negatively affect other performance-related aspects such as attention, concentration, and memory. Irrelevant speech has been shown to have a profound detrimental effect on children's literacy tasks. In open plan schools, speech from adjacent teaching areas has been cited as the most common cause of disturbance; perceived by both teachers and pupils as a problem [38]. Irrelevant meaningful speech has been shown to be a distracting source of noise, and open plan schools are particularly vulnerable to this effect. Surveys of noise in classrooms have shown that noise levels depends on the classroom activity; typical mean levels for primary schools are 44 dBA when pupils are silent, 56 dBA when pupils are engaged in quiet activities, 65 dBA for individual work (for example, working at tables where some talking is allowed), and 70-77 dBA for group work. For comparison purposes, a 35 dBA one-hour average background noise levels has been recommended for unoccupied classrooms [39].

### **Environmental Noise Level Programs and Standards**

Public health standards for noise exist but may not be completely protective against all noise-related health effects, especially to children. In the U.S., the focus of government standards has been on auditory damage and annoyance. Under the Noise Control Act of 1972 and the Quiet Communities Act of 1978, the U.S. Environmental Protection Agency (EPA) provided a basis to state and local governments in setting environmental noise standards [40] as a 24-hour exposure level of 70 dBA to prevent any measurable hearing loss over a lifetime. Standards of 55 dBA outdoors where human activity takes place, and 45 dBA for indoor residential areas, hospitals and schools, were established to prevent activity interference and annoyance. In 1982, primary responsibility for noise control and enforcement was shifted to state and local governments, which generally adhere to these guidelines, but which in most cases have not actively attempted to address or reduce the public health hazard associated with noise.

The U.S. Federal Highway Administration (FHWA) policy on highway traffic noise and construction noise provides guidance to states in implementing the FHWA Noise Standard (23 CFR Part 772, Appendix A) that reflects state-specific attitudes and objectives in approaching the problem [41]. FHWA recognizes three approaches to reducing noise from highway traffic: source control, mitigation measures associated with road project and operation design, and noise-compatible land-use planning, promoting the latter to attain in-home noise levels from 40 to 45 dBA [42]. In addition, most states have banned the use of car horns for any purpose other than to express warning. New York City has further banned operation, sale, and installation of audible car alarms.

The Guidelines for European Union Noise [43] acknowledge effects of environmental noise, including annoyance, as a serious health problem. In 2002, the European Parliament and the Council adopted the Environmental Noise Directive, which requires Member States to: (1) determine exposure to environmental noise through noise mapping, (2) adopt action plans based upon mapping results, and (3) ensure that information on environmental noise is made available to the public. European Union (EU) Member States are required to use specified noise indicators of a day-evening-night noise indicator (L<sub>DEN</sub>) and L<sub>Nieht</sub> and report the noise exposure of the population of 55 dBA and 50 dBA or more, respectively. The first round of noise mapping suggests that around 40 million people across the EU are exposed to noise above 50 dB from roads within agglomerations during the night, and more than 25 million people are exposed at the same level from major roads outside agglomerations. These numbers are expected to be revised upwards as more noise maps are received [4]. It is important to note that roads also represent only one source of community noise; noise from ports, rail traffic, and construction and industrial sources may add substantially to these estimates of overexposure.

The current EU reporting, which focuses on annoyance, neglects the fact that a considerable fraction of the EU population is exposed to noise pollution at levels which are likely to cause other harmful effects on health. The World Health Organization (WHO) and the Joint Research Centre of the Commission (2011) now propose a guide value for night-time levels as low as 40 dB, L<sub>Night</sub>, outdoors [4].

# Exposure Measurement, Assessment Methods, Research Needs and Challenges

There are a number of considerations to be made in developing an approach (es) to measure and evaluate noise exposures over various

stages of a child's life in the NCS. Measurement methods must be reliable, reproducible, and scalable to the large number of study participants. Deployment must be efficient and economical with minimal burden to technicians and participants. Methods must be affordable in terms of the cost of the device, calibration and maintenance requirements, and data capture and transmission capability. Data capture must be of high quality with results that can be related to participant activities, events, or location.

### **Characterization of Current Noise Exposures**

In general, environmental noise exposure assessment has been limited to point activities, such as construction, traffic from a given road or airport, or a noisy commercial establishment in affected localities. There has been little attempt to assess and characterize environmental noise levels across the country. Even where such information might exist, changes in traffic volume and flow, use of traffic noise barriers, housing construction methods, ventilation technologies, aircraft flyover routes, and neighborhood composition and other characteristics serve to alter exposures over time and space. In addition, noise standards usually focus on outdoor levels at property boundaries, and thus noise levels in homes and non-occupational environments are largely unknown and uncharacterized.

Studies of non-auditory health effects have not typically measured sound levels directly; rather exposure is often defined as a crude proximity to a point source (e.g., "near airports or high traffic areas"). When measurements have been made, they are most often done using a sound level meter in an outdoor location, e.g., at the property boundary when assessing traffic and airplane noise, or positioned in a single location in a *neonatal intensive care unit* (NICU) or classroom. They have also often been made using equipment with inappropriate thresholds, i.e., they do not include sound levels below a certain value, typically 70 dBA. However, in one study, noise levels in "quiet" homes away from an airport averaged 38.5 dBA [31] and even among adolescents living in farm and rural homes, the lower mean daily noise exposure was 55.4 dBA [44]. Further characterization of exposures in the home and many environments where pregnant women and children spend time has not been investigated.

### **Exposure Assessment Tools**

Assessment methodology and standards for noise exposure related to hearing loss in work environments is well established. However, for assessments of the general population, and children in particular, whose noise levels are lower and more varied, methodologies are less well specified [45]. Both qualitative and quantitative assessment tools have been used.

Qualitative measures have included proximity to a noise source and the respondent's subjective reporting via questionnaire of home noisiness. Kawada [25] notes that from the point of view of disturbance of daily living, subjective recognition of "noisiness" or annoyance is an important issue. A number of questionnaires for subject reporting of home noisiness have been used. The International Commission on the Biological Effects of Noise (ICBEN) systematically created high-quality survey questions that would yield internationally comparable measures of overall reactions to noise sources [46,47]. However, these have not been tested specifically in homes with pregnant mothers or children.

Three instruments are typically used to measure noise levels: the sound level meter (SLM), the octave-band analyzer (OBA), and the noise dosimeter [48] (Table 1). Such instruments are generally expensive, ranging from \$300-5000, depending on the model and desired capabilities. Additional equipment such as calibrators,

Device	Measurements	Advantages/Disadvantages	
Sound level meter (SLM)	Basic hand-held measuring instrument, consisting of a microphone, a frequency selective amplifier, and an indicator. Measures sound level in decibels (dB) of sound pressure level (SPL). Responses are modified with frequency-weighting networks. The A-scale, which approximates the human ear's response to moderate-level sounds, is commonly used in measuring noise.	Relatively simple to use when noise levels are continuous and the participant remains essentially stationary during the sampling period. Where quantitative measurements have been made in a home of road and air traffic noise, SLMs have been utilized [31]. For the NCS, SLMs would be useful to get an instantaneous or integrated measurement while study staff is at the home or other location. SLMs are relatively expensive to be left in a participant's home (\$1500-3000) and cannot be worn by the participant for measurement over time/space.	
Octave-band analyzer (OBA)	In addition to measuring sound level, divides noise into its frequency components. The human ear is most sensitive around 4000 Hz and least sensitive in the low frequencies. Discrete pure tones, both very high and very low frequency can be audibly disturbing to some people [57].	OBAs are more expensive than SLMs, and as SLMs often include OBA features OBAs are not considered particularly useful for ongoing data collection in the NCS	
Noise dosimeter	Small (about 3 in x 2 in), typically worn by the participant. Measure sound levels, configured to determine personal noise dose during the sampling period.	Dosimeters are preferred when noise levels are varying or intermittent over time; contain impulsive components, or the participant moves around frequently. Can be used to measure ambient or personal noise exposures.	
	Typically designed to accurately measure dose in the occupationally regulated range of 70 to 130 dB, although a few models capture noise levels as low as 40 dB.	Relatively expensive to be left with participant over extended time period. Use of dosimeters on young children will require testing and perhaps development of a wrist-mounted option.	
Noise application	Can be loaded onto a phone or tablet.	Unknown how well these perform as compared to more sophisticated instrumentation. There are potential battery life issues. Software changes to phones which are common can change the characteristics of application. Cost of application is very inexpensive (free to \$30). The cost of the device on	
		which the app is loaded increases the overall cost (\$400-1200).	

Table 1: Summary of noise assessment instrumentation

protective cases, etc. adds to the overall cost. There can also be a large amount of data to store and analyze when datalogging measurements are made over long time periods on many participants.

Several researchers are working to add noise monitoring capability to portable real time air monitoring stations that measure a number of air contaminants simultaneously over time. One has placed an electret microphone in their monitor to record peak dBA (Weisel, C.P, personal communication, July 22, 2013). Another has proposed a study to develop, fabricate, and field test a sound measurement system for use in home environments, ideally connecting this to their remote sensing real time air monitor (Dearborn, D.G., personal communication, March 22, 2012). These instruments may lack portability required for averaging noise exposures over many locations and also must address how internal noise from the air monitor pump will be corrected, especially if the microphone is built into the monitor.

While the term 'noise' commonly connotes loudness, perhaps of even more interest is 'sound clutter,' the mixture of sound character regardless of amplitude. The question is how specific sounds (e.g., parental yelling), or combination of sounds, impact the cognitive neurodevelopment of the young child. Technically this would require a time/frequency characterization of the 'noise' in the context of both time domain and frequency domain patterns. Often times, spectral content from various sources of sound overlap and it is difficult to separate them with frequency deconvolution alone. One approach is to develop a baseline for the home so as to identify and categorize the various sources of sound both individually and collectively. Background, outside sounds would be contrasted with indoor sounds which would include electronic (TV, radio) sources and voices (child vs parent vs siblings, etc). Collection of such data presents a significant analytical and sound characterization challenge.

A new category of noise measurement devices are computer applications (apps) that can be installed on a smartphone or other portable device and are inexpensive (free to \$30). The built-in microphones in portable devices exhibit a remarkably flat frequency response, making them suitable for basic sound level measurements. Given that cell phones are ubiquitous and their use among younger children is on the rise, there is great potential for participants to do their own data collection in their varied listening environments. However, there are a number of issues to address before they may be used in a study such as the NCS. Such apps have generally not been tested against more sophisticated instruments, but a few technical limitations anticipated with the available phone apps and devices include restricted frequency ranges and inability to quantify very loud (100 + dBA) and very quiet sounds (below 20-30 dBA). If noise levels are measured on a continual basis over a long period, the phone battery may discharge quickly, requiring either additional batteries or external power. In addition, smartphone technology poses a number of study operational challenges such as the feasibility, acceptability and cost of deployment of the device to participants, and ensuring compliance with study protocols. Data collection and transmission requirements, storage and transmission of potentially large data files, and data security must all be considered, especially in light of participant privacy issues. Some of these issues are being investigated, e.g., Kardous and Shaw [49] have recently shown reasonably good measurement accuracy of selected apps for use in occupational noise measurements.

Regardless of the specific instrumentation employed, the result of noise measurements made on children will be a set of instantaneous or short-term (e.g., measured over periods of hours to weeks) sound pressure levels (in dBA) associated with individual children, locations frequented by those children, and/or specific activities conducted by those children. Basic analysis of these levels will provide descriptive information about noise levels routinely encountered by U.S. children in a variety of settings, and can be used to identify exposures which feature excessive noise levels or substantial temporal variability. This descriptive analysis, while basic, will contribute to our understanding of the details of children's noise exposures. However, the true potential in the development of a large dataset of noise exposure measurements on children lies in the use of statistical modeling to extend these data to unmonitored children and locations. This approach requires determining or assigning an exposure for a given location or activity and then applying that exposure for the duration of the time the participant spends in that location or activity. When combined with information about the duration and frequency of activities and locations for an individual child, noise exposure measurement data allow for the statistical prediction of expected activity- and location-specific and total (e.g., summed across all activities and locations) exposure levels. The validity of these predicted levels can then be assessed to determine the accuracy of the prediction model. Whether the information required for such modeling can be easily obtained and applied to the NCS cohort is unknown, but this exposure assessment tool allows for at least the possibility of modeling of total noise exposures for the entire NCS cohort in a highly efficient and validated manner. Such an approach has been used to estimate overall noise exposures for a diverse sample of adults in New York City [50,51] and to predict expected hearing loss for this sample [52] using a widely-accepted mathematical model [53] developed specifically for the estimation of noise-induced hearing loss expected from a range of noise exposure durations and intensities.

## Noise Exposure Assessment Approach being Considered for the NCS

Based on the current state of knowledge, additional information is needed before selecting economical noise exposure assessment methodologies appropriate to the NCS needs. In particular, noise in the home and other public environments has not been well characterized, but it is known to be generally lower (though potentially more variable over time) than in workplaces. Initial testing of available devices in the home and other environments, and development of sampling procedures to evaluate the location and duration of sampling required to obtain the desired data must be conducted to identify the most

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suitable candidate measures/device(s) and sampling procedures before noise measurements can be scaled up and conducted in the NCS Vanguard Study.

Noise assessment approaches will vary based on the life stage of the child and feature measures from different sources and in various microenvironments (Table 2). The planned approach is to use a core questionnaire(s) with supplemental modules, assess sound levels the children's indoor environments, and move to measuring full or multiday personal exposures in a systematic manner for older children.

The current Vanguard Study core questionnaire includes a number of questions regarding perceived noise levels and intensity in the home from indoor and outdoor sources based on the ICBEN recommendations [46] and others [31,54]. Core questions will be asked at periodic study visits; supplemental modules will be added as the child ages to address noisy activities (band, sports), use of personal electronic devices and headsets or ear buds, and work exposures. Subsequent pregnancies of NCS participants will allow for assessment of maternal pre-conception exposures.

Ideally, personal noise exposure to the mother during pregnancy, and to the child after birth, would be assessed as an average sound pressure level over all locations over a period of several days to a week. Measurement of personal exposure requires a dosimeter be placed on the pregnant woman or child, or a phone application carried with the woman or child, over a multi-day period. One problem with this approach is that at present it is unknown whether these devices can accurately integrate the very low noise levels expected in some locations. There is also the problem of keeping these devices with the participant. While the dosimeter (or phone) could be clipped in places other than on the child (e.g., hanging on a backpack/car seat/etc. when traveling and hung some place in the room during longer stays at home or child care), it is inevitable that the dosimeter will periodically be far from where the child is situated. A wristband-mounted dosimeter is an option, although this would need to be designed and tested.

Until personal dosimeters are further evaluated for these purposes, average and peak area noise levels will be measured in the home, and if possible, in other locations where participants spend time. Initial testing of approaches for home noise measurement is currently underway in a pilot of nine homes with young children and with different noise characteristics (near traffic, apartment building, single family home, in a rural area, etc.). Factors being investigated are: performance features and cost of measurement devices, location and duration of sampling to characterize noise in homes, data capture and transmission requirements to transmit data to the NCS Vanguard Data Repository, and acceptance of the device by participants. The results of this testing will guide the development of a protocol for testing noise in homes of the Vanguard Study cohort. The Vanguard Study data will allow systematic characterization of noise exposures in home environments and evaluate measurement devices. As children may spend a good deal of time outside of the home, in child care locations and schools where noise levels may also be elevated, area measurement of noise in these

	Study Visit Factors	Proposed Study Visit Measurements		
Life stage		Questionnaire Topics	Area measure* (multiple days)	Personal Measure* (multiple days)
Pre-conception (M)	Use subsequent participant births	Perceived noise levels by mother location	x	×
Pregnancy Fetal Stage (M, fetus)	Studies link maternal noise exposure to decreased body weight and growth (but not exposure at a specific stage in pregnancy)	Perceived noise levels by mother location	Home	M- All locations
Infant Stage (0-12 months)	Measurement focus on the home in the room most used by the child	Report of perceived noise levels by child location (include any NICU experience)	Home	M-Transit to child care/ other location with child
Toddler Stage (13-24 months)	Child may spend considerable amount of time outside of the home	Report of perceived noise levels by child location	Home	M-Transit to child care/ other location with child
Early Childhood (2-5 years)	Child likely will be spending time outside of home, more locations Child may be participating in noisy activities Child may start using personal electronic devices and other electronic media	Report of perceived noise levels by child location Report of child noisy activities (band, sports) Report of headphones/ear buds use and electronic media use	Home	C- All locations
Middle Childhood (5-11 years)	Child is likely participating in noisy activities Child is likely using personal electronic devices and other electronic media	TBD	TBD	C- All locations
Adolescence (12-21 years)	Child may be exposed to tools/equipment that can emit loud sounds (machinery, power tools, musical instruments) in different microenvironments - workplace, school, clubs, concerts Child is likely using personal electronic devices and other electronic media	TBD	TBD	C- All locations, all day C-Sound level of PED setting

M: Mother; C: Child; PED: Personal Electronic Device

Area and personal measures are quantitative measures of noise level. The particular device to be used (SLM, dosimeter or an app) is under investigation. **Table 2:** Noise exposure measures by life stage under consideration for testing in the NCS Vanguard Study locations is being considered.

As the children age, additional noise sources contribute to the child's total exposure. In particular, the increase in the use of personal electronic devices (PEDs) by young children, as well as headsets/ ear buds for other technologies, such as cell phones and computers, dictates that this source of noise be considered. As described above, PEDs have been shown to cause hearing effects, but it is unknown whether voluntary exposure to elevated sound levels is associated with health effects other than hearing effects. Addressing this source of sound will require development of specialized measures. A number of personal music device questionnaires have been developed for use in other studies, including questions on frequency and duration of device use, volume levels used, types of earphones used, typical environments in which device is worn, and specific activities related to safety while listening [8,13,19,55]. These kinds of questionnaires will be evaluated and may be used for development of a supplemental exposure module for use in the NCS.

As children in the NCS move into adolescence and get jobs, occupational noise exposures will be considered. Even in workplaces not ordinarily associated with high noise levels (restaurants, juice bars, gyms, and even some clothing stores), noise levels above allowable OSHA levels have been recorded [56]. Instruments and procedures used by others [44] will be evaluated and study tools developed to systematically collect information about the nature of the workplace and noise exposure during work.

### Conclusions

Noise is an exposure of interest in the NCS. We have described the complexities associated with estimating exposure to noise and described the various outcomes attributed to noise exposure in pregnant women, children, and adults. We have outlined here an approach to develop and test noise measurement methods along with the challenges and factors likely to be encountered. Testing the feasibility, acceptability, and cost of measurement methods in the Vanguard Study ensures the selection of a measurement modality that is scalable and sufficiently informative. Questionnaires, in-home measurements, and personal measurements (using a dosimeter or app) made over a period of days to weeks will be investigated to test instrument performance characteristics, acceptance by participants, and informative value provided by the data collected. This approach will enable us to develop appropriate procedures to measure noise in the NCS and may be useful to other large scale birth cohorts with an interest in investigating participant exposure to noise.

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