Dean&Francis
ISSN 2959-409X

Synergistic Effects of Occupational Noise and Aging on Hearing Loss: A Nationwide Industry-Based Analysis

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Abstract:
Due to the underestimation of the combined effects of aging and occupational noise exposure, hearing loss is a significant global public health problem. This study looked at how age and noise exposure from the workplace affected hearing loss in American workers. The pure-tone average (0.5–4 kHz) across twelve industry categories categorized by the North American Industry Classification System (NAICS) was used to define hearing thresholds using more than 1.1 million de-identified audiometric records (2000–2008) from the National Institute for Occupational Safety and Health (NIOSH). Industry×age interactions, between-industry differences, and within-industry age effects were evaluated using logistic regression models. Age-related hearing deterioration is made worse by occupational noise, according to a substantial interaction between age and industry that suggests a synergistic rather than additive connection. These results demonstrate the increased risk among older workers in high-exposure jobs and offer extensive evidence of varying vulnerability to hearing loss across industries. To reduce cumulative auditory impairment in the aging workforce, it may be crucial to integrate wearable or mobile health devices and strengthen targeted hearing conservation initiatives.

Keywords: Occupational noise exposure; Age-related hearing loss; Interaction effect; Industrial epidemiology; Hearing conservation

1. Introduction

Despite decades of prevention, hearing loss remains one of the fastest growing and least reversible global health burdens. Throughout life, individuals with hearing loss have greater depression rates and worse quality of life compared to their hearing counterparts. Social disengagement and altered relationships are common; individuals with hearing loss may experience shame, rejection, and anxiety [1]. All of these demonstrate that hearing loss is a serious public health concern in aging populations around the globe.

ISSN 2959-409X

Yet how aging interacts with external risk factors, such as occupational noise exposure, remains less understood.

Among modifiable risks, occupational noise remains the most preventable cause. Approximately 16% of adult hearing loss and more than 4 million DALYs worldwide are caused by occupational noise-induced hearing loss (NIHL), one of the most prevalent yet completely avoidable occupational illnesses [1]. A gradual, irreversible, and multifactorial degenerative condition of the auditory system, age-related hearing loss (ARHL) is largely caused by cellular changes associated with aging and influenced by numerous intrinsic and extrinsic factors [2]. Occupational NIHL is a preventable external risk, while ARHL (presbycusis) is an inevitable intrinsic degenerative process, and both often coexist and exacerbate hearing loss in ageing populations.

Prolonged exposure to occupational noise results in persistent threshold shifts, mostly impacting the high-frequency spectrum (~4 kHz), which deteriorate gradually with continued exposure [3]. This aligns with findings that workplace noise exposure is associated with high-frequency hearing loss (3–6 kHz), particularly with 4-kHz notches on audiograms [4]. Similarly, progressive high-frequency sensorineural decline is a hallmark of ARHL [5]. Cochlear pathology evidence indicates that previous noise trauma leaves lasting sensory cell damage that exacerbates age-related degenerative changes [6].

Large-scale epidemiological data confirm a significant age × noise interaction, in which older adults experience accelerated high-frequency hearing loss under occupational noise exposure [7]. ARHL is characterized by progressive degeneration of inner and outer hair cells, strial atrophy, and neural loss; these declines are more severe in cochleae previously exposed to noise, suggesting that early acoustic trauma leaves a persistent cellular footprint that accelerates later sensory cell loss [6].

Recent large-scale studies further demonstrated that occupational noise significantly increases the risk of high-frequency hearing loss in older adults (OR = 2.564, 95% CI: 2.456–2.677), with a significant age × noise interaction (additive: RERI = 2.075, AP = 0.502, SI = 2.967; multiplicative: OR = 1.265, 95% CI: 1.176–1.36) [7]. Long-term cohort data from the Blue Mountains Hearing Study also showed that older persons with a history of occupational noise exposure were far more likely to develop ARHL over time [8].

Collectively, these findings provide convergent epidemiological and mechanistic evidence that older adults exposed to occupational noise experience faster auditory decline because prior noise damage amplifies age-related cochlear degeneration. However, existing studies are often cross-sectional, rely on self-reported exposure, and rarely quantify interaction effects. This study addresses these gaps using 1.1 million audiometric records to test the age × industry interaction on hearing loss. Moreover, formal interaction measures (RERI, AP, SI) are seldom applied. These limitations highlight the need for long-term studies incorporating rigorous confounder control, interaction analysis, and objective exposure assessment.

2. Method

Data were sourced from the "Prevalence of Hearing Loss in the United States by Industry, 2000–2008" dataset published by the National Institute for Occupational Safety and Health (NIOSH) via the Centers for Disease Control and Prevention (CDC) open data platform (Data.CDC.gov) [9]. The collection comprises de-identified, industry- and age-stratified audiometric data from 2000 to 2008, standardized according to the North American Industry Classification System (NAICS) [10, 11].

The data cleansing adhered to audiological norms. The frequencies at 3, 6, and 8 kHz (L3k, L6k, L8k, R3k, R6k, R8k) and the variable area were excluded since they do not constitute the conventional pure-tone average (PTA) and are irrelevant to the study's objective [12]. Records classified as 997 (Refused), 998 (No answer), and 999 (Not tested) were eliminated due to their representation of incorrect or absent audiometric data [13]. While 999 represented around 15% of cases—predominantly among older employees—exclusion mitigated bias and preserved analytical integrity [14]. More than 1.1 million de-identified audiometric recordings were examined, categorized by industry (NAICS) and age demographic. Hearing loss was characterized by the conventional pure-tone average (PTA) at frequencies of 0.5, 1, 2, and 4 kHz [15, 16].

Industry codes were standardized to guarantee analytical uniformity. The initial six-digit NAICS codes were condensed to the two-digit sector level and then amalgamated into ten principal industrial groupings, according to the categorization standards of the U.S. Bureau of Labor Statistics. Two extra categories, Information and Other Services, were included to provide coverage of smaller industries, resulting in twelve analytic industry files [17]. Each dataset included de-identified audiometric outcomes categorized by industry and age group.

The dependent variable was hearing loss status (yes/no), determined by the pure-tone average (PTA) threshold at frequencies of 0.5, 1, 2, and 4 kHz. The primary independent variables were industry, age group, and their interaction term (industry × age group). Three supplementary logistic regression models were utilized.

Within-industry trend (age effect): Logistic models correlating hearing loss with age groups were estimated for each industry to evaluate age-related patterns;

Between-industry comparison (industry effect): Stratified by age group, models correlating hearing loss with industry assessed whether inter-industry disparities were more pronounced among older workers compared to younger ones.

Interaction analysis (synergistic effect): A combined model correlating hearing loss with industry, age group, and the interaction of industry and age group investigated potential additive or synergistic effects of occupational noise exposure (represented by industry) and aging.

All models generated odds ratios (ORs) and 95% confidence intervals (CIs). The model's fit and collinearity were evaluated. Sensitivity tests were unnecessary due to excellent data completeness and internal consistency across industry-age strata, and model estimates remained stable throughout early evaluations. Descriptive statistics were performed to include demographic Mix and the prevalence of hearing loss across various age groups and sectors.

3. Results

3.1 Descriptive Analysis

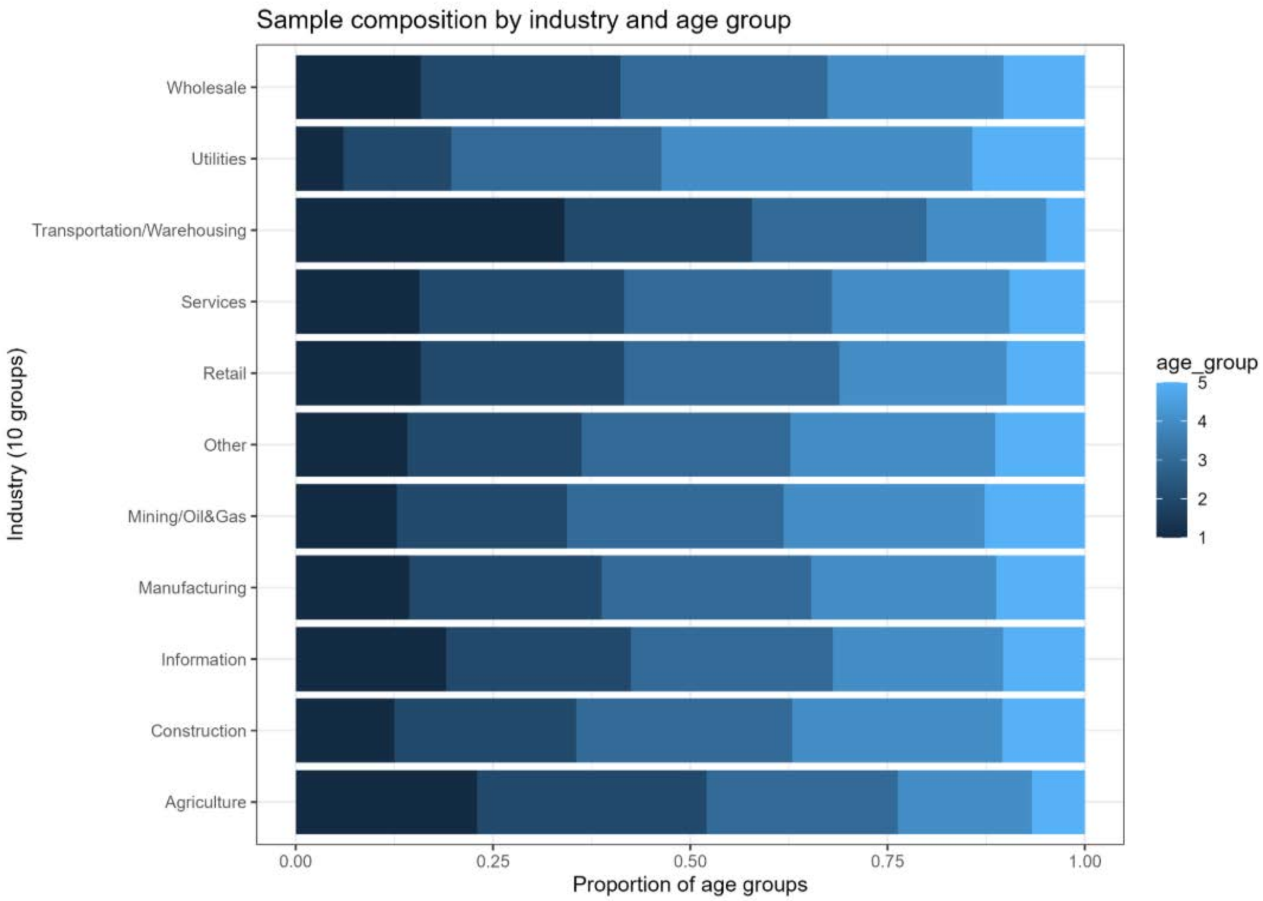

Fig. 1 Sample composition diagram (Picture credit: Original)

Descriptive statistics were performed to delineate the distribution of hearing loss across various sectors and age cohorts. Figure 1 illustrates the sample distribution by industry and age, indicating that most industries have a balanced representation throughout the five age categories, hence providing comparability across groups. Figure 2 illustrates age patterns in hearing-loss prevalence among industries. In all 12 sectors, the incidence of hearing loss significantly escalated with age, exhibiting a similar dose–response relationship. The rate of growth was notably pronounced in Mining/Oil & Gas, Agriculture, and Construction, indicating elevated cumulative noise exposure or inadequate protection in these industries.

ISSN 2959-409X

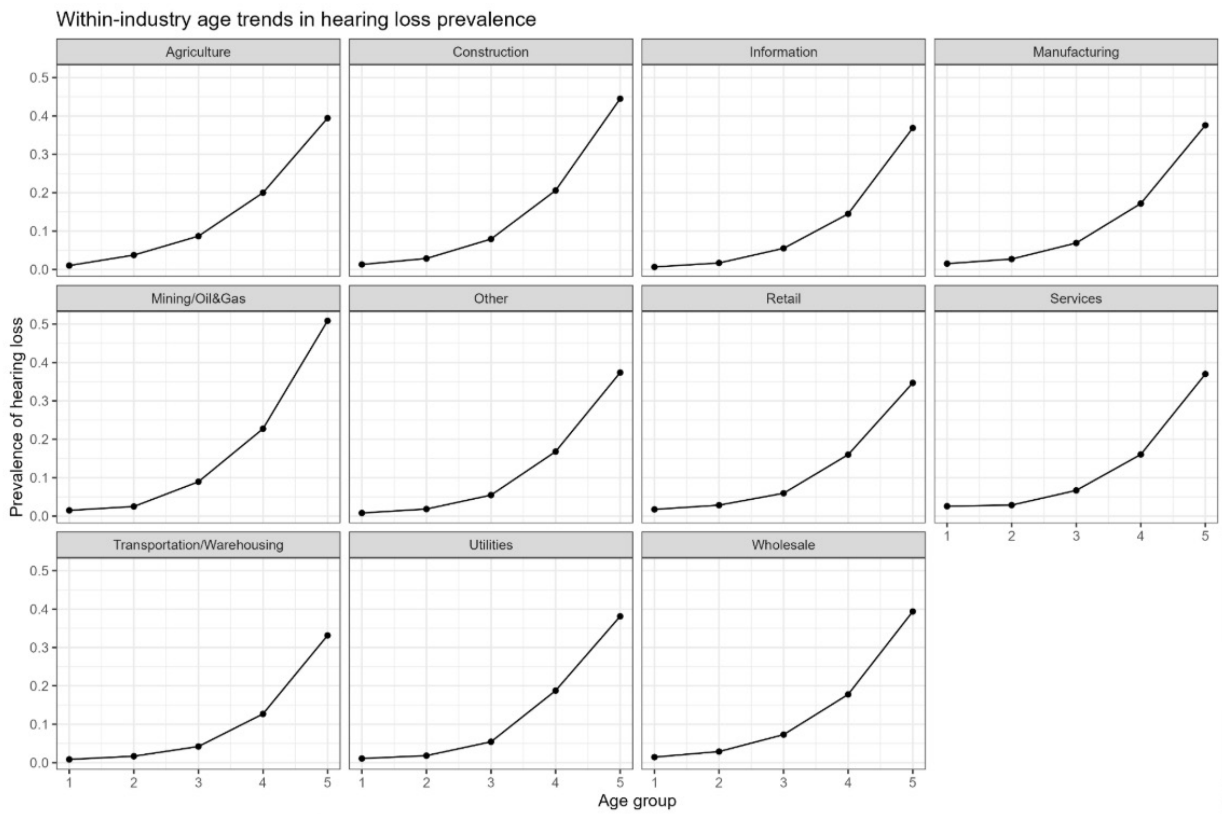

Fig. 2 Within-industry age-specific trends in hearing-loss prevalence (Picture credit: Original)

Figure 3 illustrates the disparities across industries, categorized by age group. In lower age groups (1–2), prevalence was often modest and uniform across sectors. Beginning with age group 3, inequalities across industries significantly increased, with Mining/Oil & Gas and Agriculture showing the greatest incidence (surpassing 0.5) in the oldest group, whilst Utilities and Transportation/Warehousing maintained the lowest prevalence. These trends underscore both age-related vulnerability and the diverse occupational noise settings.

Collectively, the descriptive data suggest that the prevalence of hearing loss is simultaneously impacted by occupational environment and aging. The pronounced age-related escalation seen in noise-intensive sectors indicates that the effects of aging may be intensified by prolonged noise exposure. This pattern facilitates the incorporation of industry, age, and their interaction factors in future regression models to investigate the possible synergistic influence of occupational noise and aging on auditory outcomes.

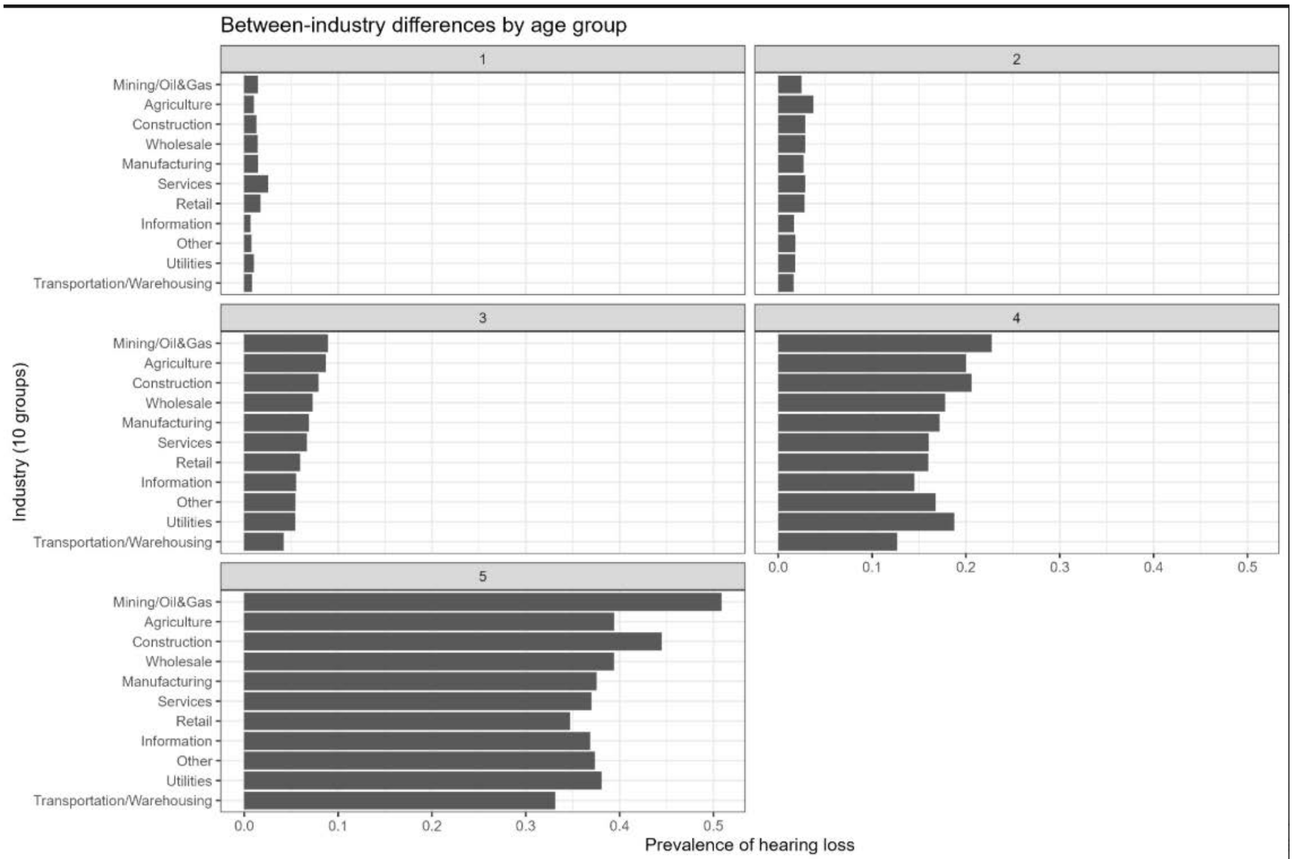

Fig. 3 Between-industry differences in hearing-loss prevalence across age groups (Picture credit: Original)

3.2 Overall Age-Related Trends in Hearing Loss Across Industries

The age-stratified prevalence of hearing loss among employees in the investigated sectors is shown in Figure 4. Prevalence increases significantly with age in all sectors, while the rate of growth varies by industry. Particularly sharp age gradients can be seen in noise-intensive industries, such as mining (including oil and gas extraction), utilities, construction, transportation, and agriculture. The prevalence of hearing loss increases from very low in the youngest group to almost half of workers in the oldest group. While older workers continue to have a much greater incidence than younger workers, the percentage of those afflicted in the oldest age group is closer to one-third. In contrast, less noise-exposed industries like retail trade and the finance/professional services sector show more moderate rises.

ISSN 2959-409X

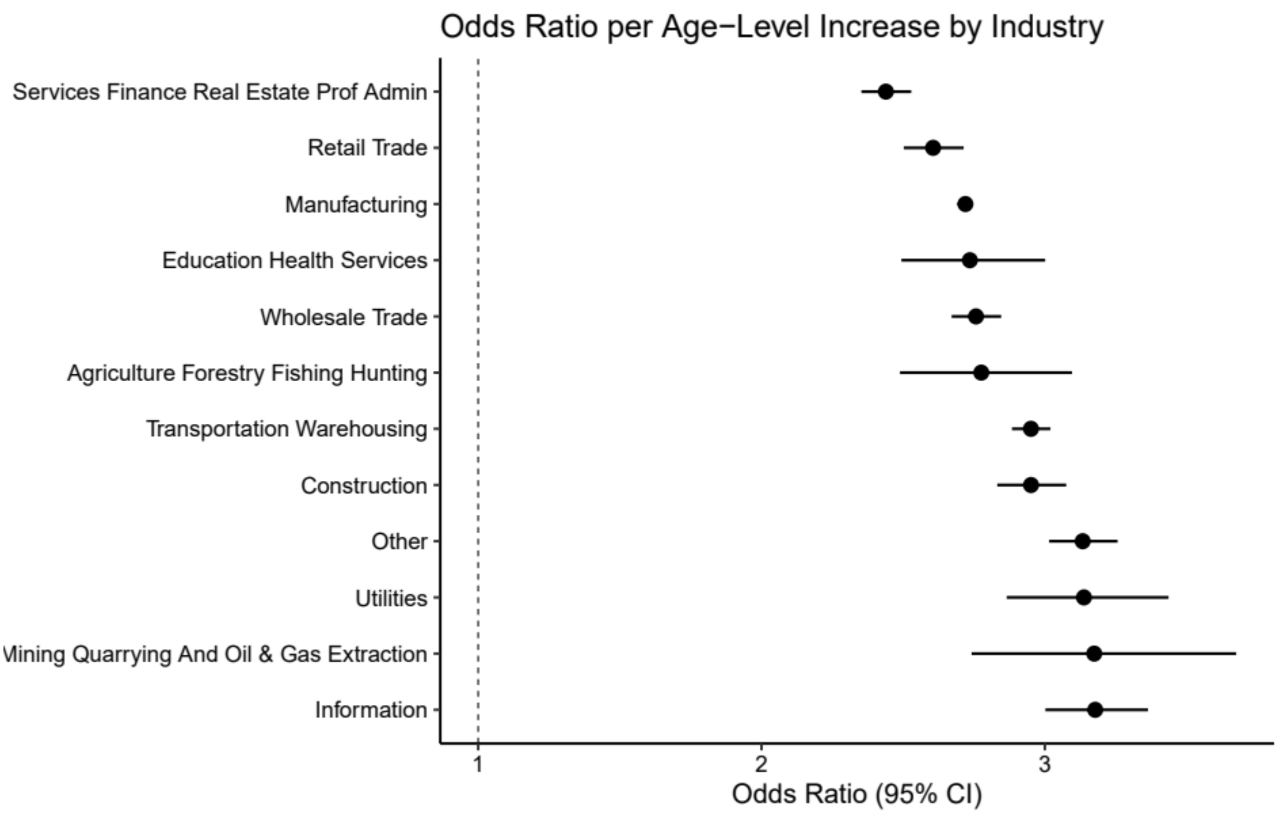

Fig. 4 Age-Specific Hearing-Loss Prevalence Across Industries (Picture credit: Original)

By showing the odds ratio (OR) and 95% CI for hearing loss for each incremental age group in each sector, Figure 5 statistically supports these trends. Higher age-related ORs in Figure 5 are linked with industries with steeper prevalence curves in Figure 4. Mining and utilities, for instance, have among of the highest ORs (around three per age-level increase), suggesting that the risk of hearing loss rises sharply with each age group. The age impact is less noticeable but still substantial in sectors with flatter age-prevalence slopes, such as retail commerce and finance/professional services, which have lower ORs (nearer 2.5). Even while the extent of age-related risk differs by sector group, it is noteworthy that all industries show ORs significantly over 1 ($p < 0.001$ for trend), demonstrating that age is a major risk factor for hearing loss across the board.

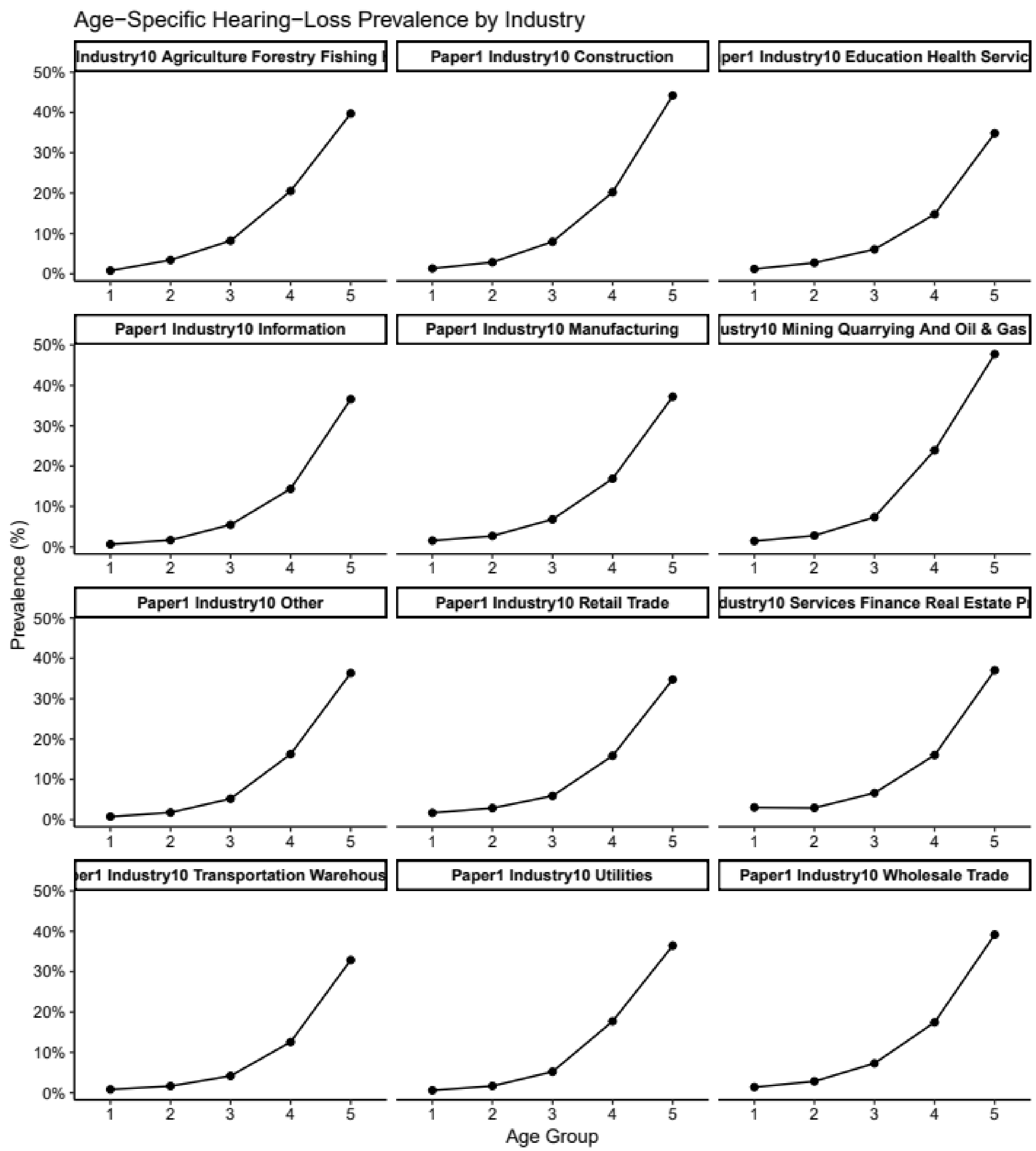

Fig. 5 Odds Ratios for Hearing Loss per Age-Level Increase by Industry (Picture credit: Original)

3.3 Cross-industry Comparison

The incidence of hearing loss in various age groups and sectors is shown in Figure 6. The prevalence of hearing loss rose significantly with age across all sectors, suggesting a strong age-related trend. The general frequency was modest (usually less than 5%) among younger persons (30–44 years old), and there were little variations across industries. A steady, virtually linear rise in hearing-loss risk with age was supported by logistic regression, which also showed that the linear age term (age_group.L) was significant ($p < 0.05$) in the majority of industries. A con-

ISSN 2959-409X

tinuous buildup of hearing deterioration with age is suggested by the large linear but non-higher-order terms seen in schooling and agriculture, for example

Conversely, nonlinear age effects were seen in several high-noise sectors. In manufacturing, there were both quadratic and cubic trends ($p < 0.001$), indicating rapid deterioration at later ages, whereas in construction, the prevalence of hearing loss increased significantly after age 55, with a significant quadratic component ($p = 0.03$). These nonlinear trends suggest that age-related hearing deterioration is exacerbated by cumulative occupational noise exposure, especially in mid- to late-life.

The differences among industries significantly increased by the age group of ≥ 65. Approximately 52% of people in construction and 45–50% of those in manufacturing had hearing loss, compared to 27% and 30% in information and finance, two sectors that are often known for having lower levels of occupational noise exposure. This discrepancy suggests that occupational risk and age-related hearing loss combine to produce noticeably steeper trajectories in industries with high noise levels. When taken as a whole, these results show that age-related hearing loss is ubiquitous and that exposure to certain industries has an increasing effect as people age.

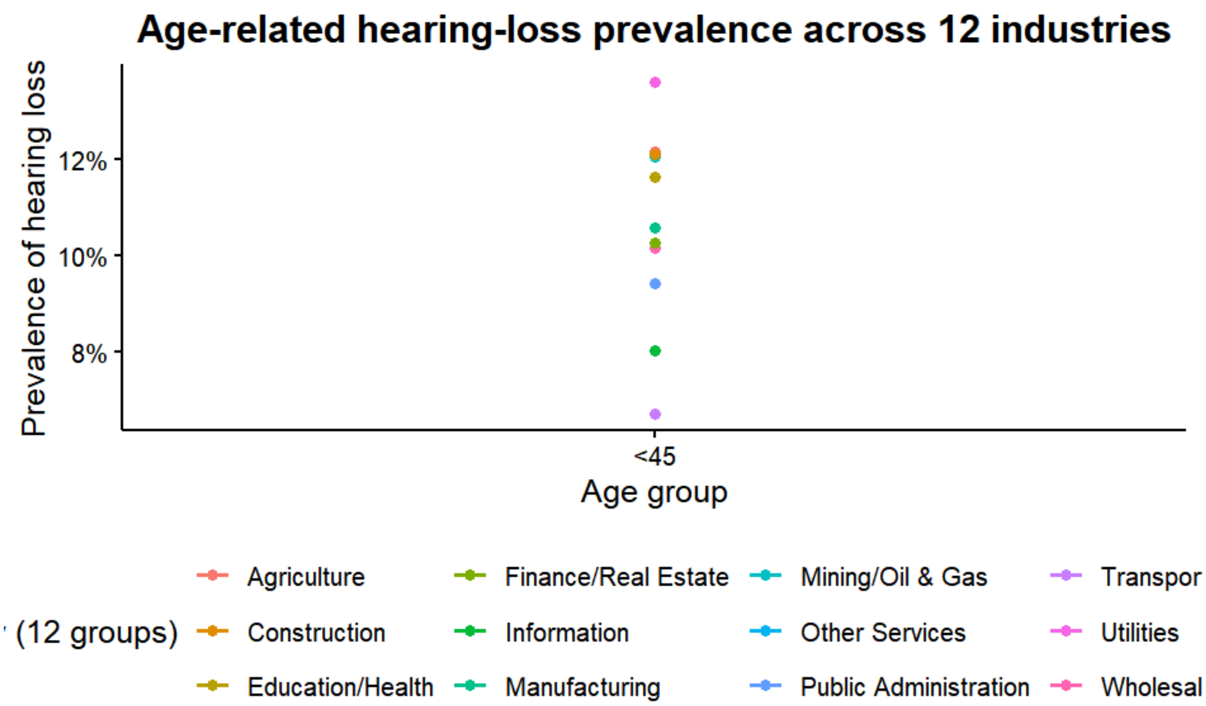

Fig. 6 Cross-industry variation in age-related hearing-loss prevalence (Picture credit: Original)

3.4 Interaction Between Industry and Age Group on Hearing Loss

When predicting the likelihood of hearing loss, the research showed a significant interaction between age group and industrial type ($p < 0.001$). The age-related rise in the incidence of hearing loss differed significantly by industry, suggesting that the workplace environment alters how aging affects auditory outcomes. The likelihood of hearing loss rose with age across all industries, as Figure 7 illustrates, but the rate of increase varied significantly by industry.

The estimated likelihood of hearing loss increased significantly in high-exposure occupations, including mining/oil and Gas, construction, and agriculture, from around 1-2 percent in the youngest group to almost 45-50 percent in the oldest. These sharp slopes reflect an age–exposure synergy, where long-term occupational noise accelerates cochlear cellular degeneration that typically accompanies aging, suggesting cumulative pathophysiological stress rather than independent effects. Conversely, sectors with lower exposure levels, such as education/health services and retail trade, showed a less age-related slope, with the oldest workers only making up 33–35% of the total. The logistic model's substantial negative interaction coefficients and this divergence support the idea that age effects are less pronounced in calmer work settings.

There was a clear trend in the Services/Finance/Real Estate/Professional category: younger employees already had somewhat higher anticipated probability (≈3%), but the percentage rise with age was very moderate, reaching ≈37% in the oldest group. These trends suggest that the extent to which aging exacerbates hearing loss is very context-dependent, even if baseline risks may vary by industry.

There were significant differences between industries within any age group. Employees in industries with high noise levels were 10–15 percentage points more likely to have hearing loss than their counterparts in less exposed industries.Together, our findings demonstrate that aging greatly increases the risk of hearing loss, but that this impact is amplified in high-noise work conditions, suggesting a mutually reinforcing relationship between biological aging and occupational exposure. Collectively, the regression results confirm that occupational noise exposure and aging interact synergistically, amplifying each other's impact on auditory deterioration, a pattern consistent with the "sensory vulnerability" hypothesis in gerontological hearing research.

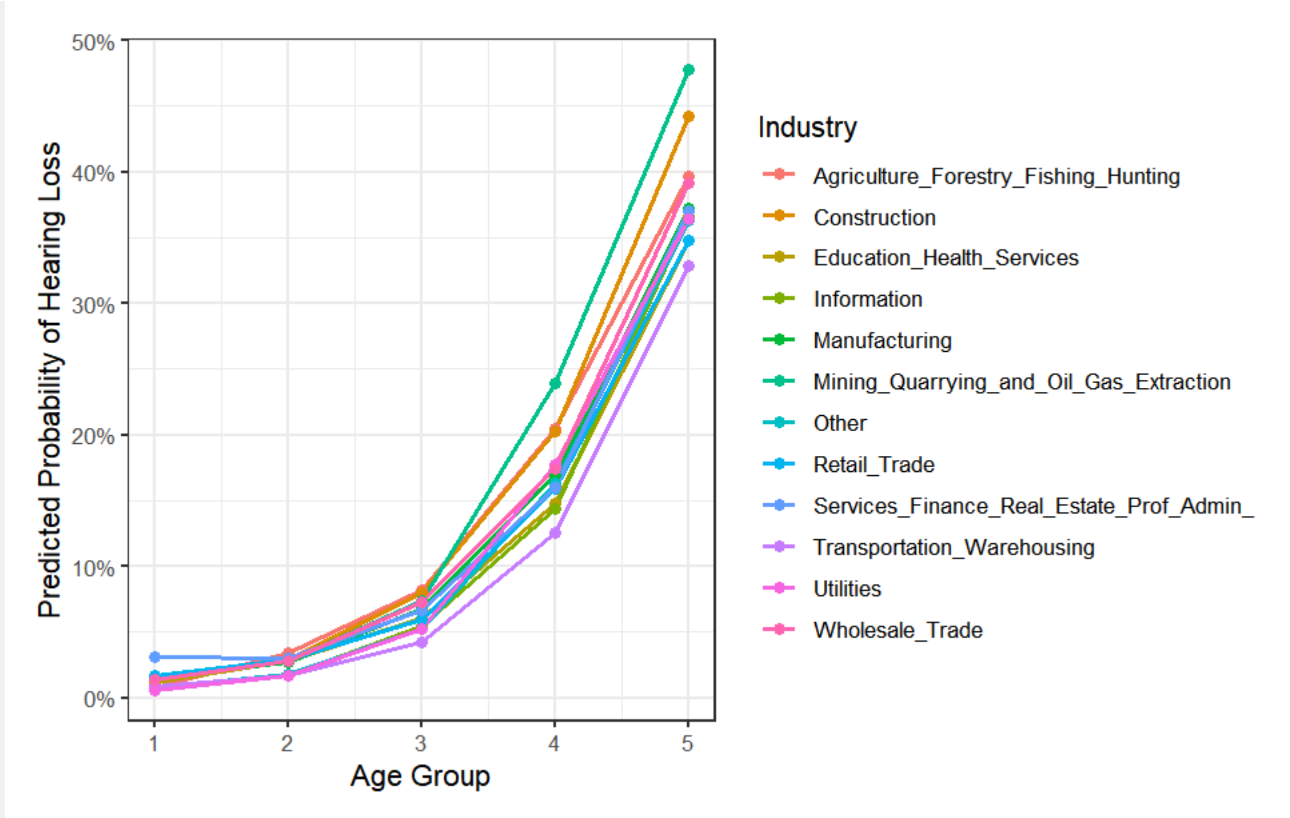

Fig. 7 Age-related trends in predicted hearing loss probability by industry (Picture credit: Original)

4. Discussion

This study provides, to our knowledge, the first large-scale industry-based evidence that occupational noise and aging act synergistically rather than additively in shaping hearing loss risk across the U.S. workforce. Previous studies lacked objective exposure measurements, were mostly cross-sectional, had inconsistent methodology, and seldom looked at interactions [3, 4, 6, 8]. To fill these gaps, over 1.1 million audiometric data using uniform NAICS industry classification and a defined definition of hearing loss (four-frequency PTA 0.5–4 kHz) were analyzed [17-19]. Modeling the age × industry interaction revealed that the risk of hearing loss was significantly influenced by both age and industry.

The interaction effects were notably diverse: compared to calmer occupations, high-noise industries (such as mining and construction) had greater age-related increases in the risk of hearing loss. This implies that age-related hearing deterioration is accelerated by occupational noise exposure. Our results expand our knowledge of occupational hearing loss factors by providing evidence of industry-specific aging trends in hearing loss at the national level.

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These findings have applications in prevention. By identifying high-risk populations (older workers in loud sectors), they allow for targeted hearing conservation. Smartphone sound-level meter applications assist employees in self-monitoring dangerous noise levels, and wearable noise dosimeters with real-time exposure alarms have been linked to a lower incidence of noise-induced hearing damage. These mobile health and wearable technologies may support customized hearing protection plans [20, 21]. The observed synergy may stem from irreversible oxidative stress and cochlear hair-cell depletion induced by chronic noise trauma, which amplifies subsequent age-related metabolic and neural degeneration.

Several constraints are worth mentioning. Inference about causality is limited by the cross-sectional design. Additive interaction metrics (RERI, synergy index [19]) were not computed, and noise exposure was proxied by industry (no personal dosimetry). If vulnerable workers quit loud employment, the healthy worker survival effect could have resulted in an underestimation of risk. Nevertheless, thorough data cleaning (removing around 15% of records with incorrect audiograms coded 997–999) reduced the need for further sensitivity tests by mitigating possible biases [13, 14]. To validate and build on these results, future research should utilize longitudinal designs with individual exposure measures, control for confounders (such as the use of hearing protection or ototoxicants), and use formal interaction metrics [19]. From a public health perspective, our findings highlight the urgency of integrating age-specific hearing conservation measures into occupational health policies, particularly in high-exposure sectors such as mining, construction, and agriculture.

5. Summary

A statistical examination of hearing loss by age and industry shows several distinct trends. In the model, the age group and industry main effects as well as their interaction were both statistically significant. First, age was shown to be a powerful predictor: the incidence of hearing loss rose significantly with age in all industries. There was a noticeable age gradient, as the model-predicted probability increased from a few percent in the youngest workers to almost one-third or more in the oldest age group. Second, there were notable variations in hearing loss across sectors. After adjusting for age, the prevalence of hearing loss was relatively lower in certain areas (such as retail trade or transportation) and greater overall in others (such as mining and construction). Lastly, a noteworthy interaction effect between age group and industry was found, suggesting that the age-related rise in hearing loss was not consistent across industries. In certain sectors, the gap between younger and older workers was more noticeable, whereas in others, younger workers had relatively high rates of hearing impairment (resulting in a flatter age gradient). These model-based results highlight the fact that age and industry both individually and together affect the risk of hearing loss, and that the patterns of age-related progression of hearing loss vary by industry.

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