Trends in the risk of hearing loss associated with occupational exposure to loud noise

Cameron Lozano

30 May 2025

Abstract

Occupational exposure to loud noise (OELN) has been the subject of research and policy for decades as a substantial risk factor for hearing loss. In the last 20 years, however, age-independent prevalences of hearing loss have declined in the U.S. despite OELN rates almost doubling. This study aims to better characterize these dynamics, hypothesizing that the increase in risk of hearing loss associated with a history of OELN has decreased in recent years. To investigate this, logistic regression analyses were performed on data collected in the nationally representative National Health and Nutrition Examination Survey between 1999 and 2016. The results of these analyses indicate that the effect of OELN on the risk of hearing loss in the U.S. significantly decreased in strength over the study period, suggesting that the nature of workplace noise-exposure or its association with other risk factors of hearing loss may have changed considerably in this time.

Contents

1 Introduction 1

2 Literature review 2

3 Data 3

4 Empirical strategy 5

5 Results 6

6 Conclusion 8

7 Data and code availability 11

References 12

1 Introduction

Hearing loss, the decline in hearing capabilities to a degree sufficient to interfere with social and job-related communication,[1] is a very common disorder, affecting about 15% of Americans aged 20–69 and about 65% of Americans aged 70 and older.[2] Although the prevalence of hearing loss in the United States has been declining within many age groups (e.g., adults aged 30-39, adults aged 40-49, etc.) in recent decades,[2,3] because the disorder is heavily associated with age – roughly doubling in prevalence with each decade of life[4] – and because the distribution of the U.S. population is shifting towards older adults, the number of American adults with hearing loss is expected to nearly double in the next 40 years if the prevalence rates do not substantially change in that time.[5]

While hearing loss can progress in severity rapidly – within hours or days in some pathologies and within weeks in the case of drug-induced ototoxicity – most cases of hearing loss progress over the course of years.[6] In these cases, hearing loss typically affects high frequencies first but later progresses across other frequencies.[6] Regardless of the pace of progression, the direct impacts of hearing loss on social function and communication are obvious, and studies have additionally shown associations between hearing loss and dementia, driving ability, walking ability, social isolation, cognition, functional decline, and falls.[7]

Although the greatest risk factor for hearing loss in adults is age, and genetic factors (i.e., family history) also contribute substantial risk, other risk factors are preventable. Among these, smoking, exposure to ototoxic medications, and exposure to loud noise have frequently been highlighted as targets for hearing loss prevention strategies.[6,8] Noise exposure, in particular, presents a challenge in this regard, as a risk factor that is both unique to hearing loss (unlike smoking) and nonspecific in its source (unlike drug ototoxicity). Much of the research into noise-induced hearing loss (NIHL) in recent years has called attention to the burden of "leisure noise" – recreational exposure to loud noise, such as through the use of personal audio devices (e.g., headphones), during live music performances, and in bars and clubs.[9] This risk is especially pronounced in teenagers and young adults: the World Health Organization (WHO) estimated in 2015 that 1.1 billion young people may be at risk of hearing loss due to unsafe listening practices, including nearly half of individuals aged 12–35 in middle- and high-income countries.[10] While prevention strategies should certainly be implemented to reduce recreational NIHL, it may be more effective (and has historically been more feasible) to target another threat, one which is an even more common cause of NIHL – occupational exposure to loud noise (OELN).

Like hearing loss, the prevalence of OELN has been changing in recent years. Although one might expect that, given its strong association with a higher risk of hearing loss, OELN is also becoming less prevalent within each age group, in actuality the reverse is true: while the prevalence of non-age-attributed hearing loss has decreased, the prevalence of OELN has increased.[11] Is OELN less of a threat to one's hearing condition than it once was? Despite this intriguing question, little research has been dedicated to understanding the phenomenon. This study seeks to better characterize it, investigating whether the risk of hearing loss associated with OELN truly has declined in recent years.

2 Literature review

Although the association between exposure to loud noise, especially in the workplace, and hearing loss has been recognized and studied for many decades, more recent developments in the availability of large-scale, representative data on the subject have led to better characterizations of this association than ever before. At the same time, some of these characterizations call attention to puzzling holes in our understanding of how OELN, hearing loss, and their connection is changing over time – questions which this study intends to help answer.

2.1 Occupational exposure to loud noise

Nelson et al. reported in 2005 that 16% of global adult-onset hearing loss could be attributed to OELN.[12] The prevalence of OELN-attributed hearing loss varies considerably between industries, with a heavier burden unsurprisingly borne by workers in economic sectors associated with high noise, such as mining, manufacturing, and construction.[12] This burden also weighs more heavily on developing nations, which both have higher rates of OELN-attributed hearing loss as well as more severe health implications of hearing loss.[12] Both the burden of OELN-attributed hearing loss in terms of disability-adjusted life-years (DALYs) and the socio-economic disparity of this burden have increased in recent years: Zhou et al. reported that the global burden almost doubled from 3.3 million to 6.0 million DALYs between 1990 and 2017, with growth rates being highest in low-income countries (increasing 110.7% on average) and lowest in high-income countries (increasing 43.3% on average).[13]

Attempts to mitigate the risk of hearing loss associated with OELN in the United States were first implemented more than 50 years ago, but these prevention strategies have changed little in the decades since. While the first occupational noise standard adopted by the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) in 1971 only applied to the construction sector, OSHA soon after adopted a more broader set of regulations under the 1983 Hearing Conservation Amendment, including a requirement for employers to provide a hearing conservation program for workers exposed to an 8-hour time-weighted average of 85 dB or more.[14] In 2002, OSHA additionally implemented a requirement for employers to provide appropriate hearing protection and regular hearing screenings for workers when workplace noise exceeds the earlier-defined hazardous level.[11]

Although these regulations likely do prevent some extent of OELN-attributed hearing loss, they comprise virtually the entirety of enforced preventative measures for what is still the most common work-related disease both in the U.S. and worldwide.[15,16] In 2014, 25% of workers in the U.S. reported a history of OELN, and about 7% of workers had hearing loss which could be attributed to OELN.[17] Pan et al. documented in 2022 that the percentage of working-age Americans reporting exposure to loud noise in current or past jobs more than doubled from 12.5% in a 1999–2004 nationally representative sample to 32% in a 2011–2016 nationally representative sample.[11] Troublingly, this increase in the prevalence of OELN did not occur alongside an increase in the prevalence of self-reported use of hearing protection (in or out of the workplace), which in fact declined over the study period from 41.3% to 32.7%.[11] The authors suggested a variety of potential causes for the increase in reported OELN, including the adoption of new technologies with louder machinery or with a wider range of noise exposures (such as powered tools and sound amplifiers in entertainment fields).[11] Regardless of the cause, their findings are striking and demonstrate the need for greater study on how the dynamics of OELN and hearing loss have changed in recent years.

2.2 Gaps in research

Comparison of recent findings related to hearing loss and OELN in the U.S. presents an interesting seeming-contradiction between three conclusions made across various literature: (a) exposure to loud noise in the workplace is significantly associated with a higher risk of hearing loss[12]; (b) the prevalence of reported OELN by adults aged 20–69 *increased* between 1999 and 2016[11]; and (c) the prevalence of hearing loss in adults aged 20–69 *decreased* between 1999 and 2016,[2,3] including in adults working in sectors associated with loud noise.[18] Is the risk of hearing loss associated with OELN decreasing? Though this seems to be the implication, there has been little to no direct investigation into whether the data sufficiently supports it. This project endeavors to perform such an investigation, drawing on the same data utilized by many of the studies heretofore referenced: the National Health and Nutrition Examination Survey undertaken by the U.S. Centers for Disease Control and Prevention and the National Center for Health Statistics between 1999 and 2016.[19]

3 Data

The National Health and Nutrition Examination Survey (NHANES) has been conducted every two years (each two-year survey period called a "cohort") since 1999 by the National Center for Health Statistics (NCHS). Combining interviews with physical examinations, NHANES datasets provide a host of information about the demographics, health, disease risk-factors, and nutritional statuses of its study participants. In conducting the NHANES, the NCHS takes great efforts to strengthen the generalizability of the data collected: the survey uses a complex, multistage, stratified, cluster design including oversampling of targeted subgroups (non-Hispanic black and Hispanic individuals, low-income individuals, and individuals over the age of 60), and the publically available datasets for each cohort include sample weights, primary sampling units, and stratification groups which allow for the data to be generalized to the entire non-institutionalized population of the United States. Some of the survey data that is relevant to this study was not collected from the populations of interest in specific cohorts – for example, several cohorts did not collect noise-exposure data from populations between the ages of 20 and 69 – and so these cohorts were not incorporated into the analysis.[3,11] Over the five NHANES cohorts examined in this study (1999–2000, 2001–2002, 2003–2004, 2011–2012, and 2015–2016), data was collected from a total of 50,853 study participants.

The data used in this study were collected during two different portions of the NHANES. The demographic characteristics, histories of exposure to loud noise in and out of the workplace, and self-reported hearing conditions were collected during the in-person household questionnaire portion, and the audiometric test measurements were collected during the physical examination portion. The household questionnaires were conducted by trained interviewers via computer-assisted personal interview. Due to some differences in the wordings of questions asked to different cohorts, variables were constructed by manipulating responses into groups that could be directly compared across all cohorts (see Section 4). The audiometric tests, which were only conducted on a portion of study participants in each cohort, were performed in sound booths in mobile examination centers. Audiometer instruments were calibrated daily for quality assurance and control.[3,11] The same protocol was used for every cohort, except for a difference between older and newer cohorts in the supra-aural headphone model used, which has not been found to have introduced statistically significant differences in results.[3] Thresholds were obtained in each ear at 0.5, 1, 2, 3, 4, 6, and 8 kHz, with the 1 kHz thresholds being recorded twice to confirm consistency. In this study, the 1 kHz threshold in each ear was calculated as the average of the two thresholds measured, and the binary variable designating hearing loss was determined (for two of three metrics) based on calculated pure tone averages (PTAs) as described in Section 4.1.3.

Because "hearing loss" is not an objectively defined outcome, this study examines its association with OELN using several different alternative metrics for hearing loss (see Section 4.1.3). The more objective/strict metrics rely on data collected from only a subset of NHANES study participants, so two different datasets (both derived from the NHANES data) were constructed for this study's analyses.

The first and larger dataset corresponds to the analyses which use a more subjective "self-reported hearing loss" metric as the outcome. All of its variables were derived from the in-person household questionnaire portions of the NHANES data. Study participants were included in this dataset if (a) they were interviewed as part of one of the five cohorts examined, (b) they were at least 20 years of age and less than 70 years of age, and (c) complete data was recorded for all variables of interest. Overall, 19,155 participants were included in this subset, with at least 3,000 included from each cohort. The unweighted characteristics of the participants included in this sample are given in Table 1.

The second dataset corresponds to the analyses which use a more objective/strict "audiometric exam-based hearing loss" metric as the outcome. This dataset is a subset of the first dataset; participants were additionally included in the second dataset if (d) complete data was recorded for the audiometric tests in the physical examination portion of the NHANES data. Overall, 12,222 participants were included in this dataset, with at least 1,300 included from each cohort. The unweighted characteristics of the participants included in this sample are given in Table 2.

While the characteristics described in Tables 1 and 2 correspond to the unweighted samples, this study's analyses utilized the sample weights provided in the NHANES data to ensure results are generalizable to the entire non-institutionalized U.S. population between the ages of 20 and 69 at the time each cohort was surveyed. Because the physical examinations were only conducted on a portion of the NHANES participants, the NCHS provides two different sample weights for each participant: one to be used for analyses only involving variables constructed from the household questionnaire portion, and one to be used for analyses involving any variables constructed from the physical examinations portion. For this reason, the former sample weights were used for the first dataset (which only includes questionnaire-derived variables), and the latter sample weights were used for the second dataset (which includes two exam-derived variables). In either case, analyses which include cohort as a variable were weighted using the 2-year sample weights provided with each cohort's data, whereas analyses which combine study participants from all cohorts were weighted using newly constructed 10-year sample weights. These new sample weights were calculated by multiplying each 2-year sample weight by $\frac{1}{5}$ (except for participants in the 1999–2000 and 2001–2002 cohorts; these participants' sample weights were calculated by multiplying the provided 4-year sample weights by $\frac{2}{5}$), in accordance with NCHS recommendations.

Table 1: Characteristics of study participants included in the unweighted "self-reported hearing loss" sample.

		Overall		By Cohort									
				1999–2000		2001–2002		2003–2004		2011–2012		2015–2016	
		N=19155		N=3156		N=3556		N=3504		N=4500		N=4439	
		n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)
Age[a]		43.16	(0.1)	42.61	(0.3)	41.92	(0.2)	42.76	(0.2)	43.78	(0.2)	44.21	(0.2)
Sex	Female	10 082	(52.6)	1704	(54.0)	1873	(52.7)	1855	(52.9)	2301	(51.1)	2349	(52.9)
Ethnicity	White	7643	(39.9)	1370	(43.4)	1767	(49.7)	1712	(48.9)	1483	(33.0)	1311	(29.5)
	Black	4309	(22.5)	596	(18.9)	739	(20.8)	775	(22.1)	1219	(27.1)	980	(22.1)
	Hispanic	5221	(27.3)	1073	(34.0)	916	(25.8)	853	(24.3)	968	(21.5)	1411	(31.8)
	Other	1982	(10.3)	117	(3.7)	134	(3.8)	164	(4.7)	830	(18.4)	737	(16.6)
Income	Under $20,000	4039	(21.1)	765	(24.2)	746	(21.0)	727	(20.7)	1023	(22.7)	778	(17.5)
	$20,000 to $44,999	5596	(29.2)	976	(30.9)	1062	(29.9)	1191	(34.0)	1214	(27.0)	1153	(26.0)
	$45,000 to $74,999	3933	(20.5)	675	(21.4)	856	(24.1)	751	(21.4)	722	(16.0)	929	(20.9)
	$75,000 and Over	4724	(24.7)	585	(18.5)	883	(24.8)	802	(22.9)	1179	(26.2)	1275	(28.7)
	Refused/unsure	863	(4.5)	155	(4.9)	9	(0.3)	33	(0.9)	362	(8.0)	304	(6.8)
Education	Less than high school	4843	(25.3)	1067	(33.8)	960	(27.0)	898	(25.6)	959	(21.3)	959	(21.6)
	High school graduate	4296	(22.4)	723	(22.9)	827	(23.3)	869	(24.8)	923	(20.5)	954	(21.5)
	Some college or more	10 016	(52.3)	1366	(43.3)	1769	(49.7)	1737	(49.6)	2618	(58.2)	2526	(56.9)
History of OELN		4580	(23.9)	525	(16.6)	629	(17.7)	622	(17.8)	1426	(31.7)	1378	(31.0)
Self-reported hearing loss		3580	(18.7)	608	(19.3)	721	(20.3)	721	(20.6)	776	(17.2)	754	(17.0)

[a]Age in "mean years (standard error)", not "n (%)".
Abbreviations: OELN = occupational exposure to loud noise.

Table 2: Characteristics of study participants included in the unweighted "exam-based hearing loss" sample.

		Overall		By Cohort									
				1999–2000		2001–2002		2003–2004		2011–2012		2015–2016	
		N=12222		N=1343		N=1557		N=1578		N=3704		N=4040	
		n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)
Age[a]		43.48	(0.1)	42.7	(0.4)	42.06	(0.4)	42.67	(0.4)	43.7	(0.2)	44.4	(0.2)
Sex	Female	6339	(51.9)	704	(52.4)	829	(53.2)	839	(53.2)	1839	(49.6)	2128	(52.7)
Ethnicity	White	4712	(38.6)	606	(45.1)	788	(50.6)	793	(50.3)	1296	(35)	1229	(30.4)
	Black	2798	(22.9)	228	(17.0)	326	(20.9)	329	(20.8)	1019	(27.5)	896	(22.2)
	Hispanic	3246	(26.6)	463	(34.5)	383	(24.6)	381	(24.1)	751	(20.3)	1268	(31.4)
	Other	1466	(12.0)	46	(3.4)	60	(3.9)	75	(4.8)	638	(17.2)	647	(16.0)
Income	Under $20,000	2461	(20.1)	320	(23.8)	318	(20.4)	321	(20.3)	809	(21.8)	693	(17.2)
	$20,000 to $44,999	3472	(28.4)	412	(30.7)	457	(29.4)	535	(33.9)	1015	(27.4)	1053	(26.1)
	$45,000 to $74,999	2459	(20.1)	287	(21.4)	390	(25.0)	320	(20.3)	610	(16.5)	852	(21.1)
	$75,000 and Over	3212	(26.3)	258	(19.2)	387	(24.9)	387	(24.5)	999	(27.0)	1181	(29.2)
	Refused/unsure	618	(5.1)	66	(4.9)	5	(0.3)	15	(1.0)	271	(7.3)	261	(6.5)
Education	Less than high school	2806	(23.0)	453	(33.7)	395	(25.4)	388	(24.6)	710	(19.2)	860	(21.3)
	High school graduate	2671	(21.9)	303	(22.6)	349	(22.4)	368	(23.3)	775	(20.9)	876	(21.7)
	Some college or more	6745	(55.2)	587	(43.7)	813	(52.2)	822	(52.1)	2219	(59.9)	2304	(57.0)
History of OELN		3302	(27)	234	(17.4)	289	(18.6)	293	(18.6)	1223	(33.0)	1263	(31.3)
HL	Self-reported	2299	(18.8)	273	(20.3)	317	(20.4)	343	(21.7)	671	(18.1)	695	(17.2)
	Exam-based, SF	1076	(8.8)	139	(10.3)	135	(8.7)	147	(9.3)	290	(7.8)	365	(9.0)
	Exam-based, HF	3049	(24.9)	339	(25.2)	354	(22.7)	383	(24.3)	918	(24.8)	1055	(26.1)

[a]Age in "mean years (standard error)", not "n (%)".
Abbreviations: OELN = occupational exposure to loud noise; HL = hearing loss; SF = speech-frequency; HF = high-frequency.

4 Empirical strategy

In order to investigate how the effect of OELN on hearing condition changed between 1999 and 2016, the variables of interest from the NHANES data were first operationalized such that, regardless of slight differences in study design between cohorts (e.g., different wordings of interview questions asking about exposure to loud noise), the characteristics of participants from different cohorts could be directly compared. Once these new variables were defined and the samples were appropriately weighted so as to represent the target population, logistic regression analyses were performed to examine the effects of OELN and time on the risk of hearing loss in the represented population. Each of these steps are described below.

4.1 Variable operationalization

The primary variables of interest to the above-described aim of this project are time, OELN, and hearing loss. Within the context of the NHANES data, each of these variables first needed to be operationalized. Time was operationalized as the specific cohort from which the data was collected, and OELN was estimated from responses to interview questions regarding exposure to noise in the workplace. The outcome, hearing loss, was operationalized in three different ways. The first operationalization is based on subjective, self-reported scorings of overall hearing condition during interviews. The second and third operationalizations are based on more objective measurements taken during audiometric examinations, indicating speech-frequency hearing loss and high-frequency hearing loss, respectively.

4.1.1 Time

The passage of time was operationalized as a numeric variable corresponding to the year at which data collection for each cohort began. For example, observations of all participants in the 1999-2000 cohort were assigned a year of 1999, observations of all participants in the 2001-2002 cohort were assigned a year of 2001, and so on. Because each cohort corresponds to the same length of time (2 years), and because data from every participant was weighted to account for oversampling and non-response (according to the sample weights and strata provided with the NHANES data for each cohort) prior to the analyses, it is reasonable to treat cohort-year as one ordered numeric variable rather than as multiple, discrete dummy variables for each cohort. The following five cohorts were used: 1999–2000, 2001–2002, 2003–2004, 2011–2012, and 2015–2016.

4.1.2 Occupational exposure to loud noise (OELN)

OELN was operationalized using responses to interview questions about workplace noise. The wordings of these questions varied slightly between cohorts, and so responses were grouped accordingly into comparable metrics of exposure. The 1999–2004 cohorts were asked two questions about OELN: (1) “Thinking of all the jobs you have ever had, have you ever been exposed to loud noise at work for at least three months? By loud noise I mean noise so loud that you had to speak in a raised voice to be heard,” with responses of yes and no; and (2) “On average, for how many hours per day are you currently exposed [if exposed to OELN in current job] or were you exposed [if exposed to OELN in a past job] to this loud noise?” with responses from 1 to 19 hours. The 2011–2012 and 2015–2016 cohorts were also asked two questions about OELN: (1) “Have you ever had a job, or combination of jobs where you were exposed to loud sounds for 4 or more hours a day, several days a week? Loud means so loud that you must speak in a raised voice to be heard,” with responses of yes and no; and (2) “For how many months or years have you been exposed at work to loud sounds or noise for 4 or more hours a day, several days a week?” with responses of less than 3 months, 3 to 11 months, 1 to 2 years, 3 to 4 years, 5 to 9 years, 10 to 14 years, 15 or more years. In order to compare OELN between cohorts asked questions with different wordings, this study operationalized OELN as a binary variable with a value of 1 if a participant reported being exposed to loud noise at work for at least four hours a day and for at least three months, and with a value of 0 otherwise.

4.1.3 Hearing condition

Three different outcomes were used to investigate the impact of time and OELN on the risk of hearing loss, each corresponding to an alternative operationalization of hearing loss.

For the first outcome, hearing loss was operationalized as a binary variable with a value of 1 if a participant self-reported that they have at least a little trouble with regards to their hearing (in response to an interview question) and with a value of 0 otherwise. Similarly to the operationalization of OELN, the specificity (and lack of nuance) in this definition is due to slight differences in the wordings of questions asked to different cohorts. The 1999-2004 cohorts were asked, “Which statement best describes your hearing (without hearing aid)? Would you say your hearing is good, that you have a little trouble, a lot of trouble, or are you deaf?” While conceptually very similar, the later cohorts were given a wider range of possible responses: “Which statement best describes your hearing (without a hearing aid or other listening devices)? Would you say your hearing is excellent, good, that you have a little trouble, moderate trouble, a lot of trouble, or are you deaf?” The “moderate trouble” option for the later cohorts, in particular, would be problematic if hearing condition were to be operationalized from interview responses as a numeric variable, because the response options offered to the earlier cohorts did not have the same “distance” between each option in terms of hearing condition. Instead, this study’s analyses operationalized hearing condition as either “good/excellent” (indicating no hearing loss) or “at least a little trouble” (indicating hearing loss) so that the earlier cohorts’ responses could be merged with the later cohorts’ responses.

For the second and third outcomes, hearing loss was operationalized as a binary variable with a value of 1 if audiometric exams indicated a participant had hearing loss and with a value of 0 otherwise. More specifically, for each participant, a pure-tone average (PTA) was calculated from the hearing-threshold levels at specific frequencies in each ear, and the PTA from the better ear (i.e., the lower of the two PTAs) was used to indicate whether the participant had hearing loss. The second outcome indicates “speech-frequency hearing loss” and used PTAs at frequencies of 0.5, 1, 2, and 4 kHz, whereas the third outcome indicates “high-frequency hearing loss” and used PTAs at frequencies of 3, 4, 6, and 8 kHz. For both outcomes, a positive indication of hearing loss was defined according to World Health Organization guidelines,[20] wherein individuals with a PTA ≥ 25 are described to have some level of hearing loss at the respective frequencies. While these guidelines further differentiate hearing loss into categories of severity by PTA (mild, moderate, moderately severe, severe, profound, and complete/total), this study grouped these together due to the relatively small sample of participants exhibiting any hearing loss (and especially more severe hearing loss).

4.1.4 Controlled-for variables

Several characteristics of the study participants may be associated with hearing loss as well as OELN and should therefore be included in all analyses as potential covariates. Based on existing literature suggesting such assocations, this study included age, sex, ethnicity, household income, and highest level of education as terms in all models.[21,22,23] All of these characteristics were obtained from NHANES participants during the interview portion of the survey, and any participants for whom responses were not recorded for all of these variables were excluded from the study samples. Due to some minor differences in the response options available to participants of different cohorts for some of these questions (specifically those regarding ethnicity, income, and education), responses were categorized into the groups listed in Tables 1 and 2 when necessary for appropriate comparison across cohorts.

4.2 Statistical analysis

For all three alternative operationalizations of hearing loss, the same general model was used to investigate the impact of time and OELN on hearing condition. Because all hearing loss metrics were binary variables, this study used a logistic regression model, given by

$$Y = \ln \frac{p}{1-p} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \vec{\gamma} \cdot \vec{Z} + \epsilon \quad (1)$$

where p is the probability of an individual having hearing loss; Y is the corresponding log-odds; α is the regression intercept; β_1, β_2, and β_3 are the regression coefficients of interest; X_1 is a dummy variable with a value of 1 if the individual reported OELN and a value of 0 otherwise; X_2 is the first survey year of the cohort to which the individual belongs; and $\vec{\gamma} \cdot \vec{Z}$ is given by

$$\vec{\gamma} \cdot \vec{Z} = \sum_{g=1}^{G} \gamma_g Z_g$$

for controlled-for variable Z_g (of G total controlled-for variables) and its associated regression coefficient γ_g.

Because log-odds values are somewhat difficult to interpret, after the regression coefficients were calculated, they were exponentiated into odds ratios (for each of the three outcomes representing hearing loss). Of particular interest in this model is the regression coefficient β_3 corresponding to the interaction term $X_1 X_2$. If this coefficient is significantly greater or less than zero for a given outcome-metric of hearing loss, it can be said that cohort-year is associated with the effect-size of OELN on the odds of hearing loss – e.g., for a negative β_3, that the effect-size of OELN on the odds of hearing loss decreased over time.

5 Results

5.1 Trends in OELN and hearing loss in U.S. population

Appropriate weighting of the NHANES data sample allowed for confirmation of the trends in OELN and hearing loss in the non-institutionalized U.S. population aged 20–69 (henceforth “the represented population”) reported by other authors referenced in Section 2. The overall and by-cohort prevalences of these variables, as well as the other demographic characteristics, are described for the represented population in Tables 3 and 4.

In the larger weighted sample this study examines, corresponding to the “self-reported hearing loss” outcome (Table 3), the percent of the represented population with a history of being exposed to loud noise in the workplace remained roughly constant from 1999 (15.9%) to 2002 (17.5%) before nearly doubling to 33.3% in 2011 and 31.3% in 2015. A similar trend was observed for OELN in the smaller weighted sample, corresponding to the “audiometric exam-based hearing loss” outcome sample (Table 4).

Conversely, in both samples, the percent of the represented population with hearing loss did not substantially change between 1999 and 2016. In the larger, “self-reported hearing loss” outcome sample, 20.4% of the combined represented population self-reported having “at least a little trouble hearing”; although this proportion did decrease slightly between the 2003–2004 cohort (21.9%) and the 2011-2012 cohort (18.7%), this decrease does not appear to be a part of any broader trend in self-reported hearing loss between 1999 and 2016. In the smaller “exam-based hearing loss” outcome sample, 8.1% of the combined represented population exhibited speech-frequency hearing loss, and 24.3% exhibited high-frequency hearing loss; neither of these two metrics’ proportions exhibited substantial changes across the cohorts examined.

5.2 Trends in the effect of OELN on hearing loss

Because “hearing loss” is not an entirely objective term, the trend in the effect of OELN on hearing loss over time was analyzed separately for three different outcome metrics of hearing loss: (1) “self-reported hearing loss”, identifying individuals who self-reported having “at least a little trouble hearing”; (2) “exam-based, speech-frequency hearing loss”, identifying individuals with better-ear pure tone averages (PTAs) ≥ 25 dB for frequencies of 0.5, 1, 2, and 4 kHz as measured by audiometric exam; and (3) “exam-based, high-frequency hearing loss”, identifying individuals with better-ear PTAs ≥ 25 dB for frequencies of 3, 4, 6, and 8 kHz as measured by audiometric exam (see 4.1.3 for more details).

Table 3: Characteristics of weighted "self-reported hearing loss" outcome sample.

		Overall	By Cohort				
			1999–2000	2001–2002	2003–2004	2011–2012	2015–2016
		% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]
Age[a]		42.5 [42.1–43.0]	40.5 [40.1–41.0]	41.0 [40.0–41.9]	42.0 [41.2–42.7]	43.3 [42.0–44.6]	43.9 [43.0–44.7]
Sex	Female	51.5 [50.8–52.2]	51.3 [49.2–53.4]	50.9 [49.5–52.2]	51.5 [50.1–52.9]	51.8 [50.1–53.5]	51.9 [50.6–53.3]
Ethnicity	White	67.3 [64.3–70.3]	69.8 [64.6–75.1]	70.9 [66.4–75.3]	70.1 [63.2–77.0]	64.9 [57.1–72.7]	62.6 [54.9–70.4]
	Black	11.4 [9.7–13.2]	10.6 [7.4–13.9]	11.3 [7.9–14.6]	11.6 [8.1–15.0]	11.9 [7.4–16.3]	11.8 [7.5–16.0]
	Hispanic	14.6 [12.2–16.9]	14.8 [9.0–20.5]	13.4 [8.1–18.6]	12.6 [7.9–17.4]	15.3 [10.1–20.4]	16.0 [10.6–21.4]
	Other	6.7 [5.8–7.6]	4.8 [2.7–6.8]	4.5 [3.2–5.8]	5.7 [4.2–7.2]	8.0 [5.7–10.2]	9.6 [7.1–12.1]
Income	Under \$20,000	15.0 [13.9–16.1]	18.2 [15.1–21.3]	17.0 [15.4–18.5]	14.4 [12.2–16.7]	15.6 [12.9–18.3]	11.0 [9.1–13.0]
	\$20,000 to \$44,999	25.4 [23.9–26.9]	29.3 [25.6–33.1]	26.1 [23.3–28.9]	30.1 [26.5–33.6]	23.2 [19.5–26.8]	20.3 [17.7–22.8]
	\$45,000 to \$74,999	23.3 [22.0–24.6]	24.5 [22.3–26.7]	25.8 [23.4–28.2]	25.3 [22.4–28.2]	19.7 [16.1–23.3]	22.1 [19.6–24.6]
	\$75,000 and Over	32.9 [30.4–35.5]	23.8 [18.4–29.1]	31.0 [26.8–35.3]	29.2 [24.2–34.2]	35.8 [29.6–42.1]	41.1 [35.7–46.6]
	Refused/unsure	3.4 [2.9–3.9]	4.2 [2.8–5.5]	0.1 [0.0–0.3]	1.0 [0.3–1.7]	5.7 [4.2–7.2]	5.5 [4.4–6.6]
Education	Less than high school	16.2 [14.9–17.5]	20.8 [18.2–23.4]	16.9 [14.6–19.1]	16.2 [14.4–18.0]	15.0 [11.5–18.4]	13.2 [10.0–16.4]
	High school graduate	22.9 [21.6–24.1]	25.7 [21.4–30.0]	24.8 [22.7–26.9]	26.1 [23.5–28.7]	19.3 [16.7–21.9]	20.1 [17.8–22.3]
	Some college or more	60.9 [58.9–63.0]	53.5 [48.4–58.6]	58.4 [54.6–62.1]	57.7 [55.2–60.2]	65.7 [60.7–70.8]	66.7 [62.1–71.3]
History of OELN		23.9 [22.6–25.3]	15.9 [13.6–18.2]	17.5 [15.5–19.4]	17.5 [14.5–20.6]	33.3 [29.5–37.1]	31.3 [28.6–34.0]
Self-reported hearing loss		20.4 [19.5–21.3]	20.4 [18.1–22.7]	21.4 [20.1–22.6]	21.9 [20.1–23.8]	18.7 [16.5–20.9]	19.5 [17.2–21.7]

[a]Age in mean years, not %.
Abbreviations: CI = confidence interval; OELN = occupational exposure to loud noise.

Table 4: Characteristics of weighted "exam-based hearing loss" outcome sample.

		Overall	By Cohort				
			1999–2000	2001–2002	2003–2004	2011–2012	2015–2016
		% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]	% [95% CI]
Age[a]		43.0 [42.4–43.5]	40.9 [40.0–41.8]	41.2 [40.3–42.0]	42.1 [41.5–42.7]	43.5 [42.1–44.9]	44.0 [43.1–44.9]
Sex	Female	51.0 [50.2–51.9]	49.8 [47.1–52.5]	52.1 [50.0–54.3]	51.0 [48.6–53.3]	50.6 [48.8–52.4]	51.6 [50.4–52.9]
Ethnicity	White	67.5 [63.9–71.1]	70.8 [64.3–77.3]	72.0 [66.8–77.1]	71.9 [65.6–78.3]	66.8 [59.1–74.6]	63.4 [55.6–71.2]
	Black	11.0 [9.0–13.0]	9.2 [6.3–12.1]	10.9 [7.5–14.2]	10.6 [7.3–13.8]	11.5 [7.1–16.0]	11.6 [7.3–15.8]
	Hispanic	14.4 [11.8–16.9]	15.9 [9.5–22.3]	12.3 [6.9–17.8]	12.0 [7.2–16.9]	14.1 [9.2–19.0]	15.7 [10.4–21.0]
	Other	7.1 [6.0–8.1]	4.1 [1.6–6.5]	4.8 [3.3–6.4]	5.5 [4.1–6.9]	7.5 [5.4–9.6]	9.3 [6.9–11.7]
Income	Under \$20,000	13.9 [12.6–15.1]	18.3 [13.5–23.1]	16.5 [14.7–18.2]	13.8 [11.4–16.1]	14.7 [12.1–17.2]	10.6 [8.6–12.6]
	\$20,000 to \$44,999	24.2 [22.4–26.0]	28.4 [22.8–34.1]	25.2 [21.8–28.5]	30.6 [26.3–34.8]	23.5 [19.6–27.3]	20.3 [17.8–22.7]
	\$45,000 to \$74,999	22.8 [21.2–24.3]	24.7 [20.7–28.6]	26.9 [23.4–30.4]	24.1 [21.5–26.6]	20.3 [16.6–24.0]	22.1 [19.6–24.7]
	\$75,000 and Over	35.3 [32.2–38.3]	24.3 [17.5–31.0]	31.3 [26.5–36.1]	30.6 [25.7–35.5]	36.2 [29.6–42.8]	41.7 [36.1–47.3]
	Refused/unsure	3.9 [3.2–4.7]	4.4 [1.7–7.0]	0.1 [0.0–0.3]	1.0 [0.2–1.8]	5.3 [3.6–7.1]	5.3 [4.2–6.5]
Education	Less than high school	14.7 [13.1–16.3]	20.8 [17.5–24.2]	15.5 [13.0–18.0]	14.9 [12.9–16.8]	13.7 [10.3–17.0]	12.9 [9.6–16.2]
	High school graduate	21.6 [20.3–22.9]	24.7 [21.1–28.2]	24.5 [22.1–26.9]	25.1 [21.9–28.3]	19.7 [16.7–22.7]	19.7 [17.7–21.8]
	Some college or more	63.7 [61.2–66.1]	54.5 [49.6–59.4]	60.0 [56.1–63.9]	60.0 [57.5–62.6]	66.6 [61.0–72.2]	67.3 [62.8–71.9]
History of OELN		27.2 [25.4–28.9]	16.7 [13.7–19.7]	18.1 [15.2–21.0]	18.3 [14.6–22.0]	34.4 [30.0–38.8]	31.7 [29.1–34.3]
HL	Self-reported	20.8 [19.7–22.0]	21.5 [18.3–24.7]	22.2 [19.8–24.6]	23.5 [21.0–25.9]	19.6 [17.2–22.0]	19.8 [17.6–22.0]
	Exam-based, SF	8.1 [7.3–8.9]	8.1 [5.8–10.4]	7.5 [5.8–9.1]	8.5 [6.5–10.5]	8.1 [6.4–9.8]	8.1 [6.9–9.4]
	Exam-based, HF	24.3 [22.9–25.7]	22.2 [19.5–25.0]	20.9 [18.0–23.7]	23.3 [20.9–25.6]	24.9 [21.5–28.2]	26.0 [23.6–28.3]

[a]Age in mean years, not %.
Abbreviations: CI = confidence interval; OELN = occupational exposure to loud noise; HL = hearing loss; SF = speech-frequency; HF = high-frequency.

For the "self-reported hearing loss" outcome, while OELN was associated with significantly greater odds of hearing loss ($p < 0.01$) in the multivariate model adjusted for age, sex, ethnicity, income, and education – in agreement with other studies referenced in Section 2 – this effect was no longer significant once the interaction term between year/cohort and OELN was added to the model (Table 5). Despite this, the interaction term itself also had no significant effect on the odds of hearing loss. Overall, this evidence supports a significant impact of OELN on the risk of self-reported hearing loss, but it does not suggest this impact significantly changed over time.

For the "exam-based, speech-frequency hearing loss" outcome, however, the logistic regression analysis tells a different story (Table 6). Here, OELN was associated with significantly greater odds of hearing loss both before and after the cohort×OELN interaction term was added to the model ($p < 0.05$ and $p < 0.01$, respectively), and this interaction term has a significant negative association with the odds of hearing loss ($p < 0.01$). In other words, while OELN does

Table 5: Factors associated with self-reported hearing loss.

		Univariate Odds Ratio [95% CI]		Multivariate Odds Ratio[a] w/o Interaction [95% CI]		Multivariate Odds Ratio[a] w/Interaction [95% CI]	
Cohort (year)		0.99	[0.98–1.00]	0.98**	[0.97–0.99]	0.98**	[0.97–0.99]
Age		1.04**	[1.04–1.05]	1.04**	[1.04–1.05]	1.04**	[1.04–1.05]
Sex[b]	Female	0.60**	[0.53–0.67]	0.65**	[0.58–0.73]	0.65**	[0.58–0.73]
Ethnicity	White	ref		ref		ref	
	Black	0.46**	[0.40–0.52]	0.47**	[0.41–0.53]	0.47**	[0.41–0.53]
	Hispanic	0.59**	[0.52–0.68]	0.66**	[0.56–0.78]	0.66**	[0.56–0.78]
	Other	0.68**	[0.56–0.84]	0.79*	[0.64–0.98]	0.79*	[0.64–0.98]
Income	Under $20,000	ref		ref		ref	
	$20,000 to $44,999	0.92	[0.81–1.03]	0.84*	[0.74–0.96]	0.84*	[0.74–0.96]
	$45,000 to $74,999	0.95	[0.84–1.08]	0.82**	[0.70–0.95]	0.82**	[0.70–0.95]
	$75,000 and Over	0.77**	[0.66–0.91]	0.68**	[0.56–0.82]	0.68**	[0.56–0.82]
	Refused/unsure	0.74*	[0.55–0.99]	0.71*	[0.54–0.93]	0.71*	[0.54–0.93]
Education	Less than high school	ref		ref		ref	
	High school graduate	1.06	[0.91–1.25]	1.02	[0.86–1.22]	1.02	[0.86–1.22]
	Some college or more	0.82**	[0.72–0.94]	0.91	[0.78–1.05]	0.91	[0.79–1.05]
History of OELN		2.10**	[1.87–2.36]	1.84**	[1.63–2.09]	8e6	[0.00–4e23]
Cohort×OELN		n/a		n/a		0.99	[0.97–1.01]

[a]Adjusted for age, sex, ethnicity, income, and education.
[b]Male as a reference group.
* $p < 0.05$, ** $p < 0.01$
Abbreviations: CI = confidence interval; OELN = occupational exposure to loud noise.

still increase the risk of hearing loss independently of time to some extent, the strength of the positive effect of OELN on hearing loss significantly *decreased* between 1999 and 2016. The odds-ratio for the interaction term was 0.95, meaning that the increase in the odds of hearing loss associated with having been exposed to loud noise in the workplace was on average 5% lower each successive year; for example, if a positive history of OELN was associated with a 100% increase in the odds of hearing loss in 2001, it would be associated with a 95% increase in the odds of hearing loss in 2002, a 50% increase in the odds of hearing loss in 2011, and so on. Notably, while cohort/year also had a significant negative association with the risk of hearing loss, this association was no longer significant once the interaction term was included, suggesting that a considerable part of the negative effect of time on the risk of hearing loss could be explained by the weakening over time of the effect of OELN on hearing loss.

Analyses using the "exam-based, high frequency hearing loss" outcome produced similar results (Table 7) as those using the speech-frequency hearing loss outcome. OELN was associated with a significantly higher risk of hearing loss both before and after the cohort×OELN interaction term was included ($p < 0.01$ and $p < 0.05$, respectively), and the interaction term had a significant negative association with the risk of hearing loss ($p < 0.05$). The interaction term was closer to one for this outcome, however (0.97 compared to 0.95 for the speech-frequency hearing loss outcome), suggesting that the decrease in strength over time of the effect of OELN on the risk of high-frequency hearing loss may be less pronounced than that on the risk of speech-frequency hearing loss.

6 Conclusion

Decades of research[11,12,13,15,16,17] have shown that exposure to loud noise in the workplace considerably increases the risk of hearing loss, and this project agrees with this conclusion – for the non-institutionalized U.S. population aged 20–69 between 1999 and 2016, a positive history of OELN was associated with significantly greater odds of exhibiting hearing loss regardless of whether this was measured as self-reported subjective hearing condition or objective results of an audiometric exam. What current research has yet to examine, however, is whether and how this observed phenomenon has changed in recent years, questions which seem prudent given the apparent contradiction between the observed decline in age-independent rates of hearing loss in the U.S.[2,3] occurring alongside an observed increase in reported OELN.[11] The most obvious implication of these observations is that occupational exposure to loud noise may not be as strong of a risk factor for hearing loss now as it once was, but, despite the availability of large-scale, broadly representative data on these trends collected as part of the NHANES studies – and the frequent use of this data by authors researching hearing loss and noise exposure – no conclusive evidence has been published in support of this implication.

This project aimed to investigate whether the effect of OELN on the risk of hearing loss truly has changed in recent years. Overall, our results support this conclusion: between 1999 and 2016, the association between reporting a history of exposure to loud noise in the workplace – for at least 4 hours per day and for at least 3 months – and exhibiting clinically significant speech- or high-frequency hearing loss as measured by audiometric exam declined in strength signifi-

Table 6: Factors associated with audiometric exam-based, speech-frequency hearing loss.

		Univariate Odds Ratio [95% CI]		Multivariate Odds Ratio[a] w/o Interaction [95% CI]		Multivariate Odds Ratio[a] w/Interaction [95% CI]	
Cohort (year)		1.00	[0.98–1.02]	0.98*	[0.96–1.00]	1.00	[0.97–1.02]
Age		1.11**	[1.10–1.12]	1.11**	[1.10–1.13]	1.11**	[1.10–1.13]
Sex[b]	Female	0.45**	[0.38–0.54]	0.39**	[0.31–0.49]	0.39**	[0.31–0.48]
Ethnicity	White	ref		ref		ref	
	Black	0.43**	[0.34–0.53]	0.39**	[0.30–0.51]	0.39**	[0.30–0.51]
	Hispanic	0.73**	[0.59–0.90]	0.83	[0.63–1.09]	0.84	[0.64–1.10]
	Other	0.80	[0.58–1.11]	0.98	[0.67–1.41]	0.97	[0.67–1.40]
Income	Under $20,000	ref		ref		ref	
	$20,000 to $44,999	0.88	[0.73–1.07]	0.90	[0.74–1.09]	0.89	[0.73–1.09]
	$45,000 to $74,999	0.78	[0.61–1.01]	0.73*	[0.55–0.97]	0.72*	[0.55–0.96]
	$75,000 and Over	0.51**	[0.38–0.68]	0.54**	[0.40–0.73]	0.54**	[0.40–0.73]
	Refused/unsure	0.76	[0.42–1.37]	0.78	[0.43–1.43]	0.78	[0.43–1.42]
Education	Less than high school	ref		ref		ref	
	High school graduate	0.63**	[0.49–0.81]	0.63**	[0.48–0.84]	0.64**	[0.48–0.85]
	Some college or more	0.43**	[0.35–0.53]	0.49**	[0.37–0.63]	0.49**	[0.38–0.63]
History of OELN		1.93**	[1.57–2.39]	1.39*	[1.08–1.78]	8e40**	[8e12–7e68]
Cohort×OELN		n/a		n/a		0.95**	[0.92–0.99]

[a]Adjusted for age, sex, ethnicity, income, and education.
[b]Male as a reference group.
* $p < 0.05$, ** $p < 0.01$
Abbreviations: CI = confidence interval; OELN = occupational exposure to loud noise.

Table 7: Factors associated with audiometric exam-based, high-frequency hearing loss.

		Univariate Odds Ratio [95% CI]		Multivariate Odds Ratio[a] w/o Interaction [95% CI]		Multivariate Odds Ratio[a] w/Interaction [95% CI]	
Cohort (year)		1.02**	[1.00–1.03]	0.99	[0.98–1.01]	1.00	[0.99–1.02]
Age		1.12**	[1.11–1.13]	1.14**	[1.13–1.14]	1.14**	[1.13–1.14]
Sex[b]	Female	0.41**	[0.36–0.46]	0.26**	[0.22–0.30]	0.26**	[0.22–0.30]
Ethnicity	White	ref		ref		ref	
	Black	0.46**	[0.40–0.52]	0.38**	[0.33–0.44]	0.38**	[0.33–0.44]
	Hispanic	0.61**	[0.53–0.69]	0.70**	[0.58–0.84]	0.70**	[0.59–0.84]
	Other	0.71**	[0.58–0.87]	0.85	[0.65–1.10]	0.84	[0.65–1.10]
Income	Under $20,000	ref		ref		ref	
	$20,000 to $44,999	0.99	[0.84–1.17]	0.99	[0.82–1.20]	0.99	[0.82–1.20]
	$45,000 to $74,999	1.04	[0.87–1.24]	0.91	[0.71–1.15]	0.90	[0.71–1.15]
	$75,000 and Over	0.77**	[0.64–0.93]	0.62**	[0.50–0.78]	0.62**	[0.50–0.78]
	Refused/unsure	1.07	[0.80–1.42]	1.03	[0.69–1.53]	1.03	[0.69–1.53]
Education	Less than high school	ref		ref		ref	
	High school graduate	0.80**	[0.68–0.94]	0.73**	[0.60–0.88]	0.73**	[0.60–0.88]
	Some college or more	0.58**	[0.49–0.67]	0.53**	[0.42–0.67]	0.53**	[0.42–0.67]
History of OELN		1.94**	[1.71–2.19]	1.41**	[1.21–1.65]	5e27*	[2e4–1e51]
Cohort×OELN		n/a		n/a		0.97*	[0.94–1.00]

[a]Adjusted for age, sex, ethnicity, income, and education.
[b]Male as a reference group.
* $p < 0.05$, ** $p < 0.01$
Abbreviations: CI = confidence interval; OELN = occupational exposure to loud noise.

cantly over time. While this trend over time was not observed between OELN and self-reported/subjective hearing loss, it seems apparent that this alternative metric of hearing loss would be subject to substantially more bias (e.g., individuals who report OELN and are aware that it is associated with hearing loss may scrutinize their hearing condition more and self-report it to be worse than individuals with comparable hearing condition but without a history of OELN) and the results of these analyses should not raise concerns about the validity of the observed trends in the more objective metrics. Figure 1 illustrates these results as trends over time in the average predicted risk of hearing loss associated with a positive history of OELN compared to a negative history of OELN (with covariates marginalized over all observations; see figure description for more details), allowing visual confirmation that, although the trends in risk for the self-reported hearing loss outcome are similar for both positive and negative OELN histories (the lines having roughly equal slopes), the risks for the exam-based outcomes decrease over time much more for those with positive OELN histories than for those with negative OELN histories, to such an extent that, by 2015, there is barely any difference at all in the risks of speech-frequency hearing loss.

Although our results do support the conclusion that the strength of the effect of OELN on the risk of hearing loss has decreased in recent years, it remains unclear why this is the case. Two potential explanations seem most reasonable. First, and perhaps most likely given the striking increase in reported OELN between 2004 and 2011, it is possible that the nature of OELN has changed such that it causes hearing loss less often even as more workers experience it. This study designated participants as having a positive history of OELN if they reported exposure to loud noise in the workplace for ≥ 4 hours per day and for ≥ 3 months; although this cutoff was chosen so that earlier cohorts could be directly compared to later cohorts despite changes in interview question wording, it is possible that the extent of OELN is different for older cohorts' participants with a positive history of exposure than for new cohorts' participants with a positive history of exposure. For example, those designated as having a history of OELN in 1999 may have been exposed to noise at a greater average volume, for a longer duration each day, or over a longer employment period than those designated as having a history of OELN in 2016. Changes such as these would cause OELN-positive participants of older cohorts to be at a greater risk of hearing loss despite having the same OELN designation as those of newer cohorts, therefore reducing the apparent effect of OELN on hearing loss over time. This would imply that greater care must be taken in collecting and analyzing data on OELN in future studies; it may not be appropriate to reduce such exposure to a binary variable if this results in a loss of crucial and informative dimensionality. A second potential explanation for the phenomenon observed in this study is the possibility that a positive history of OELN has, over time, become more strongly and negatively associated with other hearing loss risk factors for which our models did not adjust. For example, while recreational/non-occupational exposure to loud noise has become more common in recent years, it is possible that this increase in prevalence has been more pronounced in those who have not had a history of OELN (and thus are perhaps less aware of the risks of loud noise exposure); in other words, if a positive history of OELN is associated with greater avoidance of recreational noise exposure, as recreational noise exposure becomes more common, the "benefit" conferred by OELN via this avoidance would have a stronger negative impact on the risk of hearing loss (if recreational noise exposure is not included in the model as a covariate). Our models did not include non-occupational exposure to loud noise as a factor because differences in the wordings of relevant NHANES interview questions varied across cohorts in such a way that made direct comparison between newer and older cohorts impossible (unlike the differences in the

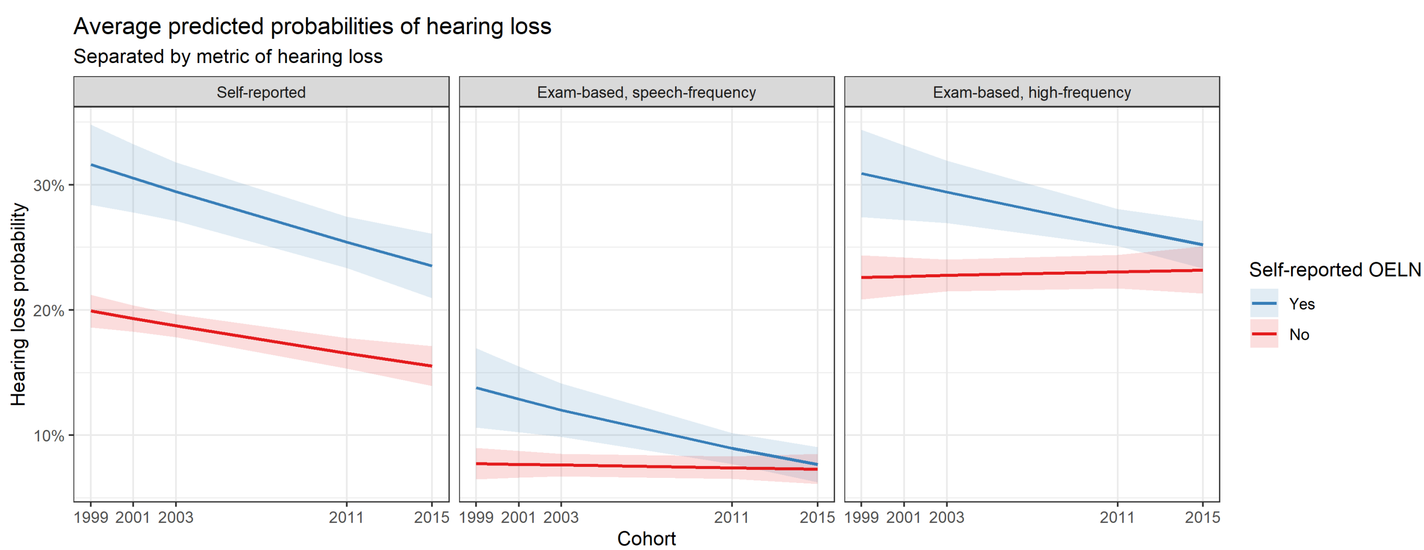

Figure 1: Probabilities of hearing loss as predicted by three multivariate logistic regression models (including the interaction term), each using a different metric of hearing loss (self-reported hearing loss, exam-based speech-frequency hearing loss, and exam-based high-frequency hearing loss, respectively). To predict these probabilities for each regression model, non-focal predictors (all variables except Cohort and OELN) were marginalized over the observations in the weighted data sample; i.e., the full dataset was duplicated once for each unique pair of focal predictor values (one Cohort year and either "Yes" or "No" OELN), and the resulting predictions of hearing loss for each of the duplicated data sets were averaged to calculate mean counterfactual prediction probabilities. Analysis was performed on the weighted data, which are representative of the entire non-institutionalized U.S. population aged 20–69. Shaded areas represent 95% confidence intervals.

wordings of hearing condition- and OELN-related interview questions, which could be mitigated by grouping responses as described in Section 4), but future research should take care to account for potential covariates such as recreational noise exposure in their analyses.

The strongest conclusion of this study is that the risks associated with hearing loss in the United States are changing, and greater resources must be dedicated to uncovering how and why. In the modern age of data availability, it is not sufficient to simply observe that a matter of public health such as hearing loss is somehow becoming less of a threat despite that preventative interventions have remained practically unchanged for decades – if anything, this observation should call for a reevaluation of how we understand hearing loss and its risk factors, as well as for subsequent adjustments of what preventative strategies are used to most effectively continue driving its prevalence down. Whether other risk factors are becoming more important drivers of hearing loss than OELN or the dynamics of OELN are changing in a way that we are failing to adequately capture in comparisons across years, it is apparent that the connection between noise exposure and hearing condition is not as well understood as is often assumed, despite the decades of research dedicated to such investigations. Further efforts into elucidating what is changing, why, and how such changes impact hearing loss are necessary before the decision can be made that our work in combating the disorder is finished.

7 Data and code availability

Data manipulation, statistical analyses, and plot generation were performed in the R programming language (version 4.5.0)[24] using the packages listed in Table 8. The code for these analyses and plots, as well as cleaned copies of the NHANES data, is available at `https://github.com/c-lozano/Hearing-Loss`.

Table 8: R packages used for the manipulation of data, generation of plots, and statistical analyses.

Package	**Version**	**Maintainer**	**Ref.**
nhanesA	1.3	Christopher Endres – cjendres1@gmail.com	[25,26]
ggplot2	3.5.2	Thomas Lin Pedersen – thomas.pedersen@posit.co	[27,28,29]
ggeffects	2.2.1	Daniel Lüdecke – d.luedecke@uke.de	[30,31]
survey	4.4.2	Thomas Lumley – t.lumley@auckland.ac.nz	[32,33,34]
Matrix	1.7.3	Martin Maechler – mmaechler+Matrix@gmail.com	[35]
forcats	1.0.0	Hadley Wickham – hadley@rstudio.com	[36]
tidyr	1.3.1	Hadley Wickham – hadley@posit.co	[37]
dplyr	1.1.4	Hadley Wickham – hadley@posit.co	[38]
readr	2.1.5	Jennifer Bryan – jenny@posit.co	[39]
stringr	1.5.1	Hadley Wickham – hadley@posit.co	[40]
pacman	0.5.1	Tyler Rinker – tyler.rinker@gmail.com	[41,42]
scales	1.4.0	Thomas Lin Pedersen – thomas.pedersen@posit.co	[43]
rstudioapi	0.17.1	Kevin Ushey – kevin@rstudio.com	[44]
knitr	1.50	Yihui Xie – xie@yihui.name	[45,46,47]

References

1. Joseph B. Nadol. Hearing Loss. *New England Journal of Medicine*, 329(15):1092–1102, October 1993. ISSN 0028-4793. doi: 10.1056/NEJM199310073291507. URL https://www.nejm.org/doi/full/10.1056/NEJM199310073291507. Publisher: Massachusetts Medical Society _eprint: https://www.nejm.org/doi/pdf/10.1056/NEJM199310073291507.

2. Fengxin Mo, Shiheng Zhu, Hanlu Jia, Yuan Xia, Li Lang, Qiutong Zheng, Xiaojing Yuan, Shan Wu, Yan Bai, Wenhan Yang, Liang Wang, and Qingsong Chen. Trends in prevalence of hearing loss in adults in the USA 1999–2018: a cross-sectional study. *BMC Public Health*, 24(1):976, April 2024. ISSN 1471-2458. doi: 10.1186/s12889-024-18426-9. URL https://doi.org/10.1186/s12889-024-18426-9.

3. Howard J. Hoffman, Robert A. Dobie, Katalin G. Losonczy, Christa L. Themann, and Gregory A. Flamme. Declining Prevalence of Hearing Loss in US Adults Aged 20 to 69 Years. *JAMA Otolaryngology–Head & Neck Surgery*, 143(3):274–285, March 2017. ISSN 2168-6181. doi: 10.1001/jamaoto.2016.3527. URL https://doi.org/10.1001/jamaoto.2016.3527.

4. Adele M. Goman and Frank R. Lin. Prevalence of Hearing Loss by Severity in the United States. *American Journal of Public Health*, 106(10):1820–1822, October 2016. ISSN 0090-0036. doi: 10.2105/AJPH.2016.303299. URL https://ajph.aphapublications.org/doi/full/10.2105/AJPH.2016.303299. Publisher: American Public Health Association.

5. Adele M. Goman, Nicholas S. Reed, and Frank R. Lin. Addressing Estimated Hearing Loss in Adults in 2060. *JAMA Otolaryngology–Head & Neck Surgery*, 143(7):733–734, July 2017. ISSN 2168-6181. doi: 10.1001/jamaoto.2016.4642. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5824202/.

6. Carrie L. Nieman and Esther S. Oh. Hearing Loss. *Annals of Internal Medicine*, 173(11):ITC81–ITC96, December 2020. ISSN 0003-4819. doi: 10.7326/AITC202012010. URL https://www.acpjournals.org/doi/full/10.7326/AITC202012010. Publisher: American College of Physicians.

7. Frank R. Lin, Roland Thorpe, Sandra Gordon-Salant, and Luigi Ferrucci. Hearing Loss Prevalence and Risk Factors Among Older Adults in the United States. *The Journals of Gerontology: Series A*, 66A(5):582–590, May 2011. ISSN 1079-5006. doi: 10.1093/gerona/glr002. URL https://doi.org/10.1093/gerona/glr002.

8. World Health Organization. Deafness and hearing loss, February 2025. URL https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss.

9. Martin Pienkowski. Loud Music and Leisure Noise Is a Common Cause of Chronic Hearing Loss, Tinnitus and Hyperacusis. *International Journal of Environmental Research and Public Health*, 18(8): 4236, January 2021. ISSN 1660-4601. doi: 10.3390/ijerph18084236. URL https://www.mdpi.com/1660-4601/18/8/4236. Number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

10. World Health Organization. *Hearing loss due to recreational exposure to loud sounds: a review*. World Health Organization, 2015. ISBN 978-92-4-150851-3. URL https://iris.who.int/handle/10665/154589. Type: Publications.

11. Dorothy W. Pan, Janet S. Choi, Albert Hokan, and Joni K. Doherty. Trends in Hearing Protection Use With Occupational Noise Exposure in the United States 1999 to 2016. *Otology & Neurotology*, 43(1):e14, January 2022. ISSN 1531-7129. doi: 10.1097/MAO.0000000000003343. URL https://journals.lww.com/otology-neurotology/fulltext/2022/01000/Trends_in_Hearing_Protection_Use_With_Occupational.8.aspx.

12. Deborah Imel Nelson, Robert Y. Nelson, Marisol Concha-Barrientos, and Marilyn Fingerhut. The global burden of occupational noise-induced hearing loss. *American Journal of Industrial Medicine*, 48(6):446–458, 2005. ISSN 1097-0274. doi: 10.1002/ajim.20223. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/ajim.20223. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ajim.20223.

13. Hongjie Zhou, Yu Zhou, Huina Zhang, Aiqing Yu, Bo Zhu, and Lei Zhang. Socio-economic disparity in the global burden of occupational noise-induced hearing loss: an analysis for 2017 and the trend since 1990. *Occupational and Environmental Medicine*, 78(2):125–128, February 2021. ISSN 1351-0711, 1470-7926. doi: 10.1136/oemed-2020-106556. URL https://oem.bmj.com/content/78/2/125. Publisher: BMJ Publishing Group Ltd Section: Workplace.

14. U.S. Department of Labor Occupational Health and Safety Administration (OSHA). Section III: Chapter 5: Noise. In *OSHA Technical Manual*. OSHA, April 2022. URL https://www.osha.gov/otm/section-3-health-hazards/chapter-5.

15. Madeleine J. Kerr, Richard L. Neitzel, OiSaeng Hong, and Robert T. Sataloff. Historical review of efforts to reduce noise-induced hearing loss in the United States. *American Journal of Industrial Medicine*, 60(6):569–577, 2017. ISSN 1097-0274. doi: 10.1002/ajim.22627. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/ajim.22627. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ajim.22627.

16. Anna Pretzsch, Andreas Seidler, and Janice Hegewald. Health Effects of Occupational Noise. *Current Pollution Reports*, 7(3):344–358, September 2021. ISSN 2198-6592. doi: 10.1007/s40726-021-00194-4. URL https://doi.org/10.1007/s40726-021-00194-4.

17. Ellen Kerns, Elizabeth A. Masterson, Christa L. Themann, and Geoffrey M. Calvert. Cardiovascular conditions, hearing difficulty, and occupational noise exposure within US industries and occupations. *American Journal of Industrial Medicine*, 61(6):477–491, 2018. ISSN 1097-0274. doi: 10.1002/ajim.22833. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/ajim.22833. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ajim.22833.

18. Elizabeth A. Masterson, James A. Deddens, Christa L. Themann, Stephen Bertke, and Geoffrey M. Calvert. Trends in worker hearing loss by industry sector, 1981–2010. *American Journal of Industrial Medicine*, 58(4):392–401, 2015. ISSN 1097-0274. doi: 10.1002/ajim.22429. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/ajim.22429. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ajim.22429.

19. Centers for Disease Control and Prevention (CDC) and National Center for Health Statistics (NCHS). National Health and Nutrition Examination Survey (NHANES) Data, 2016. URL https://wwwn.cdc.gov/nchs/nhanes/default.aspx.

20. World Health Organization. *World report on hearing*. World Health Organization, March 2021. ISBN 978-92-4-002048-1. URL https://www.who.int/publications/i/item/9789240020481.

21. Yuri Agrawal, Elizabeth A. Platz, and John K. Niparko. Prevalence of Hearing Loss and Differences by Demographic Characteristics Among US Adults: Data From the National Health and Nutrition Examination Survey, 1999-2004. *Archives of Internal Medicine*, 168(14):1522–1530, July 2008. ISSN 0003-9926. doi: 10.1001/archinte.168.14.1522. URL https://doi.org/10.1001/archinte.168.14.1522.

22. Yuri Agrawal, Elizabeth A. Platz, and John K. Niparko. Risk Factors for Hearing Loss in US Adults: Data From the National Health and Nutrition Examination Survey, 1999 to 2002. *Otology & Neurotology*, 30(2):139, February 2009. ISSN 1531-7129. doi: 10.1097/MAO.0b013e318192483c. URL https://journals.lww.com/otology-neurotology/fulltext/2009/02000/risk_factors_for_hearing_loss_in_us_adults__data.2.aspx.

23. Arve Lie, Marit Skogstad, Håkon A. Johannessen, Tore Tynes, Ingrid Sivesind Mehlum, Karl-Christian Nordby, Bo Engdahl, and Kristian Tambs. Occupational noise exposure and hearing: a systematic review. *International Archives of Occupational and Environmental Health*, 89:351–372, 2016. ISSN 0340-0131. doi: 10.1007/s00420-015-1083-5. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4786595/.

24. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2025. URL https://www.R-project.org/.

25. Laha Ale, Robert Gentleman, Teresa Filshtein Sonmez, Deepayan Sarkar, and Christopher Endres. nhanesA: achieving transparency and reproducibility in NHANES research. *Database*, Apr 15, 2024. doi: 10.1093/database/baae028. URL https://doi.org/10.1093/database/baae028.

26. Christopher Endres, Laha Ale, Robert Gentleman, and Deepayan Sarkar. *nhanesA: NHANES Data Retrieval*. 2025. URL https://cran.r-project.org/package=nhanesA.

27. Hadley Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2016. ISBN 978-3-319-24277-4. URL https://ggplot2.tidyverse.org.

28. Hadley Wickham, Winston Chang, Lionel Henry, Thomas Lin Pedersen, Kohske Takahashi, Claus Wilke, Kara Woo, Hiroaki Yutani, Dewey Dunnington, and Teun van den Brand. *ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics*. 2024. URL https://ggplot2.tidyverse.org.

29. Hadley Wickham, Winston Chang, Lionel Henry, Thomas Lin Pedersen, Kohske Takahashi, Claus Wilke, Kara Woo, Hiroaki Yutani, Dewey Dunnington, and Teun van den Brand. *ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics*. 2025. URL https://ggplot2.tidyverse.org.

30. Daniel Lüdecke. ggeffects: Tidy Data Frames of Marginal Effects from Regression Models. *Journal of Open Source Software*, 3(26): 772, 2018. doi: 10.21105/joss.00772.

31. Daniel Lüdecke. *ggeffects: Create Tidy Data Frames of Marginal Effects for ggplot from Model Outputs*. 2025. URL https://strengejacke.github.io/ggeffects/.

32. Thomas Lumley. Analysis of Complex Survey Samples. *Journal of Statistical Software*, 9(1):1–19, 2004.

33. Thomas Lumley. *Complex Surveys: A Guide to Analysis Using R: A Guide to Analysis Using R*. John Wiley and Sons, 2010.

34. Thomas Lumley, Peter Gao, and Ben Schneider. *survey: Analysis of Complex Survey Samples*. 2024. URL http://r-survey.r-forge.r-project.org/survey/.

35. Douglas Bates, Martin Maechler, and Mikael Jagan. *Matrix: Sparse and Dense Matrix Classes and Methods*. 2025. URL https://Matrix.R-forge.R-project.org.

36. Hadley Wickham. *forcats: Tools for Working with Categorical Variables (Factors)*. 2023. URL https://forcats.tidyverse.org/.

37. Hadley Wickham, Davis Vaughan, and Maximilian Girlich. *tidyr: Tidy Messy Data*. 2024. URL https://tidyr.tidyverse.org.

38. Hadley Wickham, Romain François, Lionel Henry, Kirill Müller, and Davis Vaughan. *dplyr: A Grammar of Data Manipulation*. 2023. URL https://dplyr.tidyverse.org.

39. Hadley Wickham, Jim Hester, and Jennifer Bryan. *readr: Read Rectangular Text Data*. 2024. URL https://readr.tidyverse.org.

40. Hadley Wickham. *stringr: Simple, Consistent Wrappers for Common String Operations*. 2023. URL https://stringr.tidyverse.org.

41. Tyler W. Rinker and Dason Kurkiewicz. *pacman: Package Management for R*. Buffalo, New York, 2018. URL http://github.com/trinker/pacman.

42. Tyler Rinker and Dason Kurkiewicz. *pacman: Package Management Tool*. 2019. URL https://github.com/trinker/pacman.

43. Hadley Wickham, Thomas Lin Pedersen, and Dana Seidel. *scales: Scale Functions for Visualization*. 2025. URL https://scales.r-lib.org.

44. Kevin Ushey, J. J. Allaire, Hadley Wickham, and Gary Ritchie. *rstudioapi: Safely Access the RStudio API*. 2024. URL https://rstudio.github.io/rstudioapi/.

45. Yihui Xie. *Dynamic Documents with R and knitr*. Chapman and Hall/CRC, Boca Raton, Florida, 2nd edition, 2015. URL https://yihui.org/knitr/.

46. Yihui Xie. knitr: A Comprehensive Tool for Reproducible Research in R. In Victoria Stodden, Friedrich Leisch, and Roger D. Peng, editors, *Implementing Reproducible Computational Research*. Chapman and Hall/CRC, 2014.

47. Yihui Xie. *knitr: A General-Purpose Package for Dynamic Report Generation in R*. 2024. URL https://yihui.org/knitr/.