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Influences of background noise on infants and children

Lucy C. Erickson and **Rochelle S. Newman**[i]
University of Maryland, College Park

Abstract

The goal of this review is to provide a high-level, selected overview of the consequences of background noise on health, perception, cognition, and learning during early development, with a specific focus on how noise may impair speech comprehension and language learning (e.g., via masking). Although much of the existing literature has focused on adults, research shows that infants and young children are relatively disadvantaged at listening in noise. Consequently, a major goal is to consider how background noise may affect young children, who must learn and develop language in noisy environments despite being simultaneously less equipped to do so.

Key terms

background noise; effects of noise on children; noise in children's environments

Background noise is ubiquitous, and has varied and far-reaching effects in many domains, such as speech perception and learning (e.g., Miller, 1974). Noise can also serve as a stressor, causing public health concerns such as vocal strain, irritability, and difficulty sleeping. Although pervasive effects of noise on people have been documented in many areas (e.g., health: Ising & Kruppa, 2004), much remains unknown about the consequences of noise on cognition, behavior, and health, particularly in young children. Understanding how background noise affects children is important, because infants and young children spend large amounts of time in noisy environments (e.g., daycares, schools; Picard, 2004; Picard & Bradley, 2001; for reviews, see De Joy, 1983; Hétu, Truchon-Gagnon, & Bilodeau, 1990; Manlove, Frank, & Vernon-Feagans, 2001; Mills, 1975), and noise may be particularly harmful early in development. Characterizing the effects of noise will enhance our understanding both of children's development in general and the way this may vary across different living environments (e.g., rural vs. urban; affluent vs. impoverished).

TYPES OF NOISE IN CHILDREN'S ENVIRONMENTS

Throughout this paper, we use the term "noise" to refer to any unwanted or unattended sound. Multiple distinct noise types are present in children's environments, and background noise is common in many settings experienced by children, often at loud volumes (e.g., daycares, classrooms; Manlove et al., 2001; see Table 1 and Table 2 for information about some common noise sources). When listening, both target signals and background noise are

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[i] Address correspondence to Rochelle S. Newman, Department of Hearing and Speech Sciences, 0100 Lefrak Hall, University of Maryland, College Park MD 20742.

funneled down the ear canal to the eardrum together, and subsequently excite the same auditory receptors and neural pathways. This makes it difficult to separate noise and a desired sound (typically speech) into distinct representations. Noise can also “cover up” speech, resulting in an incomplete representation of the speech sound pattern, and impairing learning.

Some noises may be more likely to impact perception and learning than others. For example, intermittent or percussive noises (like sudden car horns) and noises that vary over time in frequency and volume (e.g., speech) are likely to cause greater distraction than noises that are relatively steady-state over time (e.g., HVAC systems). However, most classroom measures focus on quantifying steady-state noise sources in unoccupied classrooms rather than the potentially more problematic human-produced noises present in classrooms. As a result, such measures may underestimate the likely level of noise faced by young children.

Moreover, children growing up in different environments likely experience different amounts and types of noise (e.g., Evans, Gonnella, Marcynysyyn, Gentile, & Salpekar, 2005). For example, urban environments are likely to have more noise from traffic and other people, and poorer communities are likely to have larger school classroom sizes, resulting in noisier learning environments. Quality of housing and family size are likely to influence noise levels in the home.

EFFECTS OF NOISE ON HEALTH

One impact of noise is on health, particularly on hearing. Repeated exposure to loud sounds stemming from sources such as loud music, firearms, and machinery can lead to well-documented and sometimes permanent decrements in hearing (via damage to cochlear hair cells; e.g., Bohne & Harding, 2000). Both volume and amount of exposure play a role, such that louder, longer, and more frequently-encountered noises produce more severe effects than quieter or less frequently-encountered noises. Animal research suggests these effects may be amplified in younger individuals (for a review of effects of noise on children, see Mills, 1975). Beyond damaging hearing, noise may also impact health in multiple other ways. For example, noise may produce stress and mental health issues (e.g., Evans, Lercher, Meis, Ising, & Kofler, 2001). Teachers and students report that noise can be a substantial source of frustration (Dockrell & Shield, 2002), and teachers are particularly susceptible to vocal strain and chronic hoarseness from raising their voices to be heard (e.g., Crandell, Smaldino, & Flexer, 1999). Stress from noise may contribute to physical effects, including headaches, ulcers, and abnormal cortisol levels and blood-pressure regulation (for a review, see Ising & Kruppa, 2004). It can interfere with sleep, causing fatigue and other sleep-related health problems (e.g., Gädeke, Döring, Keller, & Vogel, 1969; Miller, 1974). Noise may further contribute to social isolation in multiple groups; for example, children with autism often exhibit heightened noise sensitivity (Dunn, Myles, & Orr, 2002) and avoid noisy situations, and older adults with poor hearing or dementia may likewise retreat from difficult listening environments.

EFFECTS OF NOISE ON PERCEPTION AND COMPREHENSION

To successfully comprehend speech in the presence of background noise, at a minimum, listeners must be able to hear the speech over the background noise, separate the speech from the background noise, and then successfully attend to the correct signal[ii]. Any of these stages may be disrupted by noise; noise can impact perception either through *energetic* masking (Fletcher, 1940) or *informational* masking (e.g., Wightman & Kistler, 2005). Energetic masking is a relatively low-level perceptual phenomenon whereby energy from a masker covers up a target signal, or makes it inaudible. Informational masking is a higher-level phenomenon occurring when target signal energy is detected, but a listener either fails to separate a target from a masker or fails to attend to the correct signal. That is, the target and masker may blend together making the listener uncertain which sounds belong to which signal. Even in cases when the signals can be separated, the masker may constitute a source of distraction. Both energetic and informational masking can impair the ability to perceive and comprehend speech in the moment; the impact depends on factors such as the signal-to-noise ratio of the target and background noise and their overlap in frequency.

Infants and young children require higher signal-to-noise ratios than adults to successfully perceive speech (e.g., Trehub, Bull, & Schneider, 1981). Although one possibility is that infants' difficulties result from immaturity of the auditory system, infants' basic auditory skills are relatively adult-like by 6 months (for a review, see Werner, 2007). This is in part because newborns have already received substantial auditory input *in utero*, although only for frequencies that pass through the mother's tissue and organs into the womb.

Despite their relatively mature auditory systems, infants and children struggle with listening in noise relative to adults, particularly when the background noise consists of speech. Understanding speech in the context of background speech appears to be more challenging than with other maskers even for adults, presumably both because the frequency overlap between signals increases energetic masking, and because the masker's time-varying properties and tendency to convey meaning increase informational masking[iii]. Infants and toddlers have particular difficulty recognizing their name and other common words when in the presence of background speech, especially background speech produced by a single talker (Newman, 2009). Moreover, whereas speech perception with steady-state background noise appears mature around age 10 (e.g., McCreery & Stelmachowicz, 2011), perception with background speech is impaired as late as age 16 (Wightman & Kistler, 2005). In general, children may experience more informational masking than adults[iv] (Leibold, Bonino & Buss, 2016; Newman, 2009). For example, infants exhibit elevated detection thresholds for pure tones presented with remote-frequency maskers that should not produce energetic masking (e.g., Werner & Bargones, 1991), and struggle to discriminate speech sounds in the presence of similar maskers (Polka, Rvachew, & Molnar, 2008). This difficulty

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[ii] This task involves additional challenges, such as linking speech to stored representations, as well as remembering and interpreting it.

[iii] It is worth noting that the meaning conveyed by a speech signal cannot be defined without considering the listener, because even a Shakespearian sonnet contains little meaning to an adult who does not speak English or a one-month-old infant.

[iv] In some cases the reverse may be found to the extent that older listeners tend to know more; for example speech that is semantically meaningful may be more distracting to listeners who can understand the meaning. This fits with findings that suggest infants are sometimes equally impaired at speech perception when the background noise consists of speech-shaped noise as when it constitutes real speech, whereas adults are relatively more impaired by meaningful speech (Leibold et al., 2016).

likely persists into much of childhood; preschoolers and school-age children also experience greater informational masking than adults (e.g., Oh, Wightman, & Lutfi, 2001).

Thus, the mismatch between the early maturity of auditory abilities, and the disproportionate difficulty children face listening with background noise may stem from other causes (e.g., cognitive factors; knowledge). It is unclear to what extent the difficulty lies in separating targets from distractors vs. distractibility, which are both aspects of informational masking and are challenging to disentangle. One likely culprit for children’s difficulties listening in noise may be differences in attention: both a failure to selectively attend to a target stream (Newman, 2009) and a tendency to listen across the frequency range rather than tuning in to the specific regions most likely to be informative (Werner, 2007). This argument aligns with research indicating the development of selective attention is protracted (e.g., Colombo, 2001), and might help explain why even adolescents sometimes struggle listening in noise (e.g., Wightman & Kistler, 2005). This is a promising possibility that we are currently investigating by testing whether individual differences in distractibility on a visual attention task is related to young children’s ability to recognize and learn from speech in a variety of background maskers.

Infants’ difficulties listening in noise may also relate to their knowledge level rather than maturational state; adult second-language learners who similarly have limited language knowledge also struggle at listening in noise (Mayo, Florentine, & Buus, 1997). Children may require substantial auditory and language input to develop representations sufficiently robust for recognition in non-ideal listening conditions. Adults may be particularly advantaged relative to children when the input is predictable from past experiences (e.g., Elliot, 1979). Adults have greater knowledge about the world and typical events, and may be able to rely on similar experiences to enhance understanding, unlike young listeners. Moreover, unlike young children, listeners with more language knowledge or larger vocabularies can fill in gaps when information is degraded or missing (e.g., Newman, 2006).

Children, like adults, can use visual information to help them attend to and understand speech in noise (e.g., Hollich, Newman & Jusczyk, 2005). However, visual information is not available in all situations, and children may be less adept at using it than adults (e.g., Hockley & Polka, 1994), such that it does not fully ameliorate the difficulties they face.

EFFECTS OF NOISE ON LEARNING

Even when speech is not made inaudible by background noise, the noise may impair the ability to learn from input, either by leaving fewer resources available for learning, or making listening particularly taxing (e.g., Hornsby, 2013; Rabbitt, 1968). Further, background noise may distract, causing attentional shifts and information encoding failures, even with readily perceptible targets. Impairments in the ability to learn from a signal would likely produce more significant and long-lasting effects than momentary impairments in speech understanding. Moreover, learning impairments likely pose particular challenges for infants and toddlers, whose successful language development depends critically on receiving language input, and who are simultaneously less equipped to process language in background noise than older individuals. Indeed, young children struggle to learn words in background noise (e.g., McMillan & Saffran, 2016). Moreover, early language difficulties likely generate cascading challenges in other domains and on academic success, because instructional content in other areas (e.g., math; science; history) relies heavily on instructor oral delivery. Indeed, research indicates aircraft noises negatively impact children's school performance (Hygge, Evans, & Bullinger, 2002).

IS BACKGROUND NOISE ALWAYS DETRIMENTAL?

Although background noise can often impair language processing and learning, under certain conditions noise may enhance performance, particularly steady-state maskers at low-volumes (e.g., noise generators; instrumental music of relatively constant amplitude). Low levels of steady-state background noise may help cover up intermittent noise, which is likely more difficult to tune out, possibly explaining why some individuals prefer to sleep with noise generators or work in moderately noisy coffee shops. Background music may increase task enjoyment, supporting attention and thus encouraging learning (Kang & Williamson, 2014; but see Barr, Shuck, Salerno, Atkinson, & Linebarger, 2010, for evidence that background music may impair infant learning). The bustle of a busy coffee shop may enhance performance by increasing arousal. The Yerkes-Dodson law describes an empirical relationship between arousal and performance (Yerkes & Dodson, 1908). Performance increases with physiological arousal up to a point, and then drops off. Background noise may increase physiological arousal, such that small amounts may sometimes benefit performance. Because different tasks and individuals may differ in their optimal level of arousal for peak performance, optimal amounts of noise may also vary. For example, the amount of concentration a task requires may determine whether background noise helps, hinders, or has no effect. Whereas visual tasks are likely to be less disrupted by noise than auditory tasks, even the latter may be enhanced in some forms of noise.

Noise may assist in another way, by changing the specificity of auditory word representations. Studies suggest that variability in a signal can enhance the ability to generalize, and noise could potentially add to that variability. High acoustic variability in a set of words has been found to help learners build appropriate representations, perhaps because the variability highlights the critical acoustic features that determine word identity (compared to other characteristics such as talker identity or voice pitch; Singh, 2008). An infant who has only heard her mother say "dog" might mistakenly believe aspects of her mother's voice are part of the word, whereas an infant who has heard "dog" spoken by multiple individuals, with varying voices, may be better able to correctly represent the word. However, even uninformative variability may be beneficial (Rost & McMurray, 2010), and to the extent that noise may add variability, it is possible that small amounts of noise may result in more robust linguistic representations.

CONCLUSIONS & FUTURE DIRECTIONS

Noise is present in infants' and young children's environments, and exerts far-reaching effects on health, perception, and learning. Noise may particularly disadvantage infants and young children on recognizing and learning from speech, especially when background noise is also speech. Further exploration into the causes of children's difficulties with noise may lead to new recommendations to parents regarding noise in the home environment (such as the amount of time the television is on in the background) or to new policy recommendations for regulating noise in schools. For example, if difficulties stem from poor attentional skills, recommendations might pertain to minimizing distractions rather than only mandating acceptable noise levels. Moreover, to the extent that noise levels correlate with socioeconomic status, our ability to reduce disparities between groups may likewise depend on a greater understanding of the impact and prevalence of noise. Consequently, exploring how noise levels and noise types may differ for children in different environments represents an important direction for future research. Measurement studies of typical noise in occupied classrooms and daycare settings, and of noise in different types of home settings would help us better understand how to create environments that lead to optimal learning and development for infants and children.

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Table 1

Average estimates of common noise levels

Common noise types	Loudness level
Threshold of hearing	0 dB
Whisper, quiet library	30 dB
Unoccupied classrooms	30–60 dB
Refrigerator hum	40–50 dB
Typical conversations	60 dB
Daytime noise volumes in open bay neonatal intensive care units (NICUs)	60 dB
Busy traffic	70–85 dB
Occupied infant and toddler classrooms	60 – 90 dB
Child “bouncy seat” at typical head distance	85 dB
Small kitchen appliances (blenders, coffee grinders, etc.)	70–90 dB
Electronic toys when held 25 cm away	70–80 dB
Estimated threshold for adult noise-induced hearing loss	85 dB
Electronic toys when held near ear	80–90 dB
Noisy restaurant	80–90 dB
Threshold of pain	120 dB
Jet plane	140 dB

Estimates come from our own measurements, from Crandell et al. (1999), from Picard (2004), from Picard & Bradley (2001), from Taxini, Kinoshita & Guida (2013), from Lahav (2015), and from common sources; measures are a mix of dB(A) and dB(SPL).

Table 2

Common noise types found in children’s environments or in studies with young children; see text for definitions of energetic vs. informational masking.

Common noise types	Properties
White noise	• Frequently used in research studies, but not found outside of the laboratory. • Equivalent in intensity across the frequency range; considered to provide mostly energetic (vs. informational) masking.
Speech-shaped noise	• Common in research; essentially, white noise modified to contain more energy at frequencies common in the speech signal. • Used as an energetic-masking comparison to speech (which produces both energetic and informational masking).
Human speech	• A common background noise source, particularly in multi-person environments. • Provides both energetic and informational masking; as the number of concurrent background talkers increases, amplitude variation over time decreases, shifting masking from highly informational to primarily energetic. • Studies with adults (Carhart et al. 1975) suggest that 3 concurrent background talkers provide the greatest level of masking (with constant overall intensity); whether this is the case for young children is unknown. • Studies in our lab suggest that multi-talker babble is less distracting than single background talkers for children.
HVAC (air conditioning/ventilation)	• Noise measurements in schools are often taken in unoccupied classrooms, thus, HVAC noise is a primary component. • Relatively constant in intensity over time; masking is primarily energetic, although initial onset may cause distraction.
Vehicular traffic (cars, trains, air)	• Common noise source especially in urban settings; linked to hypertension in adults (van Kempen & Babisch, 2016). • Traffic noise levels in homes may be correlated with socioeconomic status (SES), because homes near major highways/train tracks tend to be less expensive. • One study suggests proximity to airplane flight paths impairs school performance (Hygge, Evans, & Bullinger, 2002).
Background TV/media	• Very common noise source that provides high levels of informational masking because it often includes speech. • Some homes (potentially tied to SES/parental education) have a TV playing in the background nearly constantly.
Music	• Some homes/daycare settings have constant low-level background music; it is unknown how this may impact learning. • Vocal music is likely to pose greater levels of informational masking than is instrumental music.
Pet noises (dogs, cats, fish tanks, etc.)	• Often intermittent, causing brief masking (e.g., a bark may mask a few words from a parent); however, some pets may bark more frequently, and loud noises may cause psychosocial stress (Ising & Kruppa, 2004). • Some preschool classrooms have fish tanks to teach children how to care for animals; the noise from some aquariums can be quite loud and provide substantial energetic masking, especially for children seated near them.
Sounds from other children	• Major noise source in multi-child homes and most child-care and school settings. • Often overlooked because school-based noise measurements are typically taken in unoccupied classrooms.

Common noise types	Properties
	• May include sounds of shifting bodies, intermittent dropped items, and speech/shouts; crying can cause psychosocial stress.
Electronic toys and activity chairs	• Can produce energetic and/or informational masking; levels depend critically on how close they are brought to the ear. • Sound level measurements from our lab from a typical bouncy seat averaged 85 dB, far louder than a typical parent’s voice.
Ambient noise in neonatal intensive care units (NICU)	• Infants in NICUs frequently experience a combination of intense and unnatural sounds from incubators and other sources, and deprivation of typical sounds present *in utero* supporting healthy auditory development (Lahav, 2015).