Occupational noise exposure: A review of its effects, epidemiology, and impact with recommendations for reducing its burden

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Occupational noise exposure: A review of its effects, epidemiology, and impact with recommendations for reducing its burden

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Exposure to hazardous noise is one of the most common occupational risks, both in the U.S. and worldwide. Repeated overexposure to noise at or above 85 dBA can cause permanent hearing loss, tinnitus, and difficulty understanding speech in noise. It is also associated with cardiovascular disease, depression, balance problems, and lower income. About 22 million U.S. workers are currently exposed to hazardous occupational noise. Approximately 33% of working-age adults with a history of occupational noise exposure have audiometric evidence of noise-induced hearing damage, and 16% of noise-exposed workers have material hearing impairment. While the Mining, Construction, and Manufacturing sectors typically have the highest prevalence of noise exposure and hearing loss, there are noise-exposed workers in every sector and every sector has workers with hearing loss. Noise-induced hearing loss is preventable. Increased understanding of the biological processes underlying noise damage may lead to protective pharmacologic or genetic therapies. For now, an integrated public health approach that (1) emphasizes noise control over reliance on hearing protection, (2) illustrates the full impact of hearing loss on quality of life, and (3) challenges the cultural acceptance of loud noise can substantially reduce the impact of noise on worker health.
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I. INTRODUCTION

Exposure to hazardous noise is one of the most common occupational risks, both in the U.S. and worldwide. Recent studies indicate that 22 million U.S. workers are exposed currently to high noise levels on-the-job and 25% of U.S. workers have a history of occupational noise exposure at some point in their careers (Tak *et al.*, 2009; Kerns *et al.*, 2018). Though global estimates are scarce, and methods vary widely, the prevalence of noise exposure at work (i.e., the percent or number of all cases at a given time) has been reported to be approximately 15% in Canada (Feder *et al.*, 2017), 20% in the European Union (Eurostat, 2004), and 20% in Australia (Williams, 2013). While some evidence indicates that occupational exposure to noise may be slowly decreasing in parts of the developed world, workplace noise is increasing in many developing countries as economies shift from an agricultural to a more industrial base (WHO, 1998; Fuente and Hickson, 2011).

Noise exposure is the primary cause of preventable hearing loss (Le *et al.*, 2017). Noise exposure at work is responsible for an estimated 16% of disabling hearing loss in adults worldwide (Nelson *et al.*, 2005). Nearly a fourth of self-reported hearing difficulty among workers in the U.S. is attributable to occupational exposures (Tak and Calvert, 2008). Left untreated, hearing loss can lead to communication difficulty, social isolation, stress, and fatigue (see review by Themann *et al.*, 2013a). It is additionally associated with depression, cognitive decline, dementia, falls, increased hospitalizations and health care costs, and mortality (see review by Basner *et al.*, 2014). Workers with hearing loss face challenges to their personal safety, show higher rates of absenteeism, may be at increased risk (probability) of work-related injuries, and are more likely to be underemployed or unemployed (Themann *et al.*, 2013a; Dzhambov and Dimitrova, 2017; Neitzel *et al.*, 2017). In addition to hearing loss, high levels of noise are associated with tinnitus, hyperacusis, cardiovascular disease, annoyance, performance decrements, and sleep disturbance (Themann *et al.*, 2013a; Basner *et al.*, 2014). Simply put, noise exposure and its effects can have a substantial negative impact on quality of life.

Noise exposure has been recognized as an occupational hazard for centuries. In the past, however, noise and its effects were limited to small groups of workers in specific professions, such as millers, blacksmiths, stonemasons, and boilermakers. Industrialization changed that. The prevalence of workplace noise and the resulting noise-induced hearing loss (NIHL) grew rapidly with the increase in mechanization of work processes. Not until the early 20th century, though, were the tools available to measure noise levels or hearing ability, allowing research into the effects of noise and prevention of its sequelae. Initial studies discovered the characteristic "notch" in hearing ability at 4000 Hz and identified frequency, intensity, and duration of the exposure as key factors influencing the degree of hearing loss sustained (NIOSH, 1998; Hawkins and Schacht, 2005; Kerr *et al.*,

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2017). Following World War II, as many military personnel returned from combat with impaired hearing, systematic efforts to prevent NIHL began. The first recommended noise exposure limit in the U.S. was promulgated by the U.S. Air Force in 1948. Eight years later, the U.S. Air Force issued an updated regulation (Air Force, 1956) specifying the seven components of an effective hearing loss prevention program which are still recognized today: noise measurement, noise control, hearing protection, audiometric testing, training, record-keeping, and program evaluation (Kerr *et al.*, 2017). Regulations for general industry in the U.S. were implemented in 1970 with the passage of the Occupational Safety and Health Act (OSHA, 1970, 1983). Today, most workers in the developed world are protected by noise exposure legislation, regulations, directives, or standards, though requirements and enforcement vary widely. Even within the U.S., noise regulations differ across industries; for example, separate regulations cover workers in mining, transportation, construction, defense, and general industry (see Arenas and Suter, 2014, for a detailed review).

Decades of research and regulations notwithstanding, occupational hearing loss continues to rank among the most common work-related illnesses both in the U.S. and abroad. This paper will review the critical public health problem of workplace noise exposure and hearing loss. It will discuss the anatomical, physiological, and clinical manifestations of noise-related health effects; the prevalence of exposure and epidemiology of health outcomes; and the personal, social, and economic burden that result from occupational noise and hearing loss. It will consider factors that may contribute to the difficulty experienced to date in reducing the problem and suggest recommendations for moving forward.

In reviewing the topic of occupational NIHL, several distinctions should be made. First, occupational noise varies widely in its characteristics, such as sound level, spectral content, intermittency, and impulsiveness. Similarly, hearing risk varies with the specific acoustic characteristics of a particular exposure. Current damage-risk criteria were established when many of these characteristics could not be accurately or easily measured and are primarily based on studies of continuous noise levels. With improved measurement technologies, noise can now be accurately characterized along multiple parameters, and it is becoming increasingly apparent that defining "hazardous noise" based on sound level alone is insufficient. In this paper, the definition of "hazardous noise" varies based on the particular study reviewed. In some cases, exposure to "hazardous noise" means noise with an intensity level above a particular exposure limit. In other cases, exposure to "hazardous noise" is based on self-report or enrollment in a hearing conservation program. The definition of "hazardous noise" is provided for each study reviewed, but the risk associated with "hazardous noise" exposure may vary substantially across studies.

Second, noise is not the only workplace risk factor for hearing loss. Some chemicals used in industrial processes have been shown to have ototoxic effects, either alone or in combination with noise or other chemicals. Ototoxic chemicals fall into four major categories: solvents (e.g., toluene, styrene, ethylbenzene, trichloroethylene), asphyxiants (e.g., carbon monoxide, hydrogen cyanide, acrylonitrile), heavy metals (e.g., mercury, lead, tin), and polychlorinated biphenyls (PCBs). The effects of ototoxic chemicals can sometimes mimic the effects of noise, making it difficult to determine, in an individual, the specific effect of individual agents (see reviews by Johnson and Morata, 2009; Themann *et al.*, 2013a; Mirza *et al.*, 2018). Ototoxicity from occupational exposures is not within the scope of this review. However, epidemiological studies of work-related hearing loss do not always have sufficiently detailed exposure data on individual workers to determine whether a hearing loss is due solely to noise or if other factors may have contributed. In this review, the term "NIHL" will be used only when studies have reasonable certainty that the hearing levels are due to noise exposure alone; the term "occupational hearing loss" (OHL) will be used otherwise.

Third, noise is not confined to work. Noise levels during some daily activities (e.g., mowing the lawn, using power tools, riding the train or subway) and some recreational activities (e.g., attending music concerts or large sporting events, listening to a personal music player, hunting or target shooting) can exceed safe levels. Noise exposures away from work contribute to overall exposure and can contribute to the development of NIHL. Ototoxic exposures also are not limited to the workplace. Exposure to ototoxic chemicals can occur in daily life (e.g., carbon monoxide exposure from traffic, recreational motor sports, or smoking) and some medications can cause hearing loss (e.g., aminoglycoside antibiotics such as gentamycin and chemotherapeutic drugs such as cisplatin). Although some research suggests that non-occupational exposures add little to overall exposures for individuals working in high levels of noise (Neitzel *et al.*, 2004), other evidence indicates that non-occupational exposure to noise can be substantial (Flamme *et al.*, 2012) and may contribute significantly to total hearing loss (Abbate *et al.*, 2005). To the extent possible, this review will focus solely on occupational exposures; however, some studies may not have sufficient data to determine whether hearing loss was due to workplace exposures alone.

Finally, noise exposure can cause hearing loss in two primary ways: through long-term, continuous exposures to loud sounds over time or through a single exposure to a very high level (typically impulsive) sound. Hearing loss from a single exposure is often called "acoustic trauma" (see reviews by Basner *et al.*, 2014; Le *et al.*, 2017). This review will focus on NIHL that is acquired gradually over time through repeated exposure to continuous, hazardous noise. As noted above, however, cases of acoustic trauma cannot be ruled out from some of the datasets discussed in this review.

II. CLINICAL MANIFESTATIONS

A. Anatomic and physiologic damage

NIHL results primarily from damage to cochlear hair cells, particularly outer hair cells in the basal turn, as shown in Fig. 1 (see Henderson *et al.*, 2006 and Le *et al.*, 2017 for detailed reviews). Damage can occur through multiple mechanisms—mechanical, ischemic, or metabolic (Hawkins and Schacht, 2005). Regardless of the route to hair cell

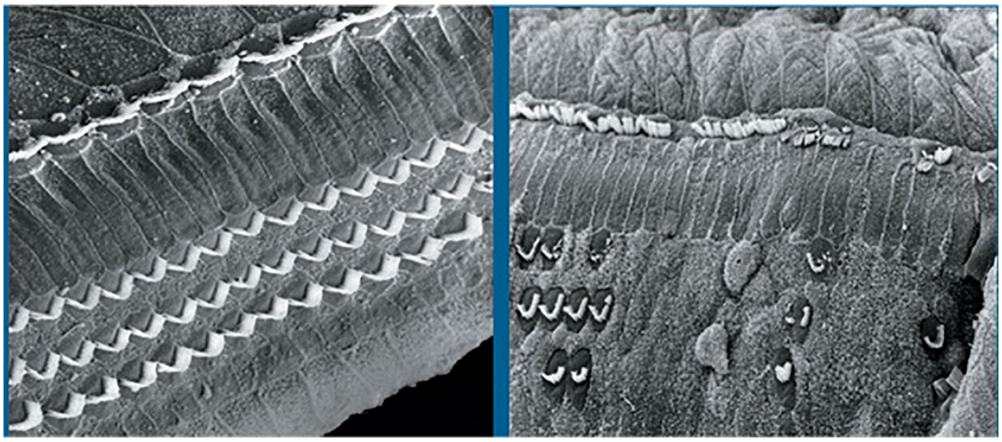


FIG. 1. (Color online) Normal rows of outer hair cells (left side). Missing and damaged outer hair cells following noise exposure (right side) (Source: NIOSH).

destruction, hair cells in mammalian species do not regenerate; thus, once the cells are destroyed, NIHL is permanent (Le *et al.*, 2017).

The theory of mechanical damage to the cochlea through excessive vibration of the delicate structures of the inner ear dates back to the French physicist Claude Perrault in the seventeenth century (see Hawkins and Schacht, 2005) and was later confirmed once microscopic techniques developed sufficiently to study the damaged cochlear structures (for review, see Harrison and Mount, 2001). The trauma created by overstimulation of the cochlea can break, fuse, or destroy hair cell stereocilia or cause them to become decoupled from the tectorial membrane. Increasing sound intensities can lead to further damage to the hair cells themselves or to the supporting pillar or Hensen's cells. It can also break the cell junctions between cochlear cells (Henderson *et al.*, 2006). A sufficiently loud exposure can even detach the organ of Corti from the basilar membrane and rupture the barrier between the endolymph and perilymph (Kurabi *et al.*, 2017; Le *et al.*, 2017). Although mechanical injury was initially presumed to underlie all NIHL, current data indicate that noise exposures of at least 130 dB sound pressure level (SPL) are required to cause direct mechanical damage to the ear (Le *et al.*, 2017).

Most gradual-onset NIHL is created through ischemic or metabolic processes. Noise exposure causes vasoconstriction of cochlear blood vessels and swelling of the stria vascularis, thereby diminishing blood flow to the inner ear. Reduced cochlear blood flow can alter hair cell function, resulting in hearing threshold shifts. Changes in the stria vascularis also reduce the endocochlear potential, thus reducing cochlear amplification of auditory signals and increasing auditory thresholds. Over time, strial swelling can cause the death of intermediate cells, permanently shrinking the stria vascularis and reducing the blood supply to the cochlea (for more detailed reviews, see Henderson *et al.*, 2006; Themann *et al.*, 2013a; Alvarado *et al.*, 2015; Le *et al.*, 2017).

Metabolic oxidative stress, though, probably underlies most cochlear damage from noise exposure. Reactive oxygen species (ROS) are a normal by-product of cellular respiration, and a certain level of intracellular ROS is necessary for various cellular processes. However, increased levels of ROS cause oxidative damage to DNA, lipids, and proteins, resulting in cell death (see reviews in Themann *et al.*, 2013a; Alvarado *et al.*, 2015; Kurabi *et al.*, 2017). Noise exposure increases the level of ROS in the cochlea. This increase occurs immediately after noise exposure and before any other signs of cochlear damage are observable, providing evidence that increased cochlear ROS concentrations may play a role in the initiation of the destructive processes associated with noise exposure (Kurabi *et al.*, 2017). ROS have been observed in the cochlea for as many as ten days after the cessation of noise exposure, explaining the phenomenon of continued hair cell loss in the absence of continued exposure (see Henderson *et al.*, 2006). Although the role of reactive oxygen species in the cascade of events that lead to cochlear noise injury is well-established, the mechanisms by which noise generates these free radicals is still under investigation (Kurabi *et al.*, 2017).

While mammalian hair cells, once destroyed, do not regenerate, evidence suggests that some types of noise-induced cochlear damage can be repaired. Nordmann *et al.* (2000) reported a crumpling of the pillar cells post-noise exposure, which resulted in reduced height of the outer hair cells and sometimes decoupling of the stereocilia from the tectorial membrane. This height reduction appears reversible and could explain temporary noise-induced hearing changes which gradually recover post-exposure. In addition, hair cell stereocilia are connected by actin filaments called tip links which are thought to gate hair cell transduction channels. These tip links appear to be susceptible to noise damage but can regenerate somewhat imperfectly following exposure, perhaps also contributing to temporary noise-induced threshold changes (Zhao *et al.*, 1996).

Recent research indicates that hair cells may not be the only target of noise-induced damage. Seminal work in the mouse model by Kujawa and Liberman (2006) found that spiral ganglion cells that synapse primarily with inner hair cells may be lost following noise exposure, even when hair cells and supporting cells are undamaged. This damage to the synaptic connections to cochlear neurons has been termed "synaptopathy." It is not manifested by changes in auditory thresholds, for which reason it is often called "hidden hearing loss." Studies of noise-induced synaptopathy to date have been limited to animal models, which allow post-mortem examination of cochlear tissues. The noise exposures used in these animal models are higher than most occupational exposures, making the generalizability to human models unclear (Kobel *et al.*, 2017). Although a recent post-mortem analysis of human temporal bones has found evidence of age-related cochlear synaptopathy in persons with little hair cell damage (Viana *et al.*, 2015), similar studies of noise-induced synaptic damage in humans have not yet been done. No clinical tests or imaging techniques are currently available to directly diagnose synaptopathy in living persons (Kobel *et al.*, 2017; Liberman, 2017).

The potential reversibility of synaptic damage is under investigation. Liberman and Kujawa (2017) report that synaptic loss observed across multiple species in their studies has been permanent and progressive. Shi *et al.* (2016), however, report at least partial recovery in both mouse and guinea pig models. The reasons for these discrepancies require further study. Therapeutic repair of synaptic damage is theoretically possible, as a time window for treatment exists and local delivery of neurotrophins within 24 h of exposure has resulted in repair of synapses in some studies (Liberman, 2017).

B. Audiological outcomes and progression

Permanent sensorineural hearing loss is the most common and most serious effect of occupational exposure to hazardous noise. NIHL is characterized by a "notch" in the configuration of audiometric thresholds, in which the poorest thresholds occur in the 3000–6000 Hz range, with better thresholds above and below these frequencies. The primary notch frequency is related to the spectrum of the noise source and the size (and consequent resonant frequency) of the ear canal. With continued exposure, the noise notch deepens and spreads to adjacent frequencies, as shown in Fig. 2 (see also reviews in Le *et al.*, 2017 and Mirza *et al.*, 2018). Age-related hearing loss begins at higher frequencies such as 8000 Hz, spreading gradually to successively lower frequencies. The combination of NIHL and age-related hearing loss can eventually make the notch appear more like a "bulge," as the lowest line (corresponding to >25 years of exposure) in Fig. 2 illustrates (Coles *et al.*, 2000; Dobie, 2005). Deterioration of hearing due to age can eventually cause the noise notch to disappear altogether (Le *et al.*, 2017).

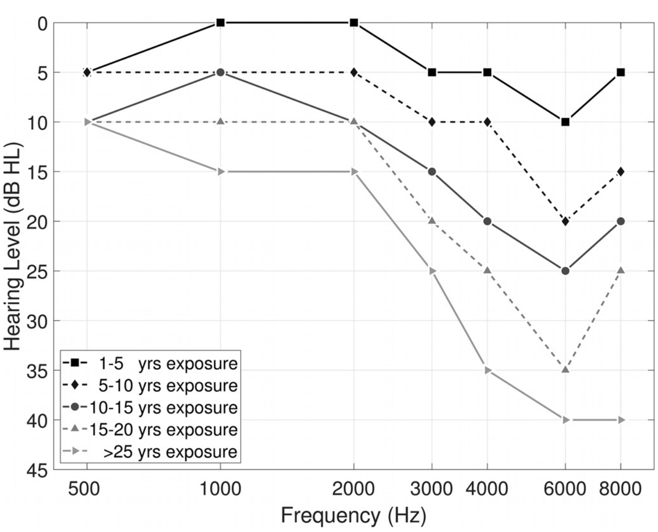


FIG. 2. Progression of noise-induced hearing loss with repeated exposure. Age-related hearing loss can eventually make the "noise notch" appear more as a "bulge," as shown in the lowest line in the graphic (corresponding to 25 or more years of noise exposure).

Most occupational NIHL is bilateral, although unilateral notches can occur when noise exposure is substantially louder in one ear than the other (for example, firearms noise, hand-held power tools, sirens, vehicle noise through an open window) (Masterson *et al.*, 2016b; Le *et al.*, 2017; Mirza *et al.*, 2018). A recent systematic review of asymmetric thresholds in noise-exposed individuals found evidence of noise-induced asymmetries in 2%–22% of cases. Poorer thresholds were more prevalent in the left ear, even after controlling for hand dominance to account for a possible "head shadow" effect (Masterson *et al.*, 2016b). Physiologic differences in auditory processing between ears has been suggested as a possible explanation for apparent asymmetric NIHL (Masterson *et al.*, 2016b; Le *et al.*, 2017).

Typically, noise alone does not cause hearing loss greater than 75 dB hearing level (HL) at the primary notch frequency or 40 dB HL at lower frequencies (Mirza *et al.*, 2018). However, research has found rates of severe to profound hearing loss in noise-exposed populations significantly exceeding the rate in the general population. Whether this is due to other contributing etiologies or to extremely damaging exposures (such as repeated impulsive noise) is unclear (Taylor *et al.*, 1984; Le *et al.*, 2017).

Noise exposure typically causes an initial temporary change in audiometric thresholds which recovers within 16–48 h. With repeated exposures, the shift eventually becomes permanent (Mirza *et al.*, 2018). Although a temporary threshold shift (TTS) is a reliable indicator of overexposure to noise, research indicates that it is not a good predictor of permanent threshold shift (PTS) (for review, see Themann *et al.*, 2013a). The mechanisms of auditory damage appear to be different between TTS and PTS. As previously discussed, TTS appears to be associated with reductions in outer hair cell height and broken stereocilia tip links, whereas PTS primarily involves loss of hair cells and adjacent nerve fibers (Zhao *et al.*, 1996; Nordmann *et al.*, 2000). Nevertheless, as the recent work on synaptopathy shows, noise may cause permanent damage to the auditory system despite full recovery of hearing thresholds after TTS.

In addition to reducing the audibility of sounds, noise-induced damage results in more subtle difficulties that become evident on more complex listening tasks. Reduced frequency resolution impairs the ability to distinguish one sound from another and often manifests in difficulty understanding speech or localizing sounds in background noise. Reduced temporal resolution impairs the ability to distinguish sounds that occur in rapid succession. Reduced spatial resolution impairs localization ability, even in quiet (see review in Hetu *et al.*, 1995).

The effects of noise exposure may also be manifested on other audiologic tests that evaluate outer hair cell function, such as electrocochleography (ECoG) and otoacoustic emissions (OAEs) (Shi *et al.*, 2016). The cochlear microphonic and summating potential recorded during ECoG are stimulus-related potentials generated in whole or in part by the outer hair cells and have been shown in some studies to be sensitive to noise exposure (Pratt *et al.*, 1978; Kim *et al.*, 2005). Other studies, however, indicate that ECoG potentials can be normal even in the presence of a 25% loss of outer hair cells (Withnell, 2001). OAEs are faint sounds generated in the cochlea by the active movement of outer hair cells. OAE amplitudes have tracked consistently with changes in audiometric thresholds in some studies (Le *et al.*, 2017) but not others (Helleman *et al.*, 2018). Both ECoG and OAEs have been considered as possible early tests of NIHL, but neither are currently amenable alternatives to audiometric monitoring. ECoG and OAEs are measures of physiologic correlates of hearing dysfunction and are not measures of hearing *per se*. ECoG requires precise electrode placement and would be difficult to implement in an industrial setting. OAEs could be more readily utilized in OHL prevention programs. However, they cannot be measured when conductive hearing loss or more than a mild sensorineural hearing loss is present, making them unsuitable for some individuals (Le *et al.*, 2017).

Hearing loss from noise accumulates most quickly in the first 10–15 years of exposure and slows over time as exposure continues; age-related hearing loss, on the other hand, accumulates on the opposite course, accelerating over time (Mirza *et al.*, 2018). Evidence suggests that noise exposure early in life increases the risk of age-related hearing loss later in life (see review in Basner *et al.*, 2014). However, the relationship between the effects of noise and age on hearing is not well understood. Although allocations of hearing loss due to noise exposure versus age may be made in certain medico-legal contexts (e.g., worker compensation; see Dobie, 2015), such application of population statistics to an individual is scientifically inaccurate (NIOSH, 1998). Allocating the relative contribution of noise and aging to an individual's hearing loss is not possible.

C. "Hidden" hearing loss

Until recently, a lack of change in audiometric thresholds has been assumed to indicate a lack of permanent noise-induced damage to the auditory system. As noted above, however, recent animal studies have shown that noise exposure can cause damage at the synapse between the inner hair cells and auditory neurons that is not reflected on the audiogram (Kujawa and Liberman, 2006; Liberman and Kujawa, 2017). Current hypotheses speculate that this synaptic damage may relate to functional hearing complaints and degradation of speech intelligibility in noise in the presence of normal audiometric thresholds (Kobel *et al.*, 2017; Liberman and Kujawa, 2017). Though currently only confirmed in animal models using very different noise exposures than typically experienced in the workplace, synaptic damage is a possible theory for the longstanding conundrum of individuals who report hearing trouble but have no measurable hearing loss based on pure tone audiometry.

The neurons most susceptible to noise-induced synaptic damage are those with high thresholds and low or medium spontaneous discharge rates. These neurons are not necessary for detection of low level signals in quiet, making pure tone audiometry insensitive to the damage. However, these neurons are essential for more difficult listening tasks, such as decoding signals when high levels of background noise overwhelm the response of more sensitive neurons with high spontaneous discharge rates (Furman *et al.*, 2013; Liberman, 2017).

The discovery of synaptic damage at the cochlear neurons has led to a flurry of research in search of a clinical test that might be indicative of such damage in humans. Electrophysiological tests which measure auditory neural activity—such as wave I amplitude from the auditory brainstem response (independently, or in conjunction with the summating potential measured in ECoG), auditory steady state responses, and the frequency following response—could conceivably be affected by damage to cochlear synapses. Behavioral tests which tax the auditory system—such as speech in noise and interaural time difference discrimination tests—might also be sensitive to synaptic damage, although these tests can be complicated by factors such as memory and cognitive function. Results thus far have been mixed (see reviews by Bramhall *et al.*, 2019 and Le Prell, 2019). While it is possible that humans may be less susceptible to noise-induced synaptopathy than animal studies suggest, it is also possible that a wider range of variability across human subjects than animal models, a low sensitivity of clinical tests evaluated to-date to synaptic damage, confounding by aging and/or abnormal hearing thresholds, variability and/or inadequate characterization of noise exposure histories, and differences in methodological approaches across studies may have impeded attempts to measure synaptic damage in living persons (Bramhall *et al.*, 2019). Much more research is required to determine whether occupational noise exposures result in cochlear synaptopathy and—if so—to identify a clinical test battery and create normative data for evaluation of results. Longitudinal studies that track test results pre- and post-exposure in persons with well-characterized noise histories are particularly needed (Kobel *et al.*, 2017; Le Prell, 2019).

The discovery of synaptopathy has challenged the long-held belief that noise exposures which do not result in audiometric threshold shifts are safe (Shi *et al.*, 2016). If cochlear synaptopathy occurs in humans and results in perceptual auditory deficits as summarized here, hearing professionals may need to completely re-examine how risk is determined in the future. At present, however, insufficient data exist to revise current hearing damage-risk criteria.

D. Other auditory/vestibular effects of noise exposure

Tinnitus—the subjective sensation of sound in the absence of a stimulus—is an effect of noise exposure which can be even more debilitating than hearing loss (see review in Themann *et al.*, 2013a). Tinnitus can have etiologies other than noise exposure. However, when hearing loss is present, the cause of the hearing loss is assumed to be the cause of the tinnitus as well, unless strong evidence exists otherwise

(Coles, 1995). Tinnitus often serves as an early indicator of auditory damage (Griest and Bishop, 1998). Although subjective, tinnitus is sometimes quantified through sound- and loudness-matching procedures (Manning *et al.*, 2019) or measures of masking and residual inhibition (Fournier *et al.*, 2018). Clinical measures of tinnitus are not currently standardized and often do not correlate with measures of tinnitus impact (Manning *et al.*, 2019). For these reasons, population measures of tinnitus rely on self-report (Shargorodsky *et al.*, 2010). Estimates of tinnitus prevalence vary widely, largely due to differences in questions used to elicit self-reported symptoms. Prevalence estimates among U.S. adults range from 8% to 25%. Studies in other countries report similar prevalences, ranging from 5% to 30% (Bhatt *et al.*, 2016).

Prevalence of tinnitus is higher among adults who report occupational noise exposure. Data from a U.S. population-based survey indicate that 10% of U.S. workers have tinnitus (Masterson *et al.*, 2016c). However, the prevalence is very different relative to occupational noise exposure. Fifteen percent of workers who have been exposed to occupational noise report tinnitus, while only five percent of workers who have never been exposed to occupational noise report tinnitus (Masterson *et al.*, 2016c). Veterans are similarly at increased risk. Folmer *et al.* (2011) reported tinnitus prevalence of 12% among veterans, compared to 5% among non-veterans. Prevalence of tinnitus also increases with increasing duration of noise exposure (Bhatt *et al.*, 2016).

Evidence shows a positive correlation with severity of tinnitus and severity of NIHL. As with NIHL, tinnitus due to noise exposure is usually bilateral. However, unilateral tinnitus is possible and is more commonly reported in the left ear (Le *et al.*, 2017).

Hyperacusis—a reduced tolerance to sound—is another auditory disorder associated with excessive noise exposure. Data on hyperacusis are scarce (Tyler *et al.*, 2014) and studies are hampered by a lack of uniform measures (Bramhall *et al.*, 2019). Most studies of hyperacusis have focused on professional musicians. In a recent review of hearing loss and auditory symptoms among musicians, Di Stadio *et al.* (2018) found reported hyperacusis prevalences ranging from 2% to 45%. Risk was highest among pop/rock musicians. The problem is not limited to musicians, however. Duarte and colleagues (2015) reported that more than half of 364 noise-exposed workers across several industries (primarily metallurgical) who were seen for hearing complaints at an occupational otorhinolaryngology clinic reported increased sensitivity to loud sounds.

The vestibular organs may also be affected by noise. They are housed in the same anatomic structure as the hearing organs, share the same arterial blood supply, and are innervated by the same cranial nerve. Exposures which cause hearing damage, then, could plausibly lead to balance difficulties as well (see review by Golz *et al.*, 2001). The ability to maintain balance is essential to nearly every occupation.

Recent human and animal studies indicate that high noise levels damage the stereocilia of the vestibular hair cells and other balance organs (i.e., the utricle and saccule) (for review, see Le *et al.*, 2017). Ylikoski *et al.* (1988) reported increased body sway in patients with noise-induced hearing damage but no symptoms of vestibular pathology compared to healthy controls. Persons with more severe hearing loss showed more sway than those with milder hearing impairments. Kilburn *et al.* (1992) found increased sway speeds in iron workers exposed to impulse noise compared to non-exposed controls, regardless of overt signs of hearing or balance damage. Wang and Young (2007) reported abnormal caloric and/or vestibular-evoked myogenic potential (VEMP) results in 14 of 20 patients with NIHL and Kumar *et al.* (2010) found similar abnormal VEMP results in 35 of 55 ears with NIHL. Although data are sparse, the importance of balance to workplace safety raises additional concern for noise-exposed individuals.

E. Non-auditory effects of noise exposure

Noise is a non-specific biological stressor which can affect the body's entire physiological system, causing effects beyond the auditory system. Studying the extra-auditory effects of noise is difficult in view of the many other variables which influence these outcomes in human populations, such as age, health, socio-economic status, tobacco and alcohol use, stress, and other environmental exposures. Data from animal studies present other challenges, particularly in generalizing from acute effects to chronic conditions (see review in Themann *et al.*, 2013a).

Noise has been found to be associated with, and potentially influence, cardiovascular health. Whether a causal relationship exists between noise and cardiovascular conditions is still under debate. The mechanism is not known, but it has been theorized to work through the autonomic nervous and endocrine systems. The stress response to noise includes elevated heart rate and blood pressure. Over time, chronic stress leads to a chronic stress response, contributing to the risks for hypertension (chronically elevated blood pressure), elevated cholesterol, and coronary heart disease. The literature has consistently indicated a moderate association between occupational noise exposure and hypertension (Kerns *et al.*, 2018; Skogstad *et al.*, 2016; de Souza *et al.*, 2015; Tomei *et al.*, 2010). A less consistent and weaker association has been found between occupational noise and elevated cholesterol (Kerns *et al.*, 2018; Arlien-Søborg *et al.*, 2016; Dzhambov and Dimitrova, 2016; Gan *et al.*, 2016).

Studies examining an association directly between occupational noise exposure and end points such as coronary heart disease and stroke have also been somewhat inconsistent, but at least two prospective studies have found an increased risk of coronary heart disease with occupational noise exposure (Eriksson *et al.*, 2018; Virkkunen *et al.*, 2005). Workers with an illness of this severity (i.e., heart disease, stroke) typically leave the workforce and do not end up in "worker" samples, thus diminishing the power in some studies to detect an association (Kerns *et al.*, 2018). Further research is needed to determine the noise level and duration that may increase the risk of cardiovascular conditions.

An association between occupational noise and cardiovascular health could necessitate hypertension and cholesterol screening programs among noise-exposed workers. Noise-exposed workers are less likely than non-exposed workers to ever have their blood pressure or cholesterol checked. Thirteen percent of workers report never having their cholesterol levels checked and 2% report never having their blood pressure checked (Kerns *et al.*, 2018).

Noise exposure during pregnancy may be associated with such adverse outcomes as increased low birthweight and preterm births (American Academy of Pediatrics, 1997). Ristovska *et al.* (2014) reviewed 14 epidemiological studies of occupational noise exposure and reproductive outcomes and reported some evidence of an association between high maternal occupational noise exposure during pregnancy and low birthweight. However, few of the studies included an objective assessment of noise levels. Also, a number of confounding factors—both occupational (e.g., standing, lifting) and non-occupational (e.g., mother's age, smoking status, parity)—may obscure the true relationship. Maternal noise exposure may also increase the risk of childhood hearing loss (American Academy of Pediatrics, 1997). A population-based study in Sweden found an increased risk of hearing loss in children whose mothers were exposed to noise levels greater than 85 dBA during pregnancy (Selander *et al.*, 2016).

The potential effect of noise exposure on reproductive outcomes is problematic from a prevention standpoint. As the non-auditory effects of noise are presumed to be mediated through the auditory system, the effects on the mother can be reduced through effective and consistent use of hearing protection. However, adverse effects on the baby could be mediated through direct *in utero* exposure to low frequency noise and vibration. In that case, reduction of potential effects on the baby could only be accomplished by reducing fetal exposure through engineering or administrative controls (NIOSH, 2017).

An important issue in considering the non-auditory effects of workplace noise is that effects can be seen at exposure levels below those imposed by occupational regulations, which have been set on the basis of auditory effects alone (Basner *et al.*, 2014). While occupational studies on non-auditory effects of noise are limited, considerably more research has been completed on the effects of environmental exposures (e.g., airport or traffic noise). These studies have reported negative effects on learning and cognitive performance (Basner *et al.*, 2014; Basner *et al.*, 2015), diabetes and obesity risk (Belojevic and Paunović, 2016), depression and migraine headaches (Niemann *et al.*, 2006), and annoyance and associated outcomes, including anger, withdrawal, anxiety, and agitation (Fritschi *et al.*, 2011).

F. Individual susceptibility

Individuals vary in their susceptibility to the effects of noise exposure. Although research has identified a number of factors associated with differences in susceptibility, the biological bases for these differences and how these factors interact are not well understood. The pathophysiology of NIHL is complex. Predicting a specific person's susceptibility to NIHL is not possible at this time (Henderson *et al.*, 1993; Mirza *et al.*, 2018).

The prevalence of NIHL is consistently higher in males than in females. Prevalence also varies by race, with sensitivity decreasing as pigmentation increases (for review, see Themann *et al.*, 2013a). These patterns are evident in the general population, as well, with males and whites showing significantly poorer hearing thresholds even after controlling for known risk factors (Hoffman *et al.*, 2017). Whether these differences reflect actual dissimilarity in biologic susceptibility (e.g., higher levels of melanin in the cochlea) or simply reflect differences in other factors which may not have been controlled (e.g., non-occupational noise exposure, high blood pressure, smoking) is unclear (see reviews in Henderson *et al.*, 1993; Daniel, 2007; Themann *et al.*, 2013a).

The ear itself may have inherent susceptibility differences, as the left ear often shows poorer thresholds both in noise-exposed and general populations (Masterson *et al.*, 2016b; Hoffman *et al.*, 2017). Tinnitus has also been reported to be more magnified in left ears (Le *et al.*, 2017). As previously noted, one theory for aural asymmetries is the "head shadow" effect, which assumes that individuals are more likely to be exposed on their left side due to handedness (e.g., when firing a weapon). However, the left ear asymmetry persists even when controlling for the dominant hand. An alternative theory is asymmetry in auditory processing at cortical or subcortical levels, or a stronger protective auditory efferent system at the right olivocochlear bundle (Masterson *et al.*, 2016b; Le *et al.*, 2017).

The acoustic reflex may also play a role in susceptibility. Bell's palsy patients with inactive reflexes on the affected side show greater TTS in the ear with the paralysis. Also, individuals with abnormalities in certain acoustic reflex parameters, including onset time, latency, adaptation, and decay, developed noise-induced threshold shifts more quickly than persons whose acoustic reflexes were entirely within normal limits (Henderson *et al.*, 1993). Studies have shown that acoustic reflexes are absent in 5%–13% of the population with good hearing, (Flamme *et al.*, 2017; McGregor *et al.*, 2018). Lack of acoustic reflexes could thus account for increased susceptibility to NIHL in some individuals.

Comorbidities such as diabetes, cardiovascular disease, and poor dental health may increase risk of NIHL (see reviews by Daniel, 2007 and Mirza *et al.*, 2018). Smoking appears to act synergistically with noise exposure to increase hearing loss (Daniel, 2007), which is consistent with the ototoxic effects of carbon monoxide (Johnson and Morata, 2009). The effect is also seen in noise-exposed non-smokers exposed to secondhand smoke (Daniel, 2007). Exercise and good physical fitness may have a protective effect against NIHL, perhaps due to improved cochlear blood flow (Daniel, 2007). Proper nutrition has also been shown to be protective. Spankovich and Le Prell (2014) found that adults with a history of occupational noise exposure who reported a healthier diet had better high frequency audiometric thresholds than those with a poorer diet. Clinical studies using controlled noise exposures have found that TTS is reduced by pre-exposure dosing with magnesium, Vitamin B12, and alpha lipoic acid; however, results from studies using real-world exposures have been mixed (Le Prell *et al.*, 2016).

Taken altogether, however, factors such as gender, race, and comorbidities account for only a small proportion of the variations in sensitivity to noise across individuals (Henderson *et al.*, 1993). Researchers have postulated that as much as 50% of the variability in NIHL susceptibility may be due to genetic factors (Sliwinska-Kowalska, 2011). Using a candidate gene approach—which identifies genes *a priori* based on their biological function related to the outcome of interest—a number of potential susceptibility genes have been identified. Aberrations in genes associated with cochlear antioxidant defense systems may be associated with increased susceptibility to NIHL. These include genes which control glutathione metabolism (e.g., GSTM1, GSTT1) and genes which control enzymes which break down superoxide anions and hydrogen peroxide [e.g., catalayse (CA), superoxide dismutase (SOD)]. Similarly, the HSP70 family of genes, which enable proper protein function in cells under stress (such as from noise) have been associated with variations in NIHL. Genes which regulate potassium ion recycling in the cochlea have also been implicated (e.g., KCNE1 and KCNQ1) (for review, see Sliwinska-Kowalska, 2011; Themann *et al.*, 2013a).

Clifford *et al.* (2016) used a freely-available, curated bioinformatics database (Reactome) to aggregate information from candidate gene studies on NIHL into a more comprehensive picture of the cellular pathways that control cochlear function. Results confirmed the significance of the cellular response to heat and stress. They also pointed to the importance of interleukin-6 signaling pathways, adherens junctions interactions, and the toll-like receptor 4 cascade, which opens new avenues for investigation. Genome-wide association studies—which look at the entire genome to identify differences between affected and unaffected populations—would be an important contribution to understanding the role genetics play in the varying susceptibility to NIHL (Sliwinska-Kowalska, 2011; Clifford *et al.*, 2016).

III. ESTIMATES OF OCCUPATIONAL NOISE EXPOSURE

A. General estimates of worker noise exposure

Though noise is a widespread occupational hazard, estimates of the number of workers exposed are few. The U.S. does not have a national surveillance system that collects noise exposure measurements; no nationally-representative, measurement-based surveys of workplace noise exposures have been completed since 1983 (see Table I) (NIOSH, 1990). A number of worksite or industry-specific studies have measured noise levels in various groups of workers and provide information on exposures in these populations [e.g., Sinclair and Haflidson, 1995 (construction); Neitzel *et al.*, 2006 (commercial fishing); Roberts *et al.*, 2017 (mining)]. The most comprehensive current estimates of noise exposure prevalence in the U.S. are based on self-reported data from nationally-representative population health surveys.

One such survey is the National Health and Nutrition Examination Survey (NHANES), which collects health data on the U.S. civilian population through a household interview and physical examination (see Table I). Tak *et al.* (2009) estimated the prevalence of occupational noise exposure using 1999–2004 NHANES data, in which currently-employed participants were asked whether they were exposed at work to noise so loud that they would have to raise their voice to be heard. This is a validated "rule of thumb" for identifying noise levels of 85 dBA or higher (Miller, 1971). Although these exposures are self-reported, recall of occupational noise exposure has been found to be valid (Neitzel *et al.*, 2009; Schlaefer *et al.*, 2009; Reeb-Whitaker *et al.*, 2004). Based on the 1999–2004 NHANES data, Tak *et al.* (2009) reported that 17% of U.S. workers (approximately 22 million) were exposed to hazardous noise at work. Because NHANES sampling targets civilian residents, these estimates are not representative of military personnel exposures to hazardous noise.

Kerns *et al.* (2018) conducted a similar analysis using data from the 2014 National Health Interview Survey (NHIS)—another nationally-representative study that collects health data annually through household interview only (described in Table I). The 2014 NHIS used similar questions to collect self-reported occupational noise exposure information, except that an exposure duration of "four or more hours a day, several days a week" was required for a positive response. They found that 25% of current U.S. workers (41 million) had a history of occupational noise exposure, and that 14% (22 million) had been exposed to loud noise at work in the past 12 months. The slight reduction compared to the earlier NHANES analysis (decreasing from 17% to 14%) could be partially attributed to the more

TABLE I. Sources of occupational noise exposure estimates in the U.S.

Data source	Years	Sample	Reported noise measure
NIOSH[a] National Occupational Hazard Survey (NOHS)	1972–1974	Nationally-representative sample of U.S. workplaces in industries covered by OSHA[b]	Measured sound level 85 dBA or higher at time of survey visit
NIOSH[a] National Occupational Exposure Survey (NOES)	1981–1983	Nationally-representative sample of U.S. workplaces in industries covered by OSHA[b]	Measured sound level 85 dBA or higher at time of survey visit
OSHA[b] Integrated Information Management System (IMIS)	1979+	Convenience sample drawn from compliance inspections and consultation surveys	Measured sound levels using OSHA-defined criteria
Occupational Information Network (O*NET)	2001+	Random sample of workers in over 1000 targeted occupations	Self-reported exposure to "distracting and uncomfortable" sounds
National Health and Nutrition Examination Survey (NHANES)	1999+ (selected cycles)	Nationally-representative sample of non-institutionalized, civilian U.S. residents	Self-reported exposure to "loud" and/or "very loud" sounds
National Health Interview Survey (NHIS)	2007, 2014	Nationally-representative sample of non-institutionalized, civilian U.S. residents	Self-reported exposure to "loud" and/or "very loud" sounds

[a]U.S. National Institute for Occupational Safety and Health.
[b]U.S. Occupational Safety and Health Administration.

stringent exposure duration in the 2014 NHIS questions. Despite the slightly lower prevalence estimate, the number of noise-exposed workers remained at 22 million, due to the increase in total employed population from 130 million in 2004 (Tak *et al.*, 2009) to 156 million in 2014 (Kerns *et al.*, 2018). Again, noise exposure among military personnel is not represented, and exposure estimates among military workers are not publicly available. However, the U. S. Department of Defense currently has 1.4 million active duty service members (DoD, 2019); presumably all of these workers have a history of exposure to weapons fire during their initial training and many continue to be exposed to noise as part of ongoing service-related assignments.

B. Industry- and occupation-specific estimates

While overall estimates of noise exposure prevalence are essential for defining the scope of the problem and tracking progress in amelioration, understanding the distribution of hazardous noise is necessary for targeting interventions. The self-reported noise exposure data from the NHANES (Tak *et al.*, 2009) and NHIS (Kerns *et al.*, 2018) analyses produced estimates by industry and occupation which are useful for this purpose.

Industry refers to type of business (where a person works). The North American Industry Classification System (NAICS) provides a standard system for classifying industries into sectors and sub-sectors (Census Bureau, 2011). Examining 1999–2004 NHANES data, Tak *et al.* (2009) found the highest prevalence of noise exposure in the Mining sector (76%), followed by the Lumber and Wood Products, Including Furniture, Manufacturing sub-sector (55%), the Rubber, Plastics, and Leather Products Manufacturing sub-sector (48%), the Utilities sector (46%), and the Repair and Maintenance sub-sector (45%). Manufacturing overall had the highest number of noise-exposed workers—5.7 million, representing one-fourth of the occupationally noise-exposed population. More recently, Kerns *et al.* (2018) examined 2014 NHIS data and similarly found the workers who report a history of occupational noise exposure are most prevalent in the Mining sector (61%), followed by the Construction (51%), Manufacturing (47%), Utilities (43%), and Transportation and Warehousing (40%) sectors.

Occupation refers to type of work (what a person does). The Standard Occupational Classification (SOC) system [Bureau of Labor Statistics (BLS), 2018] provides a standard scheme for grouping workers according to the type of work they do. The same occupation can exist in multiple industries. Kerns *et al.* (2018) found that workers who report a history of occupational noise exposure are most prevalent in Production (55%), followed by Construction and Extraction (54%), Installation, Maintenance, and Repair (54%), Transportation and Material Moving (44%), and Protective Service (36%). As Tak *et al.* (2009) observed, noise exposure prevalence can vary considerably within a single occupation, depending on the industry. For example, in their analysis, the prevalence of noise exposure for the Construction Trades occupation ranged from 50% in the Services industry sector to 76% in the Transportation, Warehousing, and Utilities combined industry sector.

Other data sources have also been utilized to glean information about industries and occupations with the most risk from noise exposure. The U.S. Occupational Safety and Health Administration (OSHA) stores exposure data collected during inspections and consultations in its Integrated Management Information System (IMIS) (see Table I). These data constitute a convenience sample from primarily manufacturing sites. They are often collected to investigate potential violations or other problems and therefore may be skewed towards higher exposures (Middendorf, 2004). However, the data are measurement-based, which provides detailed exposure information that cannot be obtained through worker self-report.

Based on IMIS data collected between 1979 and 1999, Middendorf (2004) found that the highest mean exposure levels were recorded from worksites in Construction (94.9–96.7 dBA), followed by Mining (93.6–93.7 dBA), Manufacturing (89.9–91.9 dBA), Agriculture (89.9–91.6 dBA), and Wholesale Trade (89.7–91.2 dBA). The Wholesale Trade sector illustrates a common situation in which the prevalence of noise exposure is low overall (20% per Tak *et al.*, 2009) but noise levels among those who are exposed are quite high. Sayler *et al.* (2019) examined IMIS noise level data through 2013. The highest percent of noise measurements in excess of the OSHA permissible exposure limit (PEL) were in Agriculture, Forestry, Fishing, and Hunting (78%), Construction (58%), Mining, Quarrying, and Oil and Gas Extraction (55%), Manufacturing (52%), and Wholesale Trade (45%).

The U.S. Department of Labor surveys workers in every SOC group about aspects of their job—including noise exposure—and stores the data in the Occupational Information Network (O*NET) (see Table I). Respondents are asked how often they are exposed at work to "sounds and noise levels that are distracting and uncomfortable" with response options ranging from never to daily. Choi *et al.* (2012) analyzed O*NET data to identify occupations in which noise exposure occurred most frequently. Transportation and Material Moving occupations, Extractive and Precision Production occupations, Vehicle and Mobile Equipment Mechanics and Repairers, and Machine Operators ranked highest.

C. Trends in worker noise exposure over time

Current estimates indicate that 22 million workers are exposed to hazardous noise levels in the U.S. (Kerns *et al.*, 2018). At face value, this seems to be a substantial increase over earlier estimates. The U.S. NIOSH conducted the National Occupational Hazard Survey (NOHS) from 1972 through 1974, using sound level meters to determine the extent of noise levels 85 dBA or greater (regardless of duration) across a representative sample of worksites (see Table I). (NIOSH, 1974) NOHS data indicated that more than 7.5 million workers were exposed to hazardous noise (Themann *et al.*, 2013a). In 1981, the U.S. Environmental Protection Agency estimated that 9 million workers were exposed to daily levels at or above 85 dBA. They estimated this by applying results from individual, industry-specific studies to the total worker population in those industries (EPA, 1981). From 1981 through 1983, NIOSH conducted the National Occupational Exposure Survey (NOES) using the same methods as the NOHS to update findings from the earlier survey (see Table I). Results indicated that 4.2 million workers were exposed to noise at or above 85 dBA (NIOSH, 1990). However, the differences in survey methodology, covered industries, and growth in the overall size of the worker population make direct comparisons across these surveys difficult.

The 1999–2004 NHANES analysis (Tak *et al.*, 2009) and the 2014 NHIS analysis (Kerns *et al.*, 2018) used similar research strategies that facilitate analysis of trends in exposure prevalence over the past decade. The overall prevalence of workers self-reporting noise exposure was 17% using the 1999–2004 NHANES data and 14% using the 2014 NHIS data (which employed a more stringent definition of exposure). Both studies estimated that 22 million workers are exposed to hazardous noise on the job each year. Considering the difference in definitions, it appears there has been negligible, if any progress, in reducing the proportion of workers exposed to hazardous noise in the time period between these surveys.

IMIS data, though not representative and covering primarily Manufacturing industries, also permit trend analyses. Middendorf (2004) reported that mean noise levels measured in inspected facilities across all industries combined declined approximately 0.3 dB per year from 1979 to 1984, then declined more quickly at a rate of 0.4 dB per year until 1994, and then began to rise slightly by about 0.13 dB per year until 1999. Sayler *et al.* (2019) looked at IMIS trends through 2013. Following the uptick noted by Middendorf in the mid-1990s, mean noise levels declined again until 2011. Between 2011 and 2013, mean noise levels were once again on the rise but were still substantially below the initial mean levels reported in 1979. While the downward trend may give rise to some optimism, the most recent IMIS data show that 33% of noise measurements exceed the OSHA PEL (90 dBA) and 78% exceed the OSHA action level (85 dBA). IMIS measurements likely represent the worst cases. The noise level trends varied by industry. Some industries showed no change over time (e.g., Construction) and others had rising noise levels (e.g., Agriculture) (Sayler *et al.*, 2019).

The Mining sector, which has been shown consistently to have some of the highest noise levels and prevalence of noise exposure, is not represented in the IMIS database. However, the Mine Safety and Health Administration (MSHA, 1999) maintains a similar database of noise measurements collected during routine inspections. Roberts *et al.* (2017) examined trends in mining exposures from 1979 to 2014 and reported similar overall trends in decreasing noise levels over time. A substantial drop of about 4.5 dBA occurred following the revision to the MSHA noise regulation in 1999 which established an 85 dBA action level and further defined noise control and hearing conservation program requirements. Parallel to recent trends in the IMIS data, the MSHA data indicate a slight rise in noise levels between 2013 and 2014.

IV. EPIDEMIOLOGY OF OHL

A. General estimates of hearing loss

NIHL is the most common consequence of occupational noise exposure. As with noise exposure, the U.S. does not have a national surveillance system for work-related hearing loss. However, several survey systems collect relevant data that can be used to generate estimates of worker hearing loss (see Table II).

The U.S. BLS collects data on non-fatal illnesses and injuries through its annual Survey of Occupational Injuries and Illnesses (SOII). Data are collected from a probability

TABLE II. Sources of occupational hearing loss estimates in the U.S.

Data source	Type	Years	Sample	Reported hearing measure	Association with workplace noise exposure
BLS[a] Survey of Occupational Injuries and Illnesses (SOII)	Cross-sectional	2004+[b]	Random national sample of U.S. workplaces in noise-regulated industries	New cases of standard threshold shift as defined by applicable regulatory body (e.g., OSHA[c], MSHA[d])	Determination of work-relatedness prior to recording case
National Health and Nutrition Examination Survey (NHANES)	Cross-sectional	1999+ (selected cycles)	Nationally-representative sample of non-institutionalized, civilian U.S. residents	Audiometric thresholds at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz	By comparison with self-reported occupational noise exposure history
National Health Interview Survey (NHIS)	Cross-sectional	2007, 2014	Nationally-representative sample of non-institutionalized, civilian U.S. residents	Self-reported hearing trouble	By comparison with self-reported occupational noise exposure history
NIOSH[e] Occupational Hearing Loss (OHL) Surveillance Project	Longitudinal	1970s+	Convenience sample of audiograms collected from audiometric service providers, hospitals, health clinics, and private companies	Audiometric thresholds at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz	Noise exposure assumed based on participation in hearing conservation programs / testing for noise regulation compliance purposes

[a]U.S. Bureau of Labor Statistics.
[b]SOII data are available for years prior to 2004, but hearing data have only been collected in an identifiable manner since 2004.
[c]U.S. Occupational Safety and Health Administration.
[d]U.S. Mine Safety and Health Administration.
[e]U.S. National Institute for Occupational Safety and Health.

sample of approximately 200 000 regulated businesses each year from industries across all fifty states and the District of Columbia (Hager, 2009; Martinez, 2012; Themann *et al.*, 2013a). Employers submit data from record-keeping forms mandated by OSHA and other regulatory agencies (Table II). Beginning in 2004, these forms provided a dedicated field for recording work-related standard threshold shifts (i.e., average threshold change of 10 dB or more at 2000, 3000, and 4000 Hz) when such shifts resulted in an absolute threshold average of 25 dB HL or more (OSHA, 2002). The most recent SOII results reported an incidence (percent or number of new cases of a condition that occur during a specified time period) of 15 900 cases of recordable threshold shifts in 2017, representing a rate of 1.4 cases per 10 000 workers (BLS, 2017).

BLS estimates of NIHL are the only data in which work-relatedness has been determined. However, the estimates have serious limitations. Standard threshold shifts that do not meet the 25 dB fence are not reported. Certain types of employers—including governments and small businesses—are excluded from the sampling frame (Leigh and Miller, 1998). More importantly, disincentives to reporting, such as avoiding OSHA inspections, keeping workers' compensation premiums low, and improving supervisory performance evaluations, are likely to lead to under-reporting. Some estimate that the BLS data underestimate the true incidence of work-related standard threshold shifts by an order of magnitude (Themann *et al.*, 2013a).

NHANES collects hearing threshold data from survey participants which can be used to estimate the prevalence of NIHL in the working population (see Table II). Carroll *et al.* (2017) analyzed data from the 2011–2012 NHANES cycle for evidence of audiometric "notches" consistent with NIHL in adults aged 20–69 years. The prevalence of unilateral or bilateral audiometric notches among working-age adults was 24.4%, or 39.4 million people. Prevalence of notches was 32.6% among those with a history of workplace noise exposure and 19.9% among those who did not report workplace noise exposure. Many individuals did not recognize the possibility of noise damage. Nearly 25% of participants who considered their hearing to be "excellent" or "good" had a unilateral or bilateral notch.

NHIS data can also provide estimates of hearing loss prevalence. These prevalence estimates are based on self-report (see Table II). However, the NHIS hearing difficulty question has been validated against audiometric thresholds (Schein, 1970). Nevertheless, the literature also indicates individuals sometimes under-report hearing difficulty, especially when the hearing loss primarily affects the higher frequencies or is mild (Valete-Rosalino and Rozenfeld, 2005; Sindhusake *et al.*, 2001; Nondahl *et al.*, 1998). It is possible that the prevalence of hearing difficulty is higher in the U.S. working population than has been reported based on NHIS data.

Using data from the 2014 NHIS, Kerns *et al.* (2018) found that approximately 12% of the U.S. working population reports hearing difficulty. Like tinnitus, the prevalence is very different relative to occupational noise exposure. Twenty-three percent of workers who have been exposed to occupational noise report hearing difficulty, while only seven percent of workers who have never been exposed to occupational noise report hearing difficulty. Similarly, the prevalence of workers who report both hearing difficulty and tinnitus differ related to occupational noise exposure (9% among the exposed; 2% among the non-exposed) (Masterson *et al.*, 2016c).

B. Hearing loss burden and risk across industries and occupations

Understanding the distribution of work-related hearing loss across industries and occupations is essential for properly targeting interventions. The NIOSH OHL Surveillance Project (NIOSH, 2018) has amassed a large collection of de-identified private sector worker audiograms (>15 million) (see Table II). All of these workers had been tested due to regulatory requirements for occupational noise exposure. These data constitute a convenience sample and are not nationally-representative. However, workers from all U.S. private sector industries are represented and longitudinal analysis of individual worker hearing levels can be performed.

Estimates generated from the OHL Surveillance Project indicate 16% of noise-exposed workers have a material hearing impairment (Lawson *et al.*, 2019). A material hearing impairment is a hearing loss that makes it difficult to understand speech. It is a substantial loss of hearing in excess of a recordable standard threshold shift that impacts daily activities and quality of life. Methods of estimating material hearing impairment vary. Estimates from the OHL Surveillance Project are based on the NIOSH definition, which is an average hearing threshold across frequencies 1000, 2000, 3000, and 4000 Hz of 25 dB or more in either ear (NIOSH, 1998). Using this definition, the estimated incidence of material hearing impairment among noise-exposed workers between 2006 and 2010 was 7% (Masterson *et al.*, 2015).

1. Mining, Construction, and Manufacturing

The prevalence and incidence of hearing loss among noise-exposed workers vary widely by industry and occupation. The Mining, Construction, and Manufacturing industry sectors and related occupations consistently have the highest, or among the highest, prevalences, incidences, and adjusted risks of hearing loss in the literature. Adjusted risks hold one or more variables (e.g., age) constant to see if the differences in risk among groups (e.g., industries) are due to other variables, such as workplace exposures. Variables adjusted for each estimate will vary by publication and analysis but will all typically include age and gender. The high prevalences and risk of hearing loss in the Mining, Construction, and Manufacturing sectors may be partially explained by the prevalence of noise exposure in these industries/occupations and the associated reporting of hearing protection use, discussed below.

Overall, as shown in Table III, 61% percent of Mining sector workers are exposed to occupational noise, the highest of any industry, and 23% report having hearing difficulty (Kerns *et al.*, 2018). Among noise-exposed Mining sector workers, 25% have a material hearing impairment and the incidence of material hearing impairment between 2006 and 2010 is reported to be 8%, the second highest among the industry sectors (Masterson *et al.*, 2015), followed by a 24% prevalence during the years 2006–2015 (Lawson *et al.*, 2019). These are overall numbers; however, industries within the Mining sector have even higher prevalences of material hearing impairment among noise-exposed workers, including Construction Sand and Gravel Mining (36%) and Uranium-Radium-Vanadium Ore Mining (31%) (Lawson *et al.*, 2019). For workers in these two industries, the adjusted risks of material hearing impairment are 63% and 36% higher, respectively, than for workers in the reference industry—Couriers and Messengers (Lawson *et al.*, 2019). A reference industry or group is an unexposed or lesser-exposed group to which the risk or probability of an event (in this case, hearing loss) in another group is compared. Despite the high prevalences and risks for material hearing impairment in this sector, 13% of noise-exposed Mining workers report not wearing hearing protection (Tak *et al.*, 2009).

The Construction sector has the second highest prevalence of noise exposure, at 51%, and 14% of all workers in this sector report hearing difficulty (Table III) (Kerns *et al.*, 2018). Among all workers within the related occupation Construction and Extraction, 15% report hearing difficulty, with 54% exposed to occupational noise (Kerns *et al.*, 2018). However, among noise-exposed Construction workers, 25% have a material hearing impairment, and the incidence is reported to be 9% between 2006 and 2010, the highest among the industry sectors (Masterson *et al.*, 2015). Like the Mining sector, these overall prevalence estimates are exceeded within some Construction industries. Thirty percent of noise-exposed workers within the Highway, Street, and Bridge Construction industry have a material hearing impairment and this industry's workers have a 40% higher adjusted risk of material hearing impairment than workers in the reference industry (Masterson *et al.*, 2013). Twenty-nine percent of workers within the Other Heavy and Civil Engineering Construction industry have a material hearing impairment and this industry's workers have a 65% greater adjusted risk than workers in the reference industry (Masterson *et al.*, 2013).

When examining occupation-industry pairs, workers report high prevalences of hearing difficulty in the Construction and Extraction Trade occupations within the Mining industry (29%) and the Construction Trades occupation within the Transportation Equipment Manufacturing industry (28%) (Tak and Calvert, 2008). The adjusted risks for hearing difficulty for these workers were 174% and 147% higher than the reference industry, respectively. These group estimates include both noise-exposed and non-noise-exposed workers, indicating the risks for exclusively noise-exposed workers would likely be even higher. Large proportions of noise-exposed Construction workers report not wearing hearing protection: 31% overall for the Construction sector, 38% in the Construction Laborers occupation and 37% in the Construction Trades occupation (Tak *et al.*, 2009).

Overall, 47% percent of Manufacturing sector workers are exposed to occupational noise, ranking third highest, and 18% report having hearing difficulty (Table III) (Kerns *et al.*, 2018). Among noise-exposed Manufacturing sector workers, 20% have a material hearing impairment (Masterson *et al.*, 2015). The incidence of material hearing impairment is estimated at 7% between 2006 and 2010 (Masterson *et al.*, 2015).

Some industries within the Manufacturing sector have even higher prevalences of material hearing impairment than the industry overall. These include Petroleum and Coal Products Manufacturing (24%), Primary Metal Manufacturing (24%), Leather and Allied Product Manufacturing (24%), and Machinery Manufacturing (24%) (Masterson *et al.*, 2013). Within Manufacturing, noise-exposed workers in the following industries have the highest risks of hearing impairment as compared with a reference industry: Wood Product Manufacturing (65% higher), Non-Metallic Mineral Product Manufacturing

TABLE III. Prevalence estimates of noise exposure, hearing protector use, hearing difficulty, and material hearing impairment, and incidence of material hearing impairment among workers in the Mining, Construction and Manufacturing sectors.

	Prevalence				Incidence
	Occupational Noise Exposure[a]	Self-Reported Non-Use of HPDs[b]	Self-Reported Hearing Difficulty[c]	Material Hearing Impairment[d]	Material Hearing Impairment[e]
Mining	61%	13%	23%	24%	8%
Construction	51%	31%	14%	25%	9%
Manufacturing	47%	24%	18%	20%	7%

[a]Prevalence of self-reported occupational noise exposure. Data from the 2014 National Health Interview Survey (Kerns *et al.*, 2018).
[b]Prevalence of self-reported non-use of hearing protection devices among noise-exposed workers. Data from the 1999–2004 National Health and Nutrition Examination Survey (Tak *et al.*, 2009).
[c]Prevalence of self-reported hearing difficulty among all workers (exposed and non-exposed). Data from the 2014 National Health Interview Survey (Kerns *et al.*, 2018).
[d]Prevalence of material hearing impairment per the NIOSH definition (an average hearing threshold across frequencies 1000, 2000, 3000, and 4000 Hz of 25 dB or more in either ear), among noise-exposed workers. Data from the NIOSH Occupational Hearing Loss Surveillance Project (Lawson *et al.*, 2019; Masterson *et al.*, 2015).
[e]Incidence of material hearing impairment for the time period 2006–2010, per the NIOSH definition, among noise-exposed workers. Data from the NIOSH Occupational Hearing Loss Surveillance Project (Masterson *et al.*, 2015).

(57% higher), Primary Metal Manufacturing (57% higher), Apparel Manufacturing (57% higher), and Machinery Manufacturing (56% higher) (Masterson *et al.*, 2013). Within the related occupation Production, 55% of workers report being exposed to occupational noise and 17% report hearing difficulty. However, overall, 24% of noise-exposed Manufacturing workers report not wearing hearing protection (Tak *et al.*, 2009). The percentage of unprotected noise-exposed workers is much higher in Electrical Machinery, Equipment, and Supplies Manufacturing (39%), Miscellaneous Manufacturing (38%), Machinery, Except Electrical Manufacturing (32%), and Textile Mill, Apparel, and Other Finished Textile Products Manufacturing (31%) (Tak *et al.*, 2009).

2. Other prominent "at risk" industries and occupations

While Mining, Construction and Manufacturing are consistently ranked at the top for burden and risk of hearing loss, other industries and occupations also have a consistently high burden of hearing loss. Within the Transportation sector, which tends to have a lower prevalence overall, the Railroad industry has been found to have a very high prevalence of reported hearing difficulty (35%) (Tak and Calvert, 2008). In a related occupation, Other Transportation, Except Motor Vehicles, within Transportation and Material Moving Occupations, 30% report hearing difficulty. Thirty-six percent of workers in the Operators occupation within the Railroads industry report hearing difficulty, and these workers have a 204% higher risk of hearing difficulty than workers in the reference industry (Tak and Calvert, 2008). All of these estimates include both noise-exposed and non-noise-exposed workers, underlining the critical risk to hearing for Railroad workers. More research is needed to characterize both noise exposures and hearing loss in the Railroad industry and related occupations.

The Utilities sector also deserves attention due to a high prevalence of noise exposure and hearing loss (both overall and among the noise-exposed). Within this sector, 43% are exposed to noise and 27% report hearing difficulty (Kerns *et al.*, 2018). Among noise-exposed Utilities sector workers, 26% have a material hearing impairment. However, the adjusted risks compared to a reference industry are fairly low in this sector. The large proportion of males and older workers in this sector likely contribute to the high prevalence, in addition to the high prevalence of noise exposure (Masterson *et al.*, 2013). Twenty percent of the noise-exposed workers in Utilities also report not wearing hearing protection (Tak *et al.*, 2009).

Occupations related to repair and maintenance, which fall within multiple industries (including the Repair and Maintenance industry), also have a high burden and risk of hearing loss. Overall, 54% of workers in the Installation, Maintenance and Repair occupation report being exposed to occupational noise and 22% report having hearing difficulty (Kerns *et al.*, 2018). Focusing on occupation-industry pairs, the Mechanics and Repairers occupation within the Primary Metal Manufacturing industry has the highest prevalence of reported hearing difficulty (39%), and workers in this occupation/industry pair have a 218% higher adjusted risk of hearing difficulty than workers in the reference industry (Tak and Calvert, 2008). Mechanics and Repairers in the Other Non-Durable Goods industry report a 35% prevalence of hearing difficulty and have a 178% higher adjusted risk than workers in the reference industry. Other high prevalences for the Mechanics and Repairers occupation exist within the industries Transportation Equipment Manufacturing (28%), Other Durable Goods (27%), and Food and Kindred Products Manufacturing (26%) (Tak and Calvert, 2008).

One factor likely contributing to these high prevalences/risks is poor compliance with hearing protection use regulations and recommendations. Within the Repair and Maintenance industry, 43% of noise-exposed workers report not wearing hearing protection (Tak *et al.*, 2009). Fifty-five percent of noise-exposed workers in the Vehicle and Mobile Equipment Mechanics and Repairers occupation also report not wearing hearing protection. Within the Technicians and Related Support occupations, which would include some workers who install, maintain and repair, 71% of those who are noise-exposed report not wearing hearing protection (Tak *et al.*, 2009). These are unacceptably high percentages of unprotected workers.

3. Less recognized or unrecognized industries and occupations at risk for hearing loss

While the preceding industries and occupations have been identified as having a high burden and/or risk of hearing loss, research indicates that there are industries and occupations in every sector that have a high burden of hearing loss, including in sectors/industries where low or no exposure would be expected (Masterson *et al.*, 2015; Masterson *et al.*, 2013). One example is the Healthcare and Social Assistance (HSA) sector. The overall prevalence of hearing difficulty reported among all workers in HSA is 10%, which corresponds to the low prevalence of noise exposure (13%) (Kerns *et al.*, 2018). The prevalence of noise exposure within the HSA related-occupations Healthcare Practitioners and Technical, and Healthcare Support are also low (13% and 13%), with corresponding low prevalences of reported hearing difficulty in these occupations (8% and 9%, respectively) (Kerns *et al.*, 2018).

A different picture emerges when focusing solely on the noise-exposed workers in these industries. Thirty-one percent of noise-exposed HSA workers in the Medical and Diagnostic Laboratories industry have a material hearing impairment (Masterson *et al.*, 2018). This is higher than industries within Mining and Construction. Noise-exposed workers in General Medical and Surgical Hospitals, and in Offices of Other Health Practitioners, have material hearing impairment prevalences of 26% and 24%, respectively. Also within this sector, workers in Child Day Care Services have a 17% prevalence and a 52% higher risk of material hearing impairment than the reference industry (Masterson *et al.*, 2018).

Another example would include the "professional" industries, such as Real Estate, Finance and Insurance, and other scientific, technical, and education-related industries. In general, overall estimates (which include both exposed and non-exposed workers) indicate a low burden and risk of hearing loss in these industries and related occupations (Tak and Calvert, 2008; Mrena *et al.*, 2007; Rubak *et al.*, 2006; Palmer *et al.*, 2001). More recent U.S. estimates are similar. For example, among all workers in Real Estate and Rental and Leasing, which is how it is grouped in NAICS, only 9% report occupational noise exposure and 22% report hearing difficulty (Kerns *et al.*, 2018).

However, among noise-exposed workers, 24% in the Activities Related to Real Estate industry, 23% in the Offices of Real Estate Agents and Brokers industry, and 22% in the Lessors of Real Estate industry have a material hearing impairment. Workers in these three industries have 98%, 39%, and 43% higher adjusted risks, respectively, of having a material hearing impairment than workers in the reference industry (Masterson *et al.*, 2013). No known studies of hearing loss or noise exposure targeting the Real Estate industries have been conducted, so the sources of occupational noise and the workers most at risk of hearing loss have not been identified. These are critical first steps to preventing OHL among these workers.

Within Finance and Insurance, the overall prevalence of hearing difficulty reported among all workers is 11%, which is consistent with the low prevalence of noise exposure in this industry (8%). Similarly low, the prevalence of workers who report hearing difficulty in the related occupation Business and Financial Operations is 9% with a noise exposure prevalence of 14% (Kerns *et al.*, 2018). These low numbers again mask the burden and risk for workers in sub-industries and occupations who are exposed to noise. Among noise-exposed workers in Finance and Insurance, 21% have a material hearing impairment with a 41% higher risk of material hearing impairment than workers in the reference industry. Within Depository Credit Intermediation, a smaller industry within Finance and Insurance, 36% of noise-exposed workers have a material hearing impairment (Masterson *et al.*, 2013). As with Real Estate, no studies of noise exposure or hearing loss targeting this industry are known to exist.

Two other examples include Education Services and Professional, Scientific, and Technical Services. The prevalence of material hearing impairment among noise-exposed workers in these industries is 23% and 20%, respectively. Workers in both of these industries have a 29% greater risk of material hearing impairment than workers in the reference industry (Masterson *et al.*, 2013).

No industry can or should be considered "safe" related to worker hearing. Exposures need to be assessed in every industry and occupation. The perception of "low risk" or a lack of awareness of hearing hazards in industries and occupations can negatively impact research interest and availability of funding for research and interventions. It can also impact intervention efforts, including the effectiveness of hearing conservation programs.

Tak *et al.* (2009) found that the prevalence of noise exposure in an industry is directly related to the use of hearing protection among noise-exposed workers, i.e., the lower the prevalence of noise, the fewer noise-exposed workers who wear hearing protection. For example, the HSA sector has among the lowest prevalences of noise exposure (13%) (Kerns *et al.*, 2018) yet 74% of noise-exposed HSA workers report not wearing hearing protection, the highest of any industry (Tak *et al.*, 2009). Large percentages of noise-exposed workers in Educational Services (56%), Finance, Insurance, and Real Estate (54%), and Professional, Scientific, and Technical Services (37%) also report not wearing hearing protection, with similar findings for occupations with low prevalences of noise exposure (Tak *et al.*, 2009). The authors theorize that industries and occupations with large proportions of noise-exposed workers may have developed a hearing loss prevention culture, while industries with a low proportion of at-risk workers do not have the awareness, experience, or resources to effectively conserve hearing among the small groups of exposed workers (Tak *et al.*, 2009). More research is needed within the industries and occupations perceived to be "low risk" to identify and characterize the hearing hazards and ensure workers are protected.

C. Trends in hearing loss over time

Similar to the trends discussed previously with regard to noise exposure prevalence, available data generally indicate that incremental progress is being made in reducing the overall burden of OHL. BLS SOII data have tracked the annual incidence of recordable standard threshold shifts since 2004. Overall incidence has steadily declined from 3.2 cases per 10 000 workers in 2004 to 1.4 cases per 10 000 workers in 2017 (Martinez, 2012; BLS, 2017). While these estimates are useful for monitoring changes in incidence, they are generally acknowledged to grossly underestimate the true magnitude of the problem (i.e., the true incidence is higher). Notably, BLS SOII data showed a general decline in total recordable illnesses and injuries over the same time period (Martinez, 2012; BLS, 2017).

The overall prevalence of hearing difficulty among all workers was $\sim$12% using 1997 NHIS data, 11% using 2003 NHIS data (Tak and Calvert, 2008) and most recently stands at 12% using 2014 NHIS data (Kerns *et al.*, 2018). While most adult-onset hearing losses (including NIHL) are permanent and prevalence will be slower to reflect a decline than incidence, the lack of any improvement in the overall prevalence over 18 years indicates little progress has been made in preventing worker hearing loss.

However, as noted previously, overall estimates can mask important information that is dependent on exposure status, industry, and occupation. Masterson *et al.* (2015) used NIOSH OHL Surveillance project data to analyze 30-year trends of the prevalence of material hearing impairment, 25-year trends of the incidence of material hearing impairment, and 25-year trends of the adjusted risk of incident material hearing impairment—all by industry sector. The prevalence of material hearing impairment for all noise-exposed workers decreased less than 1% over 30 years (1981–2010) beginning at 20% and ending at 19% (Fig. 3; Masterson *et al.*, 2015). A later estimate using data from 2006 to 2015 stands at 16% (Lawson *et al.*, 2019), indicating a continued decline. The incidence for all noise-exposed workers decreased 2% over 25 years (1986–2010), from 9% to 7% (Fig. 4); the adjusted risk for incident material impairment decreased 46% over 25 years (1986–2010) (Fig. 5; Masterson *et al.*, 2015). While the improvements in prevalence and incidence are modest at best, the steady reduction in adjusted risk among these high-risk workers is encouraging.

Figures 3 and 4 (Masterson *et al.*, 2015) indicate that the trends in the prevalence and incidence of material hearing impairment among noise-exposed workers are a picture of both progress and regress over time, depending on industry. The Manufacturing, Wholesale and Retail Trade, and Services sectors closely follow the prevalence and incidence for all industries combined. However, dramatic drops in prevalence (from 33% to 14%) and incidence (from 11% to 6%) occurred in the Agriculture, Forestry, Fishing, and Hunting (AFFH) sector. The Transportation, Warehousing, and Utilities (TWU) combined sector consistently has the lowest prevalence and incidence for almost every time period. However, Masterson *et al.* (2015) indicate that the TWU sample contains relatively few high risk workers, such as Railroad workers, while containing a large proportion of workers from the industry used as the reference industry in other studies, artificially lowering the estimates.

The material hearing impairment prevalence and incidence trends among noise-exposed workers in the Mining, Construction, and HSA sectors indicate a lack of progress. The Mining sector prevalence is consistently the highest since 1996 and increased from 24% to 25% over 20 years (1991–2010) (Masterson *et al.*, 2015), followed by a return to 24% (Lawson *et al.*, 2019). Mining sector incidence increased less than one percent from 2001 to 2010. The Construction sector prevalence is the second highest during most time periods. After dropping from 28%, the Construction prevalence has steadily increased from 21% to 25% over 20 years (1991–2010). Construction sector incidence is also the highest in almost every time period and increased from 7% to 9% between 1996 and 2010. The trends in prevalence and incidence for noise-exposed workers in the HSA sector are particularly noteworthy considering the "low-risk" perception associated with this sector. The HSA prevalence consistently increased over time with only a small reduction in the last time period; increasing from 12% to 18% over 25 years (1986–2010). The HSA incidence also increased from 6% to 7% over 15 years (1996–2010) (Masterson *et al.*, 2015).

The trends in the adjusted risks of incident material hearing impairment among noise-exposed workers (Fig. 5) are far

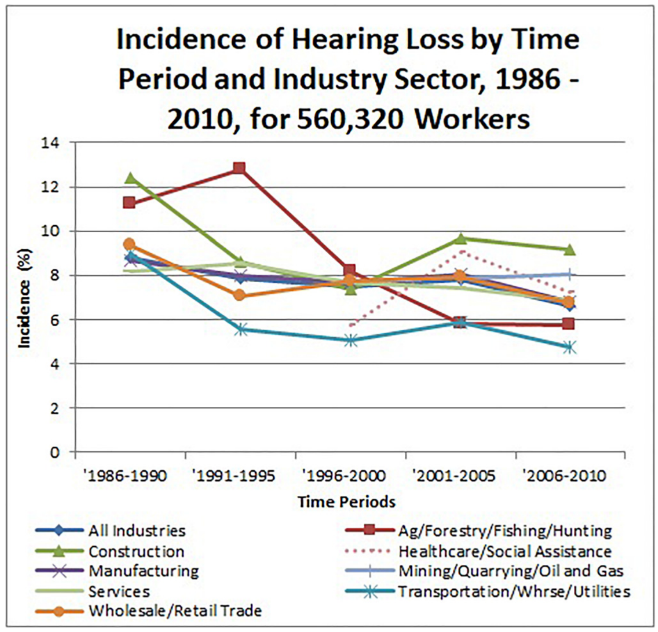


FIG. 4. (Color online) Incidence for noise-exposed workers by industry sector over 25 years (adapted from Fig. 2, Masterson *et al.*, 2015).

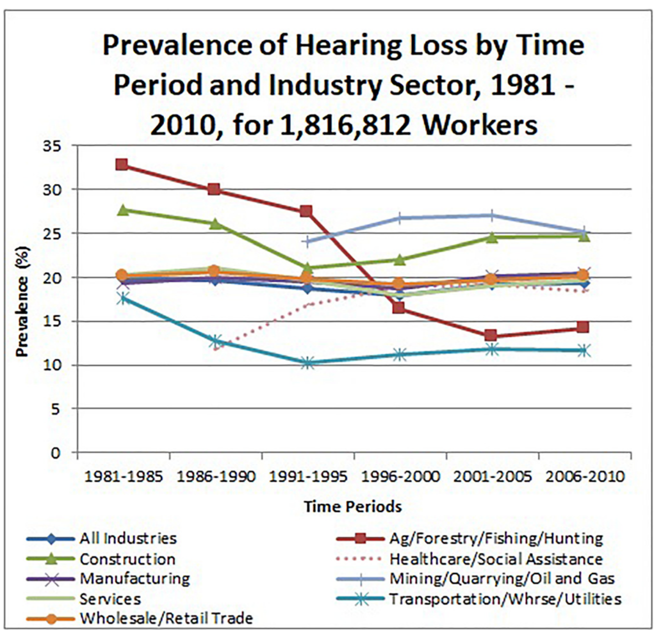


FIG. 3. (Color online) Prevalence for noise-exposed workers by industry sector over 30 years (adapted from Fig. 1, Masterson *et al.*, 2015).

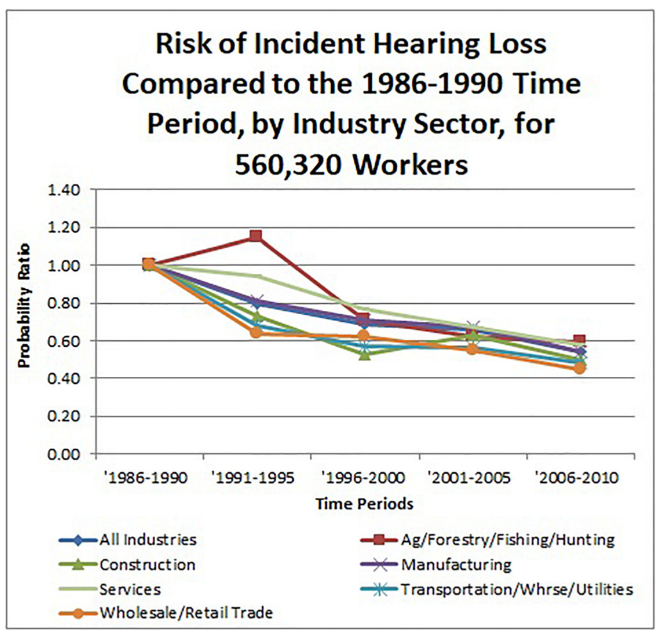


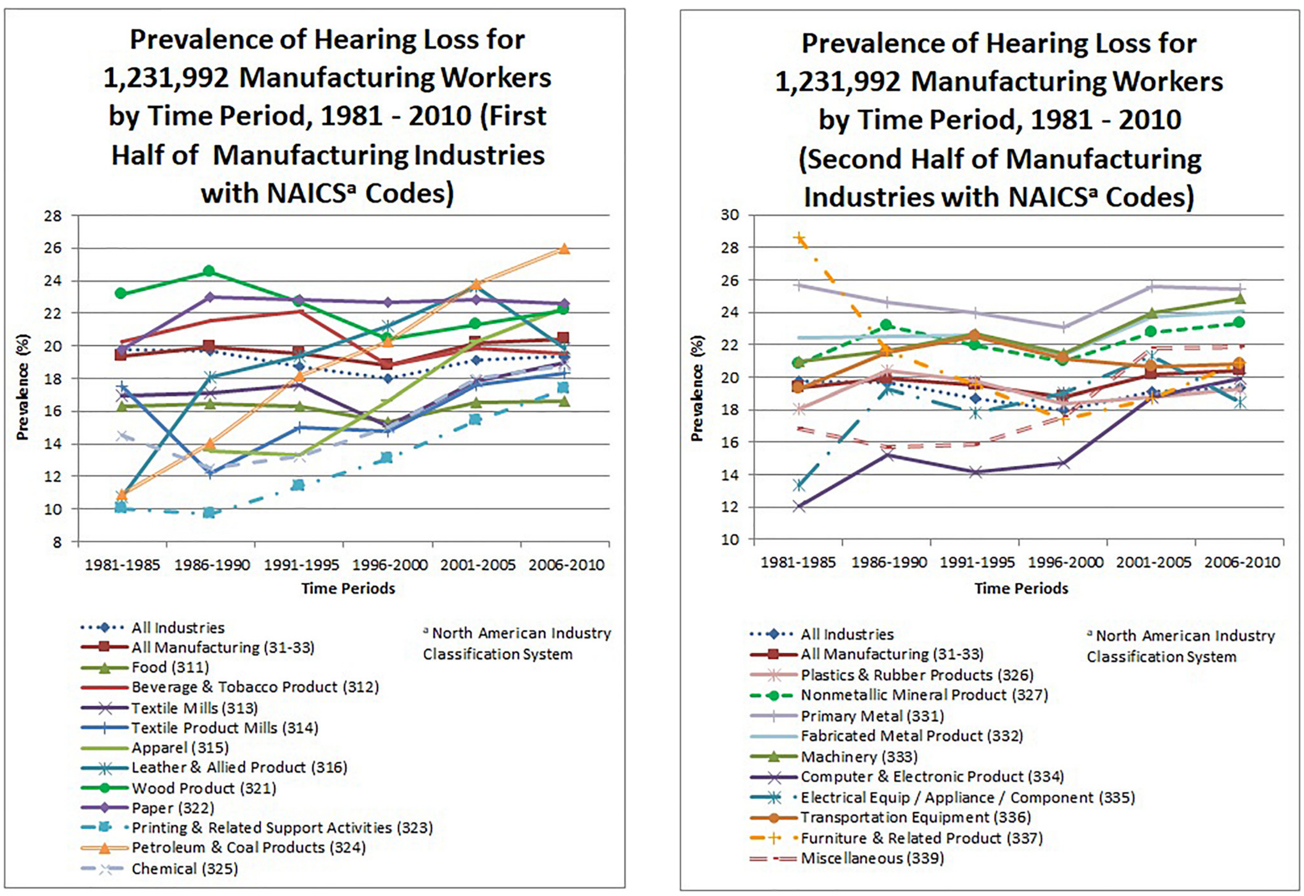
FIG. 5. (Color online) Adjusted risk for noise-exposed workers by industry sector over 25 years (adapted from Fig. 3, Masterson *et al.*, 2015).

more uniform, depicting a clear reduction in adjusted risk that was significant for almost all industry sectors (Masterson *et al.*, 2015). AFFH had the largest reduction in adjusted risk (56% over 25 years). Not depicted in this figure are the Mining and HSA sectors, due to insufficient sample sizes in earlier time periods. These were the only two sectors that did not have an adjusted risk significantly lower in the last time period than in their reference time periods (Masterson *et al.*, 2015). This again highlights the lack of progress in these sectors. However, most sectors did see a significant reduction in adjusted risk. Multiple factors likely contribute to this improvement, including significant progress in hearing loss prevention strategies, better treatment of middle ear disorders, and the significant reduction in smoking in the U.S. over the last thirty years (Agrawal *et al.*, 2009).

The trends for noise-exposed workers in the Manufacturing sector closely follow the trends for all industries combined, in part because the vast majority of noise-exposed workers in the United States are employed in the Manufacturing sector. This is reflected in the study sample (Masterson *et al.*, 2015). However, the trends in prevalence and incidence among the industries within the Manufacturing sector are very disparate [Figs. 6(a), 6(b), and 7(a), 7(b)] (Masterson, 2015). The depicted trends clearly indicate that some industries need immediate attention to stop fairly dramatic increases in prevalence and incidence of material hearing impairment among noise-exposed workers. These industries include: Petroleum and Coal Products Manufacturing, which had a 15% increase in prevalence over 30 years and a 2% increase in incidence over 25 years; and Apparel Manufacturing, which had an 8% increase in prevalence over 25 years and a 3% increase in incidence over 20 years (Masterson, 2015).

Only 4 of the 21 Manufacturing industries had a reduction in prevalence over 30 years. Some Manufacturing industries had a steady and high prevalence of material hearing impairment, including Paper Manufacturing, Wood Product Manufacturing, and Primary Metal Manufacturing. However, the incidence of material hearing impairment is slowly decreasing in Paper Manufacturing and Wood Product Manufacturing (∼3% over 25 years), which should eventually lead to a reduction in prevalence. However, Primary Metal Manufacturing has only seen a 1% reduction in incidence over 25 years. Fifteen of the twenty one Manufacturing industries have seen a reduction in incidence over time (Masterson, 2015).

Trends in adjusted risk for incident material hearing impairment among noise exposed workers across Manufacturing industries are depicted in Figs. 8(a) and 8(b) (Masterson, 2015). The Apparel, Textile Product Mills, and Leather and Allied Product Manufacturing industries are not displayed due to insufficient sample sizes in earlier time periods. The adjusted risk decreased in all of the Manufacturing industries over time, and all but four



(a) (b)

FIG. 6. (Color online) (a) and (b): Prevalence by Manufacturing Industry sub-sector over 30 years (adapted from Figures I and II, Masterson, 2015).

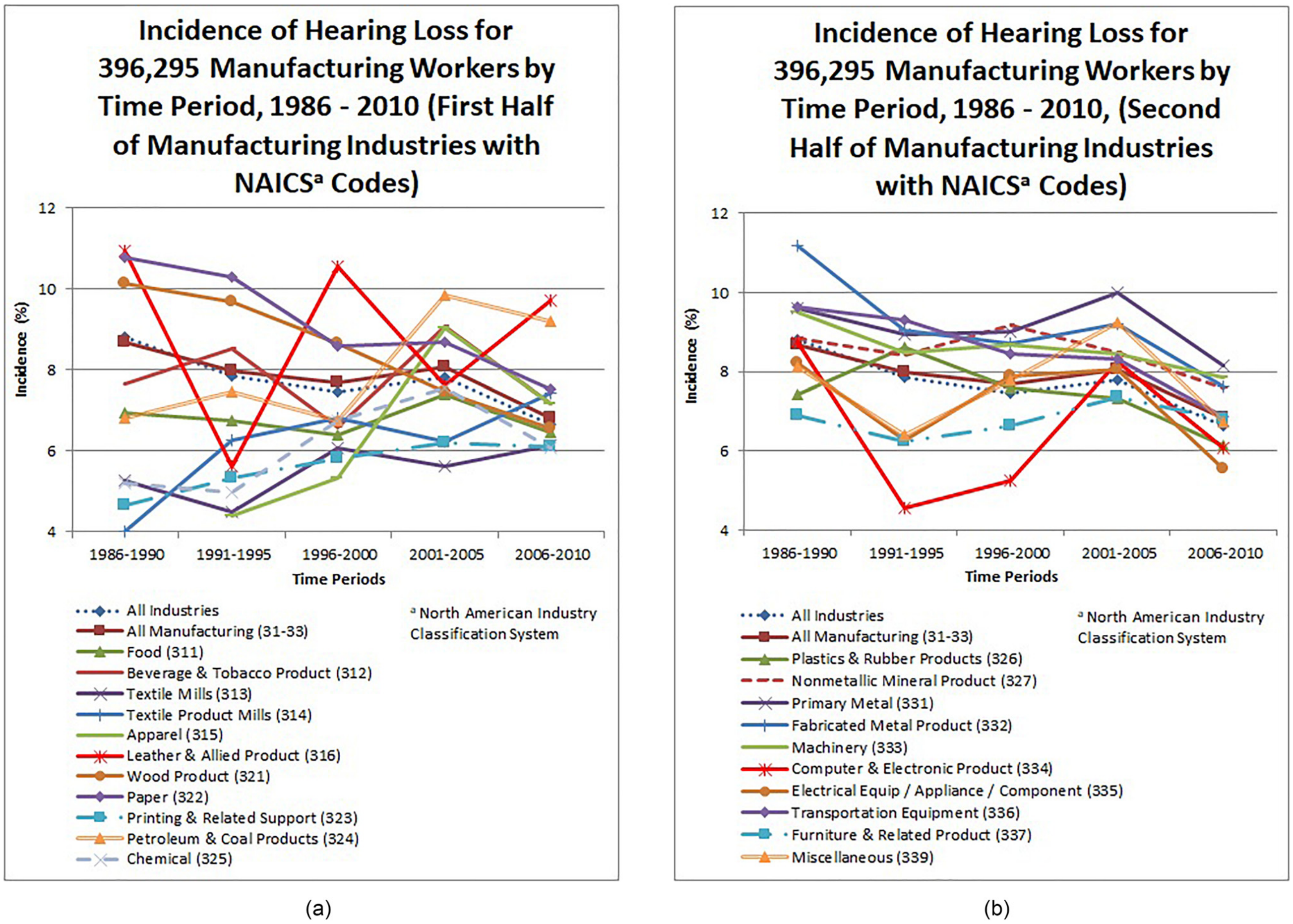


FIG. 7. (Color online) (a) and (b): Incidence by Manufacturing Industry sub-sector over 25 years (adapted from Figures III and IV, Masterson, 2015).

industries had a significant reduction in adjusted risk compared to the reference time period. These four industries are Textile Mills, Textile Product Mills, Apparel, and Leather and Allied Product Manufacturing (Masterson, 2015). These and other identified Manufacturing industries should be targeted for additional hearing conservation efforts.

V. IMPACT OF WORKPLACE NOISE AND HEARING LOSS

A. Communication difficulties

In many jobs, speech communication is critical to job performance and/or safety. High noise levels can interfere with speech communication. In general, speech must be 6–12 dB louder than the background noise level in order to be clearly understood (Robinson and Casali, 2003; Shadle, 2007). The minimum signal-to-noise ratio can vary considerably depending on the type and spectrum of the noise, the predictability of the message, the gender and articulation of the speaker, the age and hearing ability of the listener, and other factors (Miller, 1971; Robinson and Casali, 2003; Shadle, 2007). In addition to simply masking the speech signal, high levels of noise require speakers to raise their voice in order to be heard (see Fig. 9). The increase in vocal effort distorts the speech signal, thus impairing communication (Shadle, 2007). On the listener's side, high signal intensities overload the cochlea, introducing further distortion which affects the ability to understand speech (Robinson and Casali, 2003).

Hearing loss exacerbates the difficulties of understanding speech in noise, and hearing-impaired workers report difficulty communicating in high noise levels on the job (Morata *et al.*, 2005). Consonant sounds are essential to distinguishing one word from another (e.g., cat vs cap). These sounds are typically higher in frequency and lower in intensity than vowel sounds (Shadle, 2007). As NIHL affects primarily high frequency sounds, speech intelligibility is necessarily reduced. Upward spread of masking occurs when lower frequency signals (such as industrial noise) mask higher frequency signals (such as consonant sounds). It increases as noise levels increase, further reducing the audibility of the speech signal for workers with hearing loss (Robinson and Casali, 2003).

Hearing protection devices (HPDs) can also alter speech intelligibility in noise. When background noise levels are high (about 90 dBA or higher), hearing protection devices generally improve speech intelligibility for normal-hearing workers, perhaps due to reduced cochlear overload. This is particularly true for HPDs that have relatively flat attenuation characteristics (see Suter, 1992 and Themann *et al.*, 2013a for more detailed reviews). However, if noise levels are below 85 dBA, the speech signal can be reduced below the audibility range (regardless of hearing ability), thus impairing communication. HPDs impair speech

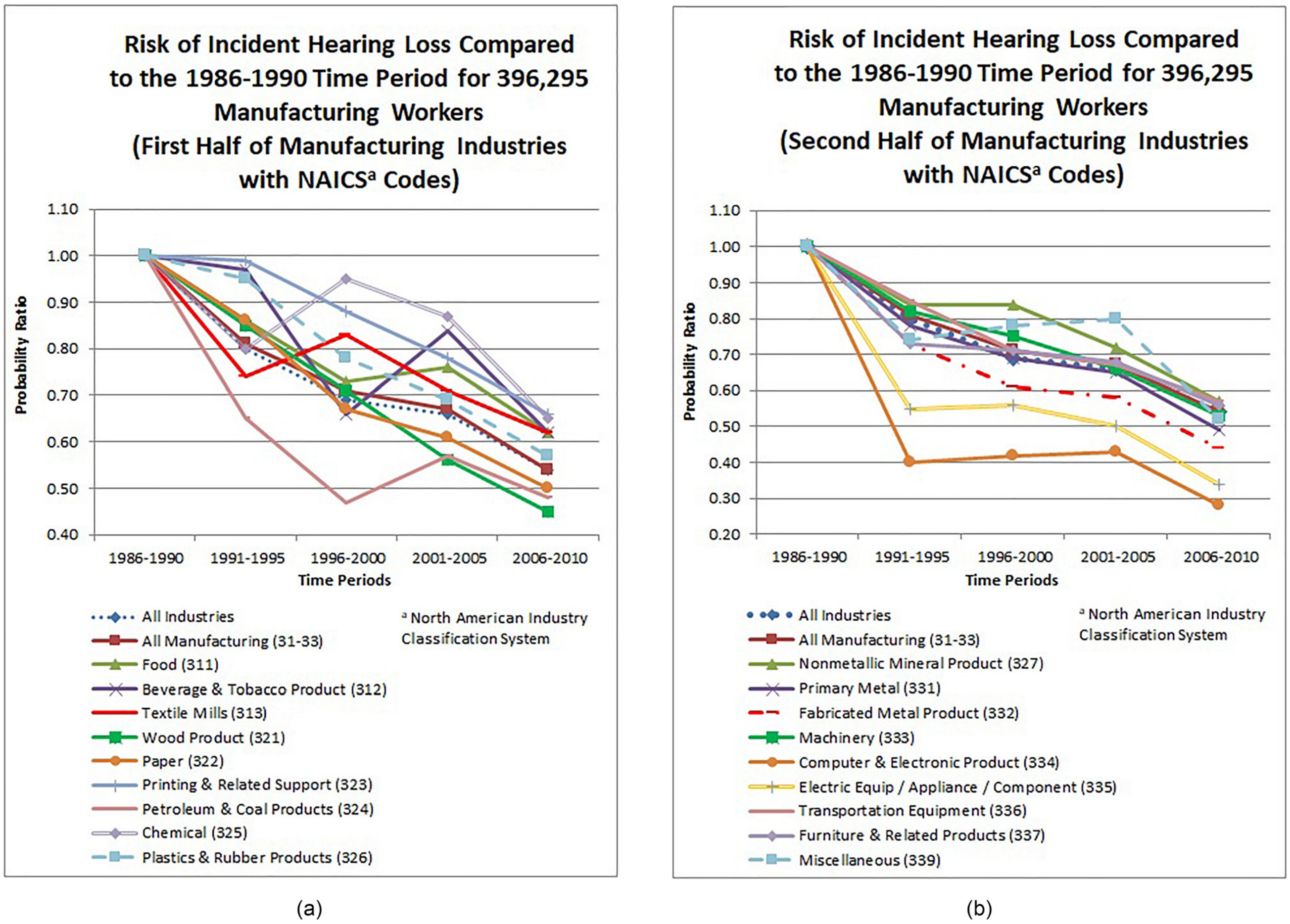


FIG. 8. (Color online) (a) and (b): Adjusted risk by Manufacturing Industry sub-sector over 25 years (adapted from Figures V and VI, Masterson, 2015b).

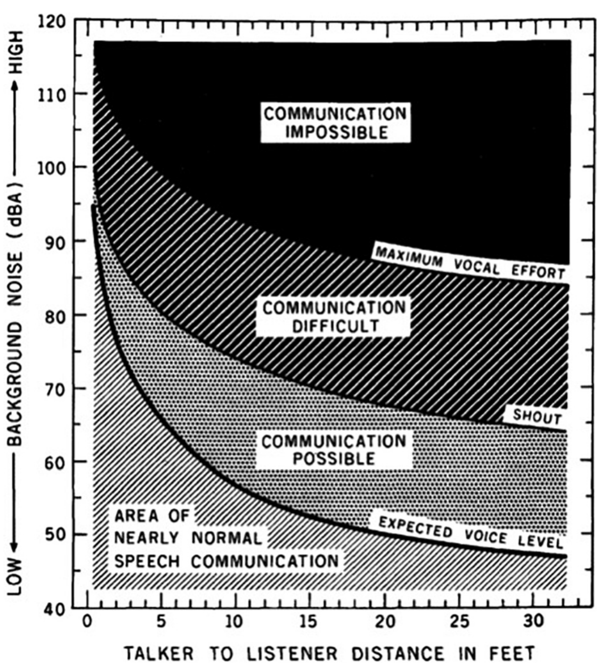


FIG. 9. Speech communication ability as a function of background noise level and talker-listener distance [Source: Miller (1971)].

intelligibility for workers with high frequency hearing thresholds (2000, 3000, 4000 Hz) poorer than 30 dB HL, again due to loss of audibility (Berger, 2003; Themann *et al.*, 2013a). Use of hearing protection affects communication by changing the speech produced by the talker as well. Tufts and Frank (2003) reported that talkers in high background noise did not raise their voices as much when wearing earplugs as they did without earplugs, reducing the signal-to-noise ratio for the listener. Difficulty understanding speech often leads workers to remove their HPDs in order to communicate, thus increasing their risk of further hearing loss (Morata *et al.*, 2005).

Protecting workers from the consequences of noise exposure while protecting their ability to communicate in noise is a substantial challenge (Tufts and Frank, 2003). OHL prevention regulations focus on preventing hearing loss due to noise exposure without consideration of speech communication issues or differences in worker hearing thresholds.

B. Safety concerns

Noise exposure and/or hearing loss can interfere with hearing workplace signals other than speech, such as alarms and equipment sounds. As with speech signals, hearing protectors can modify the perception differentially for normal-hearing and hearing-impaired workers. Due to reduced distortion, HPDs may improve the ability of normal hearing listeners to accurately perceive simple warning signals in the presence of high background noise. At least one study (Lazarus, 2005) has found that this advantage occurs when using earplugs but not earmuffs. Workers with hearing loss, however, have increased difficulty hearing warning signals when using HPDs (see Themann *et al.*, 2013a).

A particular safety issue of concern is localization. Hearing loss impairs the temporal and spatial cues that enable the ear to determine the direction of a sound (Hetu *et al.*, 1995). HPDs, particularly earmuffs, further impair localization ability (Suter, 1992). Localization problems can be particularly severe when earmuffs and earplugs are worn in combination (see Themann *et al.*, 2013a), which is recommended when sound levels exceed 100 dBA (NIOSH, 1998).

Perhaps because of difficulties hearing and localizing workplace signals, both noise exposure and hearing loss have been associated with increased risk of occupational injuries. Zwerling *et al.* (1997) found that hearing loss increased injury risk in a national sample of non-farming workers in the United States. Choi *et al.* (2005) reported increased risk of work-related injuries among farmers with hearing loss. Risk increased further among noise-exposed, hearing-impaired farmers. Girard *et al.* (2015) found similar results among Canadian manufacturing workers. The relative risk of an on-the-job accident was higher for both noise-exposed workers and hearing-impaired workers and it increased even further among noise-exposed workers who had hearing loss. Cantley *et al.* (2015) found an increased risk of injury among a cohort of aluminum workers when mean noise levels equaled or exceeded 88 dBA. The same study found that tinnitus in conjunction with high frequency hearing loss increased injury risk, and that HPD use reduced overall injury risk among these workers. Two recent systematic reviews reported a dose-response relationship between noise exposure levels and increased risk of occupational injuries, though the quality of evidence was considered very low (Dzhambov and Dimitrova, 2017) and the relationship was not well understood (Estill *et al.*, 2017).

C. Job performance

High noise levels can lead to poorer job performance when working on complex tasks or multi-tasking. This does not hold true for simple, monotonous, or repetitive tasks. In fact, low-to-moderate noise can actually improve performance for these types of jobs. Intermittent noise, particularly aperiodic intermittent noise which the worker cannot control, is more disruptive than continuous noise (for review, see Suter, 1992). Noise levels also contribute to absenteeism. Based on 1970s data, OSHA estimated that workplace noise levels of 85–90 dBA caused 362 000 lost workdays annually and noise levels above 90 dBA led to an additional 477 000 lost workdays (OSHA, 1981). A study from the same time period found that implementing a hearing conservation program reduced absenteeism due to sickness or job-related injury by more than 50% (Cohen, 1976).

Hearing loss can also affect job performance, especially in those jobs deemed "hearing critical." Jobs may be considered hearing critical either for safety reasons (e.g., police officers, firefighters, airline pilots, and traffic controllers) or because of the auditory nature of the job itself (e.g., musicians, acoustic engineers) (Tufts *et al.*, 2009). Even in non-hearing-critical jobs, hearing loss has been associated with higher rates of sick leave, particularly for stress-related reasons (Kramer *et al.*, 2006).

Morata *et al.* (2005) reported that noise-exposed, hearing-impaired workers did not consider their hearing loss to negatively impact their job performance. However, Hetu *et al.* (1995) found that nearly 40% of the workers with OHL in their study believed that their hearing loss hindered their ability to do their work. Hetu *et al.* (1995) also reported that these workers were concerned that management viewed their hearing loss negatively. However, Morata *et al.* (2005) interviewed supervisors of hearing-impaired workers as part of their study and found little evidence that managers believed hearing loss impacted their employees' job performance. Such disparate findings across small studies are understandable, as the impact of hearing loss on job performance can be expected to vary considerably due to a number of factors, including degree of hearing loss, type of job, worker experience, and available accommodations. Workers in both studies expressed concerns about advancement opportunities or future employability. These concerns may not be unfounded, as U.S. employment statistics indicate that workers with hearing loss are twice as likely to be unemployed or underemployed as workers with normal hearing (Emmett and Francis, 2014).

D. Quality of life

As with any hearing loss, OHL impacts life away from work as well. As people lose their ability to hear, corresponding changes may occur in the auditory portions of the brain. Greater cognitive resources may be required to process auditory signals. Decreased auditory input may cause re-assignment of the auditory centers of the brain to other functions, or deterioration and atrophy within the auditory cortex (Uchida *et al.*, 2019; Glick and Sharma, 2017). As such, hearing loss is associated with cognitive decline, which includes loss of memory and thinking skills (Lin *et al.*, 2013; Lin *et al.*, 2011). All of these challenges can affect mental health. Hearing loss is strongly associated with depression and depressive symptoms (Scinicariello *et al.*, 2019; Cosh *et al.*, 2018; Yueh *et al.*, 2003; Hetu *et al.*, 1995). Those who are depressed may also be less likely to participate in activities with others, increasing isolation. Depression and anxiety are also associated with tinnitus (Shargorodsky *et al.*, 2010). All of these factors can have a detrimental effect on quality of life – both for the workers themselves and for their spouses, family members, co-workers, and friends (see Themann *et al.*, 2013a).

Quality of life can be quantified in ways that allow comparisons across groups and monitoring trends across time. One important measure is disability-adjusted life years (DALYs), which are the number of healthy years lost due to a disease or other health condition. The DALYs calculation assigns a "disability weight" which takes into account life limitations caused by a condition and represents a lost portion of a healthy year of life. Using an early calculation of disability weights developed by the Global Burden of Disease (GBD) Study and NIOSH noise exposure data adjusted to the distribution of the workforce in various countries, Nelson *et al.* (2005) estimated that occupational noise exposure accounts for 16% of adult-onset hearing loss and 18% of DALYs due to hearing loss worldwide. Burden varies across regions, with the lowest burden in countries such as Australia and New Zealand and the highest burden in countries such as China. As expected, burden is higher in certain industries, including the three previously shown to have the highest prevalence of OHL – Mining, Construction, and Manufacturing. Also consistent with other epidemiologic studies, males incur more DALYs due to hearing loss (2.8 million) than females (1.4 million) globally.

Masterson *et al.* (2016a) used a more recent set of GBD Study disability weights to estimate the DALYs associated with hearing loss among noise-exposed U.S. workers. These weights incorporate not only hearing impairment (i.e., hearing loss that affects day-to-day activities), but also the impact of tinnitus and mental health (Global Burden of Disease Study 2013 Collaborators, 2015). The calculations are conservative and based on average hearing thresholds at 500, 1000, 2000, and 4000 Hz in the better ear. These averages are categorized into mild (20–34 dB), moderate (35–49 dB), moderately severe (50–64 dB), severe (65–79 dB), profound (80–94 dB) and complete (≥95 dB) levels of hearing impairment.

The study used data from the NIOSH OHL Surveillance Project to estimate the prevalence of hearing impairment and associated DALYs at six severity levels and by industry sector (Masterson *et al.*, 2016a). Tinnitus estimates for workers were derived from 2007 NHIS data (Masterson *et al.*, 2016c). Table IV depicts an excerpt of their results for all industries combined (Masterson *et al.*, 2016a). Overall, 2.5 healthy years are lost each year for every 1000 noise-exposed U.S. workers due to hearing impairment. Lost years of good health are shared among the workers who had hearing impairment in both ears (13%, or 130 per 1000 workers), with more days lost from those with greater hearing impairment. This equates to about 75 healthy years lost among 130 workers during working years, assuming a 30-year career. This does not include the additional years of healthy life lost during retirement.

Related to severity of hearing impairment, about 52% of the healthy years lost were attributable to mild hearing impairment among noise-exposed workers and 27% were related to moderate hearing impairment (Masterson *et al.*, 2016a). This highlights the importance of preventing even "mild" and "moderate" hearing impairment, which represent most of the burden of hearing impairment within this population. As this is a permanent condition, the hearing impairment persists into retirement culminating in many more years of healthy life lost.

The study also examined DALYs by industry sector. The proportions of healthy years lost due to "mild" and "moderate" impairment were fairly similar across industry sectors and comparable to the proportions for all industries combined (Masterson *et al.*, 2016a). However, the magnitude of the DALYs among industry sectors varied widely. Consistent with the earlier discussion of burden and risk among industries, Mining, Construction, and Manufacturing sector workers lost more healthy years than workers in other industry sectors. Mining sector workers lost 3.5 healthy years, each year, for every 1000 workers, Construction sector workers lost 3.1, and Manufacturing sector workers lost 2.7. In this sample, 70% of the healthy years lost were among Manufacturing workers. This is further evidence that these three sectors need additional efforts in hearing loss prevention (Masterson *et al.*, 2016a).

E. Economic impact

The economic consequences of OHL—on individual workers, employers, and society as a whole—are vast; however, they can be difficult to assess with precision. As previously discussed, estimates of the incidence and prevalence of work-related hearing loss vary widely depending on the sampled population, the measure used, and the definition of

TABLE IV. Annual number of Global Burden of Disease (GBD) disability-adjusted life years (DALYs) per 1000 workers, estimated prevalence of workers with hearing impairment, and percent of DALYs by impairment severity—1 413 789 workers in the United States, 2003–2012. Annual number of DALYs per 1000 workers represent how many years of healthy life were lost by 1000 workers each year and can be compared across different health conditions. (Excerpted/adapted from Table III, Masterson *et al.*, 2016a).

		Hearing impairment severity[a]							
DALYs/ 1000 workers	Measure	No hearing impairment	Any hearing impairment (mild—complete)	Mild (20–34 dB)	Moderate (35–49 dB)	Moderately severe (50–64 dB)	Severe (65–79 dB)	Profound (80–94 dB)	Complete (≥95 dB)
2.53	No. (prevalence %)	1 230 811 (87.06)	182 978 (12.94)	153 330 (10.85)	24 103 (1.70)	4261 (0.30)	925 (0.07)	265 (0.02)	94 (0.01)
	% DALYs	–	100	51.64	26.66	4.83–22.38[b]	5.58	1.82	0.69

[a]Hearing impairment severity audiometric definitions are the same as the GBD Study audiometric definitions, except that the workers in this sample with hearing aids did not wear them during testing. All levels of impairment are average hearing threshold levels across 500, 1000, 2000, and 4000 Hz in the better ear.
[b]The GBD Study did not calculate a disability weight for moderately severe hearing impairment. DALYs are presented as a range, applying the disability weight for moderate impairment to obtain the lower limit, and applying the disability weight for severe impairment to obtain the upper limit. The average of the lower and upper limits was used to calculate the total DALYs in each industry sector and overall.

impairment (Neitzel *et al.*, 2017). Furthermore, the measures used to generate prevalence statistics often do not capture the full extent of impairment brought on by excessive exposure to hazardous noise. For example, pure tone threshold averages do not encompass communication difficulties, cardiovascular problems, stress, and the myriad of other auditory and non-auditory sequelae described earlier. Even if a suitable measure existed that accounted for all the consequences of occupational noise exposure, assigning monetary values to health-related problems and decrements to quality of life is a difficult task (see review in Themann *et al.*, 2013a). Nonetheless, efforts to estimate the cost of OHL are useful for drawing attention to the scope of the problem and identifying intervention approaches that might be most impactful in reducing the burden.

At the individual level, income is typically lower among hearing-impaired workers than among workers with normal hearing. Analyzing data from NHANES 1999–2002, Emmett and Francis (2014) reported that hearing-impaired persons had 1.5 times the odds of low income (<$20 000 per year) than persons with normal hearing, even after controlling for education and other socio-demographic factors. Hearing-impaired workers had nearly twice the odds of unemployment (having no job) or underemployment (working less than 35 h/week). These results are consistent with employment inequities in other countries (Emmett and Francis, 2014). Hearing loss can also be an impediment in career progression, and workers with hearing loss may be unable to be hired into or continue working in hearing-critical occupations. As economies shift to more service-oriented industries, communication ability becomes an essential employment criterion for many jobs (Themann *et al.*, 2013a).

Employers bear the costs of hearing conservation programs, which could be avoided if the noise was reduced to a safe level. Sayler *et al.* (2018) estimated these programs have an average cost of $308 per worker (range: $203–$438) in metal manufacturing plants. Overall costs were not associated with better or worse hearing health outcomes, but spending on certain program components (e.g., training and hearing protector fit-testing) was correlated with fewer OSHA standard threshold shifts. Garcia *et al.* (2018) analyzed the cost-effectiveness of a military hearing loss prevention program and estimated that preventing a single case of hearing loss cost $10 567.

Employers also bear workers' compensation costs—probably the most common metric of the economic impact of OHL. Compensation for OHL varies widely across U.S. states and territories as well as in other nations. Hearing loss and tinnitus are the two most common disabilities among current and former U.S. service personnel. In 2012, veterans' compensation benefits for auditory impairment were nearly $1.2 billion (Alamgir *et al.*, 2016). Recent estimates of U.S. civilian compensation costs are scarce. Daniell *et al.* (1998) reported that workers' compensation costs for hearing loss in the State of Washington were $4.8 million in 1991. Extrapolating from that estimate, workers' compensation for the entire U.S. would have exceeded $242 million that year—if all states had workers' compensation statutes identical to the State of Washington in 1991, which had a high level of compensation for hearing loss (NIOSH, 2001). However, statutes vary widely by state (e.g., some states do not compensate for chronic hearing loss), as do the mix of industries by state. Actual U.S. workers' compensation costs are likely much lower than $242 million.

Society bears a wide range of costs—direct and indirect—that stem from OHL. These include costs associated with lost productivity, absenteeism, reduced earnings, lost tax revenues, welfare payments, special education and vocational rehabilitation programs, and health care (Themann *et al.*, 2013a; Neitzel *et al.*, 2017). Focusing just on lost productivity, Neitzel *et al.* (2017) estimated that the economic impact of hearing loss was nearly $615 billion in 2013. They further estimated that preventing just 20% of the hearing loss from excessive noise would realize an economic benefit of approximately $123 billion a year (Neitzel *et al.*, 2017).

VI. CHALLENGES AND RECOMMENDATIONS

Noise exposure and OHL remain highly prevalent in the U.S. and worldwide. Workplace noise exposure accounts for 16% of disabling adult hearing loss across the globe (Nelson *et al.*, 2005) and 58% of hearing loss among U.S. workers (Kerns *et al.*, 2018). Occupational noise exposure is regulated in most developed countries, including the U.S. Hearing loss from noise is nearly always preventable. However, lack of emphasis on noise control, over-reliance on hearing protection, inability to identify early indications of hearing damage, failure to recognize the impact of hearing loss on quality of life, and cultural acceptance of loud noise likely contribute to the continuing high burden of hearing loss among noise-exposed workers.

Lack of emphasis on noise control. The hierarchy of controls—which ranks methods for controlling workplace exposures in order of effectiveness—indicates that eliminating or reducing hazardous noise is the most effective method of preventing hearing loss and other noise-related sequelae (Morata and Meinke, 2016). For decades, noise control solutions have been largely overlooked in the U.S. due to lack of regulatory enforcement and a general assumption that noise controls are too difficult and expensive to be feasible (Kerr *et al.*, 2017). Recent examples from the Safe-In-Sound Excellence in Hearing Conservation Award™ (2018), however, show that this is not always the case. One award-winning company reduced noise to safe levels in 11 of its 24 noise hazard areas at zero cost (Morata and Meinke, 2016). Another dropped over 8000 employees from its hearing conservation program through noise abatement projects, some of which were as simple as putting rubber wheels on machine carts and replacing audible alarms with visual warning signals.[1]

Prioritizing noise control and implementing Buy Quiet strategies (Beamer *et al.*, 2016) are critical to reducing workplace noise. Studies indicate that decreasing noise levels by 5–10 dB is all that is necessary to reduce the exposures of 99% of U.S. workers to within the OSHA limit (see Themann *et al.*, 2013b). While some workers exposed to noise below the OSHA action level would still be at risk for developing material hearing impairment over their working lifetime (NIOSH, 1998), this small decrease in occupational noise levels would dramatically reduce new cases of noise-induced threshold shift.

Reducing noise can lead to dramatic reductions in the prevalence of associated auditory and non-auditory conditions. Among all U.S. workers, 58% of hearing difficulty cases can be attributed to occupational noise exposure and could be prevented if the noise was reduced to safe levels (Kerns *et al.*, 2018). That equates to preventing 5.3 million of the 9.2 million cases of hearing difficulty among noise-exposed workers. Some cardiovascular conditions also might be prevented. If a causal relationship exists with occupational noise, then 1.7 million cases (14%) of hypertension and 1.2 million cases (9%) of elevated cholesterol among noise exposed workers could potentially be prevented if the noise was reduced to safe levels (Kerns *et al.*, 2018).

Over-reliance on hearing protection. Lack of noise control efforts has led to a default reliance on hearing protection to prevent the deleterious effects of noise exposure. When used correctly and consistently, hearing protectors can effectively prevent NIHL. However, research has repeatedly shown that workers generally receive far less attenuation from HPDs than the labeled Noise Reduction Rating (NRR) would predict. Removing the protector for just 30 minutes of an eight-hour workday can cut the effective level of protection in half (NIOSH, 1998). Groenewold *et al.* (2014) found that self-reported hearing protector use was only marginally associated with reduced odds of high frequency hearing shifts over a five-year period, suggesting that hearing protectors are providing inadequate noise reduction for many workers.

Increasing availability of hearing protector fit-test systems has made it possible to determine the level of protection achieved by individual workers, increasing the likelihood that worker exposures are reduced to safe levels (Schulz, 2011; Themann *et al.*, 2013b). Saylor *et al.* (2018) reported that the four facilities that utilized fit-testing in their study of hearing conservation program effectiveness achieved the lowest rates of hearing shift among the fourteen participating sites.

Although sufficient noise reduction is crucial, most workers only need 5–10 dB of noise reduction to reduce exposure to a safe level and nearly any protector—properly fit and consistently worn—can produce this level of attenuation. Tak *et al.* (2009) has reported that 34% of noise-exposed workers indicate that they do not use hearing protectors when exposed to hazardous noise. Shifting the focus of hearing protector selection from the assumption that higher NRRs mean better protection to the consideration of factors that contribute to non-use of HPDs (e.g., communication, comfort, and convenience) could improve the consistency of hearing protector use. Such a shift in focus could help ameliorate the low rates of HPD use, thus improving worker protection and reducing the rate of NIHL (Tak *et al.*, 2009; Themann *et al.*, 2013b).

Inability to identify early indications of hearing damage. Most occupational NIHL accumulates gradually over time. Persons with auditory damage caused by noise frequently do not recognize it. One in four U.S. adults who self-report good or excellent hearing has audiometric evidence of possible noise damage (Carroll *et al.*, 2017). The prevalence of unrecognized auditory damage is likely far higher, as substantial pre-clinical injury to the auditory system can occur; up to 50% of cochlear hair cells can be lost without a measurable change in audiometric thresholds (Daniel, 2007). Noise-induced damage may create deficits only evident on supra-threshold tasks (such as understanding speech-in-noise) which are not measured in workplace audiometric monitoring programs (Shi *et al.*, 2016).

Current practices for detecting the effects of occupational noise on worker hearing may be insufficient. Masterson *et al.* (2014) found that the OSHA criterion for identifying threshold shifts missed 28%–36% of workers compared to the NIOSH recommended metric. The proportion of missed workers increased to 65%–74% when age-correction was used. While more sensitive threshold criteria would serve to identify workers sooner, before the hearing shift becomes a hearing impairment, any metric based on pure-tone thresholds can only document hearing damage after it occurs. A pre-clinical marker of auditory damage or a reliable indicator of worker susceptibility to noise effects could allow better monitoring and earlier intervention to preserve worker hearing.

Failure to recognize the impact of hearing loss on quality of life. The gradual accumulation of hearing loss may also contribute to the failure to recognize the impact hearing loss has on quality of life and the lack of motivation to prevent it. Early hearing changes may not affect workers' day-to-day life. As a result, they may not understand the necessity of prevention efforts (for review, see Themann *et al.*, 2013b). The sense of hearing is always active, making it difficult to simulate what life will be like once hearing is lost.

Increasing public awareness of the effects of hearing loss is essential to making headway in prevention. Public health campaigns have successfully reduced risky behaviors and increased healthy activities in other areas such as tobacco use and cancer screening. Such campaigns require partnerships with health educators, public relations professionals, and policy-makers to identify motivations and develop strategies that will help re-shape beliefs, attitudes, and behaviors regarding hearing. The "Favorite Sounds" project is one example of a campaign to encourage people to think about how sound affects their lives and how hearing loss might impact their quality of life (Dix, 2012).

Cultural acceptance of loud noise. Loud sound is an integral and celebrated part of many social activities, including concerts, sporting events, and movies. The cultural acceptability of noise outside the workplace makes it difficult to raise a sense of urgency for reducing noise inside the workplace (Themann *et al.*, 2013b). Expanding prevention efforts to include non-auditory effects of noise exposure (e.g., cardiovascular disease, cognitive decline) and the secondary consequences of hearing loss (e.g., job safety, reduced income) could provide more tangible motivation for protection from overexposure to noise than the risk of hearing loss alone.

Hearing loss prevention should be approached holistically—considering both occupational and non-occupational risks to hearing as well as monitoring other health effects such as blood pressure and cholesterol levels. The negative consequences associated with noise exposure are not confined to the workplace or the working years. Nearly everyone encounters hazardous sound exposures throughout life, regardless of their job. Therefore, raising awareness and encouraging protective behaviors when individuals are exposed to noise outside of work is crucial. Similarly, other risk factors—both on and off the job—can interact with noise to increase or decrease risk. A Total Hearing Health approach that considers risk factors as a whole and promotes overall health and well-being is key to effectively preventing the negative consequences of over-exposure to noise (NIOSH, 2019).

Emerging strategies. In addition to behavioral strategies for reducing the burden on NIHL, pharmaceutical therapies may have a future role in hearing loss prevention. As understanding of the metabolic processes involved in NIHL expands, potential pharmacological interventions emerge. Interventions that inhibit cellular damage (e.g., by reducing the formation of reactive oxygen species or inhibiting apoptosis) or improve cellular defenses (e.g., by triggering survivor genes or increasing protective neurotrophins) have been beneficial in some animal models (see reviews in Hawkins and Schacht, 2005; Kurabi *et al*., 2017; Le *et al*., 2017). Translation from animal models to humans, however, cannot be assumed. Effects of high-level, acute noise exposures used in most animal studies may not equate to the effects from lower level, chronic exposures typical of worker populations (see Themann *et al*., 2013a). Noise damage cannot be purposely induced in human subjects for research purposes (Le Prell, 2012; Kurabi *et al*., 2017). Effectiveness of therapeutic interventions in animal models is measured through tissue pathology. An appropriate outcome measure in humans that correlates to known changes in the function of certain auditory structures or pathways has yet to be identified (Le Prell, 2012; Kobel *et al*., 2017). Efficacy of pharmacologic treatments in human populations remains under study.

Potential biochemical or genetic markers for noise risk also open potential new avenues for prevention of NIHL. Chemical markers including catecholamines, cortisol, and salivary chromogranin A have been associated with noise stress and may be useful in identifying individuals at increased risk from noise exposure (for review, see Themann *et al*., 2013a). Identification of genes that increase risk of NIHL could similarly be used to target personalized interventions for persons with higher risk—such as custom hearing protection, fit-testing, and more frequent audiometric monitoring. Gene therapies and personalized medicine may ultimately be available (Sliwinska-Kowalska, 2011; Themann *et al*., 2013a). While genetic markers hold exciting possibilities for hearing loss prevention, caution must be taken to avoid using this knowledge to discriminate against individuals who might be more susceptible to noise effects.

Here and now. Even while these novel and potentially promising approaches remain under study, substantial progress in preventing NIHL could be made through better implementation of existing knowledge. A substantial "know-do" gap—the difference between what we know to do and what we actually do—exists in OHL prevention. This gap is often due to failure to involve all stakeholders, differing priorities between research generators and research users, emphasis on passive knowledge exchange (i.e., reports, websites) rather than active exchange (personal, face-to-face), poor infrastructure (e.g., separate rather than coordinated systems, fragmented knowledge sharing), and lack of sufficient funding (van den Driessen Mareeuw *et al*., 2015). In describing the values and characteristics of successful hearing loss prevention programs, Meinke and Morata (2012) discuss strategies that directly address these factors contributing to the "know-do" gap. These include: an interdisciplinary, inclusive approach to problem solving; frequent communication meetings involving key personnel; assigning a specific individual to provide daily program support, obtain resources, and ensure accountability; seeking worker input on noise hazard identification, hearing protector selection, and other key determinations; providing workers with inexpensive sound level meters or sound measuring apps to identify hazardous noise levels and monitor the effectiveness of existing controls; trusting worker judgements; customizing training to the unique needs of the company and employees; and adaptability to workplace changes. Better implementation of current knowledge and continuing research into new approaches to hearing loss prevention can substantially reduce the burden of worker hearing loss.

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[1]For more information, see http://www.safeinsound.us/swf/UTC/index.html.

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