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# Quantitative levels of noise exposure and 20-year hearing decline: findings from a prospective cohort study (the HUNT Study)

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**ABSTRACT**

**Objective:** We aimed to assess the association between occupational noise exposure and long-term hearing decline.

**Design:** This prospective cohort study used linear regression to investigate the association between occupational noise exposure and 20-year hearing decline, adjusted for important confounders.

**Study sample:** The Norwegian cohort (*N* = 4,448) participated in two population-based health studies with pure-tone audiometry; HUNT2 1996–1998 and HUNT4 2017–2019. Exposure assessments included a quantitative job exposure matrix (JEM) and questionnaires.

**Results:** The participants (40.2% men, 20–39 years at baseline) had a mean 20-year decline (3–6 kHz) of 11.3 ± 9.8 decibels (dB). There was a positive association between 20-year logarithmic average noise level (JEM-based, $L_{EX,20y}$) and 20-year hearing decline among men. Compared with no exposure ≥80 dB during follow-up, minimum 5 years of exposure ≥85 dB (JEM-based) predicted 2.6 dB (95% CI: 0.2–5.0) larger 20-year decline for workers aged 30–39 years at baseline, and −0.2 dB (95% CI: −2.2 to 1.7) for workers aged 20–29 years. Combining JEM information with self-reported noise exposure data resulted in stronger associations.

**Conclusion:** This large longitudinal study shows an association between JEM-based noise exposure level and increased 20-year hearing decline among men. Contrary to expectations, the associations were weaker among younger workers, which might reflect a latency period.

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Hearing loss; hearing thresholds; JEM; job exposure matrix; occupational

## Introduction

Hearing loss is ranked as number three on the global list of causes of years lived with disability (GBD 2019 Hearing Loss Collaborators 2021) and is associated with several negative health-related outcomes (Wilson et al. 2017). Occupational noise exposure is an important risk factor for hearing loss (Lie et al. 2016; Nelson et al. 2005), and occupational noise-induced hearing loss is still a prevalent occupational disease (Chen, Su, and Chen 2020).

Many studies on noise exposure and hearing loss are small, cross-sectional or focus on a specific occupation or workplace. A Finnish systematic review on predictors of noise-induced hearing loss points to the need for 'better large studies' with 'a follow-up of at least 5 years in workers exposed to noise louder than 80 dB(A)' (Sharea Ijaz et al. 2014). In addition, self-reported exposure data is common, but can be prone to recall-bias and inaccuracy with respect to noise levels. Job exposure matrices (JEMs), providing a connection between occupation and specific exposures, have been shown to be reproducible and especially useful in large general population studies (Peters 2020).

This large longitudinal study of workers in Norway spans the first two decades of the 21st century. We use noise exposure data from a quantitative JEM and self-reported noise exposure to assess the association between quantitative levels of occupational noise exposure and 20-year hearing decline.

## Materials and methods

### *Participants*

#### *The Trøndelag Health Study (HUNT)*

HUNT is a population-based health study performed in Trøndelag (Krokstad et al. 2013; Åsvold et al. 2022) which includes a wide range of questionnaires and measurements. It serves as a solid base for research on numerous health-related outcomes, and data have been collected in four waves (HUNT1-4) from 1984 to 2019.

#### *The hearing investigations*

Only two of the HUNT waves included pure-tone audiometry, namely HUNT2 Hearing (1996–1998) and HUNT4 Hearing

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(2017–2019) (Engdahl, Strand, and Aarhus 2020). The first hearing study included persons from 17 (out of 24) municipalities in Nord–Trøndelag, with a participation rate of 63% and a total of 51,529 participants. The second hearing study was conducted in the six larger municipalities (which covered ∼2/3 of Nord–Trøndelag), with a participation rate of 43% and a total of 28,388 participants. For simplicity, HUNT2 Hearing and HUNT4 Hearing will hereby be referred to as HUNT2 and HUNT4, respectively.

### The present sample

The present study included individuals who attended both studies, with baseline at HUNT2 and endpoint at HUNT4. Exclusion criteria were age 40+ years at HUNT2, missing questionnaires, missing pure-tone audiometry results, no registered occupational codes or missing self-reported exposure to occupational noise. The age range of this study was restricted to examine a population who had limited years of exposure prior to study start, who was more homogeneous with respect to confounding, and who would not be likely to reach retirement age during the study period. Included participants gave written consent. The study was approved by The Regional Committee for Medical Research Ethics (23178 HUNT hørsel).

## Measurements

### JEM-based occupational noise exposure

We used a quantitative JEM developed by Stokholm et al. (Stokholm et al. 2020), which provided estimates of full-shift personal occupational noise exposure levels from 1998 to 2017, specific for sex, age, collar (white- or blue-collar worker), calendar year and occupation.

We assessed occupation by yearly registrations (2003–2017) of STYRK-98 codes (the Norwegian version of the International Standard Classification of Occupations ISCO-88 (Statistics Norway, 1998), by Statistics Norway. The reporting of such codes is mandatory for employers. The STYRK-98 codes were recoded to DISCO-88 codes, the Danish version of ISCO-88 (Danmarks Statistik 1996), which was used in the JEM. The registration of occupational codes was more complete towards the end of the study period, for example, it was limited for the municipality sector and the hospital trusts until 2008 (Håland and Naesheim 2016). Missing occupational codes for 2000–2017 were checked against employment status. If the status was 'wage earner' or 'self-employed', we replaced the missing occupational code with the closest available occupational code from the preceding years (last observation carried forward). If no previous codes were available, we replaced the missing code with the closest available occupational code from the following years (next observation carried backward). Missing occupational codes for 1998–1999 were replaced by the closest occupational code from the following years if the income was >3.5 G (G units are decided annually by the Norwegian Government; Arbeids- og velferdsetaten (NAV) 2019), as this includes the core workforce (Widding Havnerås 2016). After imputation of the missing occupational codes, the average number of codes during the study period increased from 12.7 to 18.1 codes per participant. Noise levels for years with missing occupational codes after the imputation process were replaced by the lowest value in the JEM altogether (67.7 dB), assuming that they represented years with no gainful employment.

We defined two JEM-based noise exposure variables. We defined a continuously scored variable based on the logarithmic average of the annual noise level registrations from the JEM for each participant during the study period. The calculation of a logarithmic average (instead of an arithmetic average) is necessary as the noise levels (in decibels) are on a logarithmic scale. The 20-year logarithmic average ($L_{EX,20y}$) was calculated as follows:

$$L_{\mathrm{EX},\,ny} = 10\log_{10}\left(\frac{1}{n}\sum\nolimits_{i=1}^{n} 10^{L_{\mathrm{EX},\,i}/10}\right)$$

In which $n$ is the number of years from 1998 to 2017 (20 years) and $L_{EX,i}$ is the annual full-shift occupational A-weighted noise exposure level normalised to an 8-hour working day for each year in this period. As can be understood from the equation, higher annual noise levels contribute relatively more to a logarithmic average than to an arithmetic average. We assume negligible effects of $L_{EX,20y}$ <75 dB on hearing. In order to study the linear effect of adequate noise exposure levels (higher exposure versus lower exposure), we only investigated the effect of $L_{EX,20y}$ of 75 dB or higher. In addition, preliminary analyses showed that hearing decline among participants exposed to <75 dB had a larger uncertainty. This could be due to confounding, for instance by socioeconomic factors or healthy worker effect. As individuals in this group could potentially have had an increased risk of hearing decline for other reasons than occupational noise, they were excluded from these analyses.

We also created a categorical JEM-based variable: The reference group (low exposure) had no annual noise level registrations of 80 dB or higher during the study period. Between one and four annual registrations of 80+ dB qualified as some exposure. At least five annual registrations of minimum 80 dB were considered medium exposure. High noise levels (high exposure) were defined as at least five annual registrations of 85 dB or higher. This limit was chosen as exposure to noise levels below 85 dB, normalised to an 8-hour working day, is associated with a low risk of hearing loss (Lie et al. 2016; Sliwinska-Kowalska 2015). As noise-induced hearing loss develops slowly, over years (Sliwinska-Kowalska 2015), 5 years of high-level noise was chosen as a minimal duration for the high exposure group. Exposure to noise <80 dB was chosen as the low exposed category, as hearing loss due to occupational noise is not expected at these noise levels (Sliwinska-Kowalska 2015).

### Combined JEM-based and self-reported noise exposure

Different measures of occupational noise each have their advantages and disadvantages. A disadvantage to self-reported noise is the possibility of recall bias. On the other hand, the JEM assumes the same exposure for all who hold the same job title, which can lead to non-differential misclassification of exposure. As such, we aimed to investigate an exposure variable that combined both JEM and self-reported data on occupational noise.

First, we defined a self-reported variable based on answers in the HUNT4 questionnaire: High exposure = at least 5 years of loud noise exposure during the last 20 years, and > 15 h of loud noise per week. Loud noise was defined as noise that made it difficult to have a conversation. Medium exposure = at least 5 years of loud noise exposure during the last 20 years and 5–15 h of loud noise per week. Low exposure = no loud noise exposure at work (reference group). The remaining participants were placed in the category 'some exposure'. We then combined information on exposure frequency and duration from self-reported data with information on exposure level and duration from the JEM, to make a combined variable. For this combined variable, the highly exposed category consisted of individuals with high noise exposure in both previously described JEM-based and self-reported categorical variables. Similarly, the reference group included individuals with low exposure in both JEM-based and self-reported variables. Participants with medium exposure in either the JEM-based or the self-reported variable, combined with medium or high exposure in the other of the two variables, were considered medium exposed. The remaining individuals were classified as having some exposure. To sum up, we assessed four exposure variables: JEM-based continuously or categorically scored, self-reported exposure and a combined variable.

### Outcome: 20-year hearing decline

The pure-tone audiometry was conducted in line with ISO 8253-1 (The International Organization for Standardization 2010), with fixed frequencies at test frequencies 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz (utilizing an automatic procedure), and has been described previously (Engdahl, Strand, and Aarhus 2020; Engdahl et al. 2005). For elderly or impaired subjects, who were unable to follow the instructions that were given in the mentioned automatic procedure, a manual audiometry was provided (Engdahl, Strand, and Aarhus 2020). Audiometers were calibrated according to ISO 389-1 and checked daily by operators prior to audiometry (Engdahl, Strand, and Aarhus 2020). The same audiometric procedure was followed for HUNT2 and HUNT4, with high reliability previously reported in HUNT2 (Tambs et al. 2006). There were some minor differences regarding equipment: The TDH-39P earphones were combined with a metal head band and MX41/AR cushions in HUNT2, whereas in HUNT4, a plastic head band and PN51 cushions were utilised (Engdahl, Strand, and Aarhus 2020). Due to different isolation booths, the background noise might have been somewhat higher in HUNT2, which could have affected hearing thresholds at the lower frequencies (0.25 kHz). Earwax was not removed. However, screening for abnormal otoscopy (including earwax) on a sub-sample of participants in HUNT2, was not found to have a significant effect on the mean hearing thresholds in a previous study (Engdahl et al. 2005). We calculated the average of hearing thresholds at 3, 4 and 6 kHz, mean of both ears. Hearing decline (continuously scored) was estimated as the difference between the average at baseline and follow-up in dB.

### Covariates

We used the baseline study questionnaire to assess recurrent ear infections and smoking history. Ear pathology (perforated ear drum, completely clogged ear canal or unspecified changes) was assessed in the follow-up study (otoscopy). Statistics Norway provided information about years out of work in the period 1998–2017. We defined missing values ($< 2.3\%$) as 'no' or 'no exposure'.

### Statistical analyses

We analysed data in Stata version 17.0. Statistical tests were calculated at a 95% confidence level ($p < 0.05$). We performed multiple linear regression analyses to assess the association between occupational noise exposure and 20-year hearing decline. The four exposure variables included: (1) JEM-based noise (continuous). (2) JEM-based noise (categorical). (3) Self-reported noise (categorical). (4) Combined JEM-based and self-reported noise (categorical). Model A (crude model) was adjusted for age (continuous) and sex. Model B (fully adjusted model) was also adjusted for earlier recurrent ear infections, smoking history, years out of the workforce (during the study period) and ear pathology. $L_{EX,20y} \geq 75$ dB was additionally analysed among participants with self-reported exposure to loud noise at work minimum 5 h a week. Robust variance estimation was utilised in all analyses.

### Interaction terms

We assessed whether the associations between noise exposure and hearing decline were modified by age group (baseline age 20–29 versus 30–39 years) or sex by testing interaction terms.

### Plot of estimated marginal means

For the three categorical exposure variables (JEM-based, self-report and combined), we used separate regression models to estimate hearing decline for each frequency (0.25–8 kHz) during the study period (1998–2017). We plotted low exposure as 'low noise' and high exposure as 'high noise'.

## Results

### Participants

#### Final sample

A total of 13,022 individuals participated in the two hearing studies. We excluded participants with age 40+ years at baseline ($N = 8061$), missing questionnaires ($N = 294$), missing pure-tone audiometry results ($N = 13$), missing information about occupation for all years in the study period ($N = 123$) or missing self-reported occupational noise exposure ($N = 83$). Altogether, our longitudinal study included 4,448 participants.

#### Loss to follow-up

A linear regression analysis, adjusted for age, sex and participation in one or two of the hearing studies, showed that individuals participating in both studies had marginally better hearing (1.1 dB at 3–6 kHz) compared with those who only participated in the baseline study. The proportion of workers reporting exposure to loud noise >15 h per week was less among workers that participated in both hearing studies (8.7%) compared with those who only participated in the baseline study (11.0%).

### Descriptive statistics

Among the 4,448 participants, 40.2% were men, mean age at baseline was 31.2 ± 5.4 years and average 20-year hearing decline (at 3–6 kHz) was 11.3 ± 9.8 dB (Table 1). Table 2 displays the distribution of participants who were exposed to noise at work during the study period, and the extent to which they were exposed (low, some, medium or high). Few women were highly exposed to occupational noise.

## Linear regression analyses

### Continuous JEM-based noise exposure (logarithmic average of noise level) $L_{EX,20y}$

For each 1 dB increase in $L_{EX,20y}$, the 20-year hearing decline increased by 0.1 dB (95% CI: −0.0 to 0.2), as displayed in Table 3. There was a statistically significant interaction with sex. Stratified analyses showed that the association for men was 0.2 dB (95% CI: 0.1–0.4), whereas for women it was negative [−0.3 dB (95% CI: −0.5 to −0.0)]. In order to reduce the inherent misclassification of noise exposure levels provided by the JEM, we performed the main analysis including only persons with self-reported occupational noise exposure of at least 5 h a week in the HUNT4 questionnaire ($N = 757$), showing a stronger positive association of 0.3 dB (95% CI: 0.1–0.6) among men.

### Categorical noise exposure variables

Table 4 presents the associations between noise exposure at work (JEM-based, self-reported and a combination of the two) and 20-year hearing decline. For all three exposure variables, workers highly exposed to occupational noise showed larger hearing declines than workers with low exposure. Largest declines were found among those who met the combined exposure criteria.

There was a statistically significant interaction between high noise exposure (max category) assessed as the combined categorical variable and age. Stratified analyses showed that the association between noise exposure (combined variable, max category) and 20-year decline in the older age group was 10.1 dB (95% CI: 3.9–16.3) and in the younger age group −0.6 dB (95% CI: −3.9 to 2.7). Medium noise exposure (combined variable) was associated with 1.6 dB (95% CI: 0.0–3.2) larger hearing decline in the older age group.

### Estimated marginal means

Figure 1 illustrates the associations between noise exposure (assessed by the three categorical variables) and 20-year hearing decline for each frequency (0.25–8 kHz), stratified by age group. The largest differences were found in frequencies 3–6 kHz.

**Table 1.** Characteristics of the total sample, 4448 participants in HUNT2 (1996–1998) and HUNT4 (2017–2019), Norway.

| | All, *N* (%) |
|---|---|
| Age at HUNT2 (years), mean ± SD | 31.2 ± 5.4 |
| Age at HUNT4 (years), mean ± SD | 52.5 ± 5.4 |
| Hearing thresholds at HUNT2 (dB), 3–6 kHz, mean ± SD | 5.6 ± 8.7 |
| Hearing thresholds at HUNT4 (dB), 3–6 kHz, mean ± SD | 16.9 ± 13.9 |
| Hearing decline[a] (dB), 3–6 kHz, mean ± SD | 11.3 ± 9.8 |
| Total | 4,448 (100.0) |
| Men | 1,790 (40.2) |
| Currently or previously smoking | 1,908 (42.9) |
| Earlier recurrent ear infections | 1,019 (22.9) |
| Abnormal otoscopy (performed on both ears, HUNT4[b]) | 338 (7.6) |
| Use of hearing protection at work | |
| Not applicable | 3,223 (72.5) |
| Always | 336 (7.6) |
| Often, seldom or never | 889 (20.0) |

[a]Through the study period (1998–2017).
[b]Perforated ear drum, completely clogged ear canal or unspecified changes.
HUNT (2 and 4), The Trøndelag Health Study (numbers 2 and 4).

## Discussion

### Main findings

The 4448 participants (40.2% men, average age at baseline 31.2 ± 5.4 years) had a mean 20-year hearing decline of 11.3 ± 9.8 dB. Increasing 20-year logarithmic average noise level (JEM-based, $L_{EX,20y}$) was associated with larger 20-year hearing decline among men (0.2 dB for each 1 dB increase in exposure level, 95% CI: 0.1–0.4). This association was stronger among men who also reported occupational noise exposure. Compared with no noise level registrations of 80 dB or higher during follow-up, minimum 5 years of exposure $\geq$ 85 dB (JEM-based) predicted 2.6 dB (95% CI: 0.2–5.0) larger 20-year decline for workers aged 30–39 years at baseline. For workers aged 20–29 years at baseline, the association was non-significant.

**Table 2.** Distribution of occupational noise exposure among 4448 participants in HUNT2 (1996–1998) and HUNT4 (2017–2019), Norway.

| | *N* | Low noise (ref), *N* (%) | Some noise, *N* (%) | Medium noise, *N* (%) | High noise, *N* (%) |
|---|---|---|---|---|---|
| JEM-based noise exposure | 4,448 | 2,751 (100.0) | 271 (100.0) | 1,232 (100.0) | 194 (100.0) |
| Men | 1,790 | 720 (26.2) | 144 (53.1) | 743 (60.3) | 183 (94.3) |
| Women | 2,658 | 2,031 (73.8) | 127 (46.9) | 489 (39.7) | 11 (5.7) |
| Age 20–29 years at baseline | 1,654 | 1,010 (36.7) | 116 (42.8) | 441 (35.8) | 87 (44.8) |
| Age 30–39 years at baseline | 2,794 | 1,741 (63.3) | 155 (57.2) | 791 (64.2) | 107 (55.2) |
| Reports always using hearing protection | 336 | 73 (2.7) | 29 (10.7) | 191 (15.5) | 43 (22.2) |
| Self-reported noise exposure | 4,448 | 3,210 (100.0) | 601 (100.0) | 353 (100.0) | 284 (100.0) |
| Men | 1,790 | 974 (30.3) | 398 (66.2) | 231 (65.4) | 187 (65.9) |
| Women | 2,658 | 2,236 (69.7) | 203 (33.8) | 122 (34.6) | 97 (34.2) |
| Age 20–29 years at baseline | 1,654 | 1,225 (38.2) | 190 (31.6) | 139 (39.4) | 100 (35.2) |
| Age 30–39 years at baseline | 2,794 | 1,985 (61.8) | 411 (68.4) | 214 (60.6) | 184 (64.8) |
| Reports always using hearing protection | 336 | 30 (0.9) | 123 (20.5) | 79 (22.4) | 104 (36.6) |
| Combined JEM-based and self-reported noise exposure | 4,448 | 2,323 (100.0) | 1,704 (100.0) | 375 (100.0) | 46 (100.0) |
| Men | 1,790 | 559 (24.1) | 888 (52.1) | 302 (80.5) | 41 (89.1) |
| Women | 2,658 | 1,764 (75.9) | 816 (47.9) | 73 (19.5) | 5 (10.9) |
| Age 20–29 years at baseline | 1,654 | 863 (37.2) | 635 (37.3) | 136 (36.3) | 20 (43.5) |
| Age 30–39 years at baseline | 2,794 | 1,460 (62.8) | 1,069 (62.7) | 239 (63.7) | 26 (56.5) |
| Reports always using hearing protection | 336 | 8 (0.3) | 180 (10.6) | 130 (34.7) | 18 (39.1) |

HUNT (2 and 4), The Trøndelag Health Study (numbers 2 and 4).
*JEM-based categorical noise exposure*: Low = no annual registrations above 80 dB. Some = 1–4 annual registration of minimum 80 dB. Medium = at least five annual registrations of minimum 80 dB. High = at least five annual registrations of 85 dB or higher.
*Self-reported noise exposure*: Low = no loud occupational noise exposure. Some = loud occupational noise exposure in the last 20 years ('medium' and 'high' criteria not fulfilled). Medium = at least 5 years of loud noise exposure in the last 20 years and 5–15 h of loud noise per week. High = at least 5 years of loud noise exposure in the last 20 years and >15 h of loud noise per week.
*Combined (self-reported and JEM-based) noise exposure*: Low = registered as 'low' on JEM-based categorical and self-reported noise exposure. High = registered as 'high' on JEM-based categorical and self-reported noise exposure. Medium = registered as 'medium' on JEM-based categorical and self-reported noise exposure or registered as 'high' on one of them and 'medium' on the other. Some = other ('low', 'medium' or 'high' criteria not fulfilled).

**Table 3.** Occupational noise exposure and mean 20-year hearing decline among 4448 participants in HUNT2 (1996–1998) and HUNT4 (2017–2019), Norway.

| | | | Total | | Age 20–29 at baseline | | Age 30–39 at baseline | |
|---|---|---|---|---|---|---|---|---|
| JEM-based continuous noise exposure, $L_{EX,20y}$a | | *N* | Model A[b], hearing decline (dB) | Model B[c], hearing decline (dB) | Model A[b], hearing decline (dB) | Model B[c], hearing decline (dB) | Model A[b], hearing decline (dB) | Model B[c], hearing decline (dB) |
| Noise exposure ≥ 75 dB | All | 2874 | 0.1 (−0.0 to 0.2) | 0.1 (−0.0 to 0.2) | 0.0 (−0.2 to 0.2) | 0.0 (−0.2 to 0.2) | 0.2 (−0.0 to 0.3) | 0.2 (−0.0 to 0.3) |
| | Men | 1673 | **0.2 (0.1 to 0.4)** | **0.2 (0.1 to 0.4)** | 0.1 (−0.2 to 0.3) | 0.0 (−0.2 to 0.3) | **0.3 (0.1 to 0.5)** | **0.3 (0.1 to 0.5)** |
| | Women | 1201 | **−0.3 (−0.5 to −0.1)** | **−0.3 (−0.5 to −0.0)** | −0.1 (−0.4 to 0.3) | −0.0 (−0.3 to 0.3) | **−0.5 (−0.8 to −0.1)** | **−0.4 (−0.8 to −0.1)** |
| Noise exposure ≥ 75 dB AND self-reported noise exposure[d] | All | 757 | 0.2 (−0.0 to 0.5) | 0.2 (−0.0 to 0.5) | −0.1 (−0.4 to 0.2) | −0.2 (−0.5 to 0.2) | **0.4 (0.1 to 0.8)** | **0.4 (0.1 to 0.8)** |
| | Men | 542 | **0.4 (0.1 to 0.6)** | **0.3 (0.1 to 0.6)** | −0.0 (−0.4 to 0.3) | −0.1 (−0.5 to 0.3) | **0.6 (0.2 to 1.0)** | **0.6 (0.2 to 1.0)** |
| | Women | 215 | −0.5 (−1.0 to 0.1) | −0.4 (−0.9 to 0.2) | −0.3 (−1.0 to 0.3) | −0.2 (−0.9 to 0.5) | −0.6 (−1.5 to 0.4) | −0.6 (−1.6 to 0.3) |

Data are estimated regression coefficients in dB, with 95% confidence intervals in parentheses.
Significant values in bold ($p < 0.05$).
[a]$L_{EX,20y}$—20-year logarithmic average of noise exposure through the study period (1998–2017).
[b]Adjusted for age and sex.
[c]Adjusted for age, sex, earlier recurrent ear infections, smoking history, years out of the workforce and ear pathology.
[d]Self-reported exposure to loud noise at work for 5 h a week or more (HUNT4).
HUNT (2 and 4), The Trøndelag Health Study (numbers 2 and 4).

**Table 4.** Occupational noise exposure and mean 20-year hearing decline among 4448 participants in HUNT2 (1996–1998) and HUNT4 (2017–2019), Norway.

| | | Model A (crude)[a] | | | Model B (fully adjusted)[b] | | |
|---|---|---|---|---|---|---|---|
| | Low noise | Some noise, hearing decline (dB) | Medium noise, hearing decline (dB) | High noise, hearing decline (dB) | Some noise, hearing decline (dB) | Medium noise, hearing decline (dB) | High noise, hearing decline (dB) |
| JEM-based | | | | | | | |
| Total | ref | 0.3 (−0.8 to 1.3) | 0.2 (−0.5 to 0.9) | 1.3 (−0.3 to 2.9) | 0.1 (−1.0 to 1.2) | 0.2 (−0.5 to 0.8) | 1.3 (−0.3 to 2.9) |
| Age 20–29 years at baseline | ref | 0.1 (−1.5 to 1.6) | 0.4 (−0.6 to 1.5) | −0.1 (−2.1 to 1.8) | 0.0 (−1.6 to 1.6) | 0.4 (−0.7 to 1.4) | −0.2 (−2.2 to 1.7) |
| Age 30–39 years at baseline | ref | 0.3 (−1.2 to 1.8) | 0.1 (−0.8 to 1.0) | **2.6 (0.2 to 5.0)** | 0.2 (−1.3 to 1.6) | 0.1 (−0.8 to 1.0) | **2.6 (0.2 to 5.0)** |
| Self-report | | | | | | | |
| Total | ref | 0.6 (−0.3 to 1.4) | 0.9 (−0.2 to 1.9) | **2.2 (0.7 to 3.7)** | 0.5 (−0.4 to 1.4) | 0.8 (−0.2 to 1.9) | **2.1 (0.6 to 3.6)** |
| Age 20–29 years at baseline | ref | 0.6 (−0.8 to 2.0) | 0.8 (−0.8 to 2.5) | −0.2 (−2.0, 1.7) | 0.6 (−0.8 to 2.0) | 0.8 (−0.9 to 2.4) | −0.2 (−2.1 to 1.6) |
| Age 30–39 years at baseline | ref | 0.6 (−0.5 to 1.7) | 1.0 (−0.4 to 2.3) | **3.6 (1.6 to 5.6)** | 0.5 (−0.6 to 1.6) | 0.9 (−0.5 to 2.3) | **3.5 (1.5 to 5.5)** |
| Combined (JEM and self-report) | | | | | | | |
| Total[c] | ref | 0.5 (−0.1 to 1.1) | **1.3 (0.1 to 2.6)** | **5.5 (1.5 to 9.5)** | 0.4 (−0.2 to 1.0) | 1.2 (−0.0 to 2.4) | **5.4 (1.4 to 9.4)** |
| Age 20–29 years at baseline | ref | 0.4 (−0.5 to 1.3) | 0.7 (−1.2 to 2.6) | −0.4 (−3.6 to 2.8) | 0.4 (−0.5 to 1.3) | 0.5 (−1.4 to 2.5) | −0.6 (−3.9 to 2.7) |
| Age 30–39 years at baseline | ref | 0.6 (−0.2 to 1.4) | **1.7 (0.2 to 3.3)** | **10.1 (4.0 to 16.3)** | 0.5 (−0.3 to 1.3) | **1.6 (0.0 to 3.2)** | **10.1 (3.9 to 16.3)** |

Data are estimated regression coefficients in dB, with 95% confidence intervals in parentheses.
Significant values in bold ($p < 0.05$).
[a]Adjusted for age and sex.
[b]Adjusted for age, sex, earlier recurrent ear infections, smoking history, years out of the workforce and ear pathology.
[c]In these unstratified analyses there is an interaction between age and occupational noise.
HUNT (2 and 4), The Trøndelag Health Study (numbers 2 and 4).
*JEM-based categorical noise exposure*: Low = no annual registrations above 80 dB. Some = 1–4 annual registration of minimum 80 dB. Medium = at least five annual registrations of minimum 80 dB. High = at least five annual registrations of 85 dB or higher.
*Self-reported noise exposure*: Low = no loud occupational noise exposure. Some = loud occupational noise exposure in the last 20 years ('medium' and 'high' criteria not fulfilled). Medium = at least 5 years of loud noise exposure in the last 20 years and 5–15 h of loud noise per week. High = at least 5 years of loud noise exposure in the last 20 years and >15 h of loud noise per week.
*Combined (self-reported and JEM-based) noise exposure*: Low = registered as 'low' on JEM-based categorical and self-reported noise exposure. High = registered as 'high' on JEM-based categorical and self-reported noise exposure. Medium = registered as 'medium' on JEM-based categorical and self-reported noise exposure or registered as 'high' on one of them and 'medium' on the other. Some = other ('low', 'medium' or 'high' criteria not fulfilled).

Combining JEM information with self-reported noise exposure data resulted in stronger associations.

### *Comparison of the results with other longitudinal studies*

Our study showed larger 20-year hearing decline among highly exposed male workers than among male workers with low exposure, as assessed by the JEM. There are few longitudinal JEM-based studies on associations between occupational noise and hearing decline, and this study contributes with important knowledge in terms of quantifying the relationship and assessing differences across age and sex. A large study on aluminium workers by Rabinowitz et al. (Rabinowitz et al. 2007), which investigated JEM-based occupational noise and 10-year hearing loss (3–6 kHz, binaural average), found lower rates of hearing loss among workers exposed to higher levels of noise. The authors have suggested that their results could be due to less use of hearing protective devices among the lower exposed participants. The present study confirms a higher use of hearing protective devices among highly exposed participants, and also that only a minority of workers with medium or high exposure to noise reported using hearing protection at work 'always'. Johnson et al. (Johnson et al. 2017) investigated JEM-based environmental exposures (including occupational noise) and hearing loss in a smaller longitudinal study of male Swedish twins. The study showed 2.8 dB (non-significant) higher hearing thresholds (average at 3, 4, 6 and 8 kHz combined) among twins exposed to higher levels of noise (compared with their lower exposed twins).

There are also longitudinal studies on occupational noise and hearing loss that involve other noise measurements or

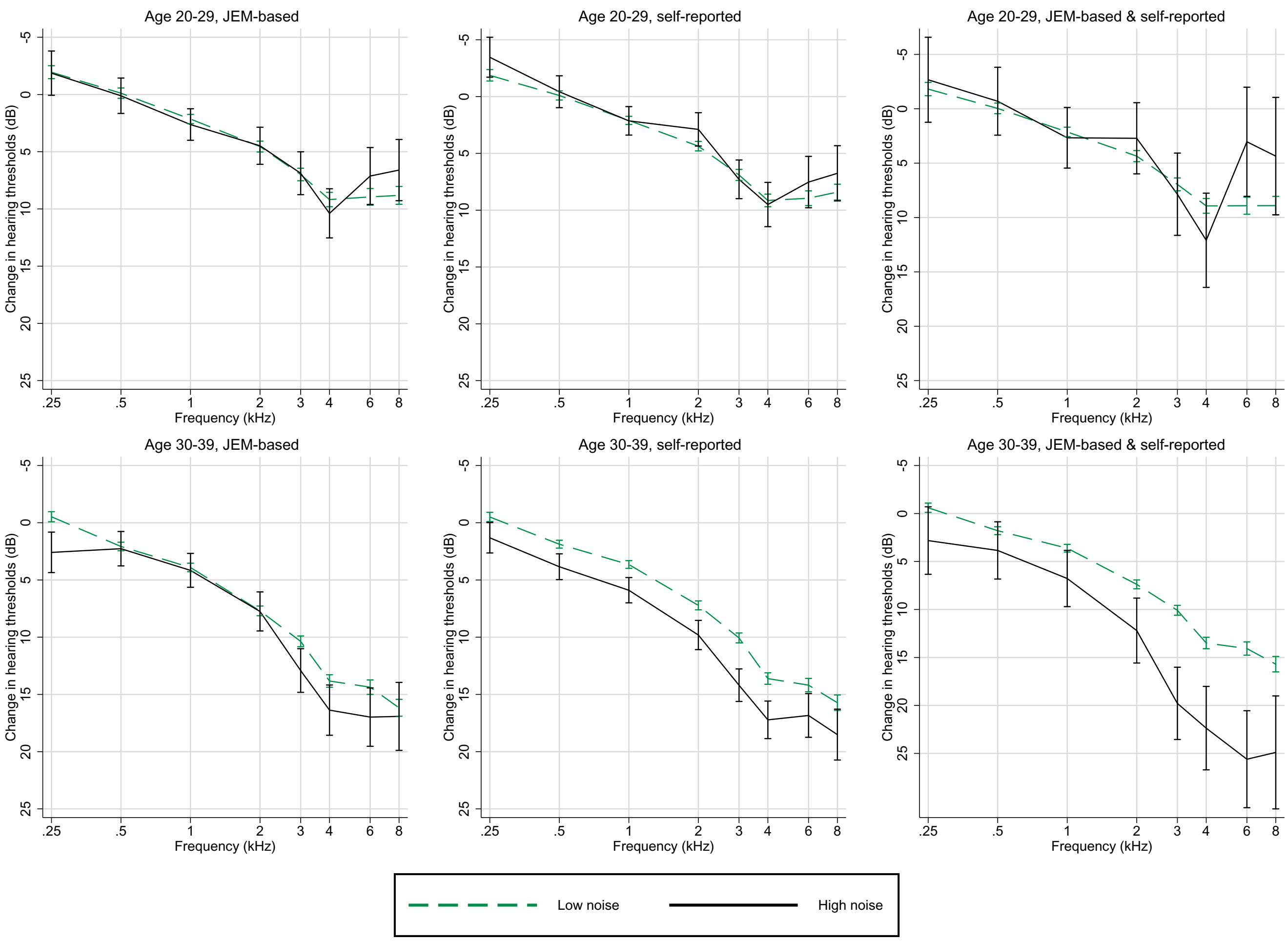


Figure 1. Hearing decline for each frequency (0.25–8 kHz) during the study period, by categorical noise exposure (JEM-based, self-reported and a combination of JEM-based and self-reported), stratified by age groups. Estimated marginal means adjusted for age, sex, earlier recurrent ear infections, smoking history, years out of the workforce and ear pathology. Error bars represents 95% confidence intervals.

calculations. Seixas et al. (Seixas et al. 2012) studied noise exposure and hearing damage among construction workers and found an estimated effect of 2–3 dB over 10 years for an increase in 10 dB. In a Danish study (Frederiksen et al. 2017), 10-year cumulative occupational noise exposure was negatively (and non-significantly) associated with hearing threshold shifts at 3–6 kHz. An international standard by ISO (The International Organization for Standardization, 2013), based on two noise and hearing study databases (Burns and Robinson 1970; Passchier-Vermeer 1968), shows an average noise-induced permanent threshold shift of $\sim$ 4 dB for 3–6 kHz (average of mean threshold shifts for 3, 4 and 6 kHz) after 20 years of $L_{EX,8\,h} = 85$ dB. Finally, another longitudinal study using HUNT data showed an association between certain occupations (building frame workers and craft and related trade workers) and hearing decline (Molaug et al. 2022).

## Combining JEM-based data with self-report

Different measures of occupational noise each have their advantages and disadvantages. A disadvantage to self-reported noise is the possibility of recall bias. On the other hand, the JEM assumes the same exposure for all who hold the same job title, which can lead to non-differential misclassification of exposure. For instance, we can imagine that one carpenter is exposed to high occupational noise levels, while another carpenter might have more administrative tasks at work and be less exposed to noise. The assumption of exposure being the same for everyone within the same occupation is a known limitation for JEMs (Peters 2020). We therefore sought to reduce misclassification by creating a variable that combined data from both JEM and self-report. Self-reported noise exposure alone was associated with a 2.1 dB (95% CI: 0.6–3.6) larger 20-year hearing decline among highly exposed workers compared with workers reporting no prior occupational noise exposure. Prior longitudinal studies found that self-reported noise exposure had no effect on change in hearing levels (Davis, Ostri, and Parving 1990) and was not associated with an increase in relative risk of hearing deterioration $\geq$ 10 dB after 5 years (Karlsmose et al. 2000). In conclusion, several longitudinal studies did not show larger hearing deterioration among people with self-reported exposure to noise.

To the best of our knowledge, combining JEM and self-reported data on occupational noise has not been investigated previously. Combining JEM information with self-reported noise exposure data resulted in larger hearing declines, both concerning the categorical and the continuous JEM variables. The larger declines may be due to a more accurate selection of the participants with the highest noise exposure in the study population, which is an advantage of including self-reported data. However, we cannot exclude recall bias, although this risk should be lowered compared with self-reported information alone, as participants need to be assessed as highly exposed both objectively and subjectively to end up in the highly exposed category. We believe it is difficult to conclude whether the assumed positive effect of less misclassification outweighs the potential effect of recall bias, and perhaps the correct estimate may lie somewhere in the middle.

### Hearing decline at 3–6 kHz

We chose to investigate hearing thresholds at 3–6 kHz as these frequencies are documented in relevant literature in relation to noise-induced hearing loss (Sliwinska-Kowalska 2015). By combining six measures (average at 3, 4 and 6 kHz in both ears) from each hearing study, we sought to create a more reliable measurement, with lower risk of regression to the mean, compared with using single thresholds. General occupational noise exposure is not associated with asymmetric hearing loss (Aarhus and Engdahl 2020). A potential downside is that shifts occurring at single frequencies will be underestimated when averaged with adjacent frequencies. But Figure 1 indicated this to be a minor problem as the specific effects at 3, 4 and 6 kHz were similar.

### The influence of age and sex on the association between noise and hearing decline

#### Age

Our study showed that the association between noise exposure and hearing decline was stronger among participants aged 30–39 than 20–29 years at baseline. Estimates from ISO indicate that larger declines happen within the first 10–15 years of exposure (The International Organization for Standardization 2013). We excluded participants older than 40 years at baseline, as these participants could have been long-term exposed to occupational noise and lost a larger part of their hearing prior to study start, which could have underestimated our results. But in fact, the younger participants in our study showed smaller declines. We can only speculate about possible underlying causes.

The idea that older subjects should be more vulnerable to noise than younger subjects is not very plausible (Ohlemiller, Wright, and Heidbreder 2000), however, it has been suggested that early noise exposure is associated with an accelerated age-related hearing loss later in life (Xiong et al. 2014). Another explanation of the weaker associations among younger adults could be related to a ‘latency period’. With a latency period, the relation between years of exposure and start of hearing decline becomes sigmoid, like it does for age-related hearing loss, and not purely logarithmic as predicted by ISO 1999. The younger age group (20–29 years) were at the beginning of their working careers. Compared with most exposure data used in ISO 1999, the exposure levels in our study were low, the participants may have worked less and had increased use of hearing protection. The low exposure levels will move the steeper part of the sigmoid to the right towards higher years of exposure. It is thus possible that young subjects starting from zero years of exposure will achieve a smaller 20-year decline than older subjects starting at 10 years of exposure. In addition, some of the difference between the age groups could also be due to measurements errors: pure-tone audiometry may be less sensitive to subtle noise-related hearing decline in persons with normal hearing (younger persons) than in persons with a certain degree of hearing loss at follow-up (the older group).

Finally, we cannot exclude that the interaction between noise exposure and age on hearing decline is somewhat related to possible bias: The (expected) higher hearing decline among the oldest participants also makes them more vulnerable to recall bias when reporting noise exposure. However, a stronger association among the older participants was also shown for the JEM-based variable, which is not prone to recall bias.

#### Sex

To our knowledge, this is the first JEM-based longitudinal study that shows stronger association between noise exposure and hearing decline among men than women. Our results comply with prior findings (Tambs et al. 2006; Wang et al. 2021). The sex differences could reflect biological differences in vulnerability to noise-induced hearing loss, as suggested in experimental animal studies (Han et al. 2022). However, the sex difference and the negative association for women in our study could also be related to the few highly exposed women, leading to uncertainty in the estimates. Lack of sufficient female subjects for analyses is common in research on noise-induced hearing loss. Further, we cannot exclude information bias: Although the overall gender-specific exposure tendency (men are more exposed to noise compared with women) was accounted for in the JEM, it might not reflect noise exposure optimally for women. Finally, we cannot exclude the possibility that there might be differences in hearing protection use for men and women. A study on attitudes towards noise and use of hearing protection at concerts among students (Widén, Holmes, and Erlandsson 2006) showed that women had a more negative attitude towards noise, and further that persons with negative attitudes were more likely to report using hearing protection. We can, however, only speculate about whether noise-exposed women are more likely to protect their hearing.

### Strengths and limitations

Strengths included the long observation period, standardised audiometric measurements, good confounder control and a large number of participants from a population-based health study, in which the population previously has been assessed to be representative for the entire country (Engdahl, Strand, and Aarhus 2020). The longitudinal design enabled us to ensure that the hearing decline occurred during ongoing noise exposure, which is a major strength in our study.

Analyses showed marginally better hearing at baseline in the longitudinal population compared with participants who only attended the baseline hearing study. There was also a slight difference in self-reported occupational noise exposure at baseline (less noise exposure in the longitudinal population). This could point to a healthy volunteer effect, which could lead to conservative results. Missing occupational codes could have led to misclassification of exposure. Although, after imputation, few job codes were missing. The missing codes were replaced by the lowest noise values in the JEM (67.7 dB), as we are all exposed to some noise during a year, but these low values are not expected to be harmful to our hearing or contribute significantly to average noise levels. The JEM is made based on Danish occupations. We believe that the Norwegian and Danish occupational situations and noise levels are sufficiently equal, and we do not suspect that this creates any significant bias. There are some limitations to the JEM; the use of hearing protection is for instance not taken into account. This and other limitations have been discussed elsewhere (Stokholm et al. 2020). Finally, the lack of information regarding leisure impulse noise at baseline (shooting, etc.) is a limitation in this study.

## Concluding remarks

This large longitudinal study from Norway shows an association between JEM-based noise exposure and increased 20-year hearing decline among men. Contrary to expectations, the associations were weaker among younger workers, which might reflect a latency period. Noise in the workplace still needs continued attention.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

## Data availability statement

The datasets generated and/or analysed during this study are not publicly available due to Norwegian legal restrictions and the current ethical approval for the study.

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