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Original Article

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A Quantitative General Population Job Exposure Matrix for Occupational Noise Exposure

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Abstract

Occupational noise exposure is a known risk factor for hearing loss and also adverse cardiovascular effects have been suggested. A job exposure matrix (JEM) would enable studies of noise and health on a large scale. The objective of this study was to create a quantitative JEM for occupational noise exposure assessment of the general working population. Between 2001–2003 and 2009–2010, we recruited workers from companies within the 10 industries with the highest reporting of noise-induced hearing loss according to the Danish Working Environment Authority and in addition workers of financial services and children day care to optimize the range in exposure levels. We obtained 1343 personal occupational noise dosimeter measurements among 1140 workers representing 100 different jobs according to the Danish version of the International Standard Classification of Occupations 1988 (DISCO 88). Four experts used 35 of these jobs as benchmarks and rated noise levels for the remaining 337 jobs within DISCO 88. To estimate noise levels for all 372 jobs, we included expert ratings together with sex, age, occupational class, and calendar year as fixed effects, while job and worker were included as random effects in a linear mixed regression model. The fixed effects explained 40% of the total variance: 72% of the between-jobs variance, –6% of the between-workers variance and 4% of the within-worker variance. Modelled noise levels showed a monotonic increase with increasing expert score and a 20 dB difference between the highest and lowest exposed jobs. Based on the JEM estimates, metal wheel-grinders were among the highest and finance and sales professionals among the lowest exposed. This JEM of occupational noise exposure can be used to prioritize preventive efforts of occupational noise exposure and to provide quantitative estimates of contemporary exposure levels in epidemiological studies of health effects potentially associated with noise exposure.

Keywords: epidemiological studies; epidemiology; job; job exposure matrix (JEM); job exposure matrix for occupational noise exposure; mixed effects model; noise exposure; occupational; occupational noise exposure

Introduction

Occupational noise is a known risk factor for hearing loss (Prince, 2002) and associated with other health effects (Selander *et al.*, 2016; Skogstad *et al.*, 2016).

In Europe, 30% of the work force reported that they were exposed to noise so loud that they had to raise their voice and this proportion was unchanged from 2000 to 2010 (Eurofound, 2016). However, in Europe no longitudinal surveillance data are available for occupational noise levels. In order to prioritize preventive efforts of health consequences of occupational noise exposure, there is a need for population-based overviews of the distribution of the relevant exposures across occupations. Such an overview can be provided by a quantitative general population job exposure matrix (JEM).

A JEM also enables estimation of job and calendar year specific exposure levels of occupational noise in community-based epidemiological studies investigating exposure–response relations. Recently, general population JEMs have been developed using quantitative exposure information from a limited number of occupations in combination with expert rating (Wild *et al.*, 2002; Peters *et al.*, 2011; Friesen *et al.*, 2012; Vested *et al.*, 2019). This approach allows calibration of the experts' ratings as well as assignment of exposure level to occupations without measurements.

We describe a quantitative JEM for occupational noise exposure assessment of the general working population combining personal noise exposure measurements with expert ratings.

Methods

Data collection and selection

Companies

During 2001–2003 and 2009–2010, we recruited workers in companies from the 10 industries reported having the highest frequency of noise-induced hearing loss in Denmark according to the Danish Working Environment Authority: manufacturers of food, wood products, non-metallic mineral products, basic metals, fabricated metal, machinery, motor vehicles, furniture, publishing and printing, and construction (The Danish Working Environment Authority, 2019). For optimizing the range in exposure levels and the between group variability, we also recruited workers of financial services. Finally, children's day care facilities were included as recent measurements in Denmark had indicated that workers of these units were exposed to high noise levels. Overall, 175 companies were enrolled in the two measurement campaigns, both performed as part of epidemiological studies previously described (Kock *et al.*, 2004; Rubak *et al.*, 2008; Stokholm *et al.*, 2014).

Briefly, Statistics Denmark, a governmental organization (Thygesen *et al.*, 2011) in 2001 provided a list of 840 eligible companies in 2001, with ≥15 workers within the selected industries. During 2001–2003, we randomly enlisted five companies with 15–49 workers and five companies with ≥50 workers from each industry. From each company a maximum of 10 workers were selected by foremen and managers. In 2009–2010 we asked these companies to participate again in a new measurement campaign and in case they declined or were closed, we invited other companies within the same industries in order to approach the initial number of companies.

Workers

Furthermore, we reinvited identifiable 2001–2003 participants in the subsequent 2009–2010 campaign. In total, the study population then included 1140 workers, 203 participated twice contributing 30% of all noise measurements (Table 1).

All workers filled in a questionnaire providing information on job according to DISCO 88, the Danish version of the International Classification of Occupations (ISCO 88) containing 372 occupations on a 4-digit level (DISCO, 2011), and use of hearing protection devices. During measurement days, the workers also provided information on work schedules. Furthermore, a subgroup

Table 1. Number of companies, jobs, workers, and noise measurements by calendar year.

	Companies		Jobs[a]		Workers		Measurements	
	N	%	*N*	%	*N*	%	*N*	%
2001–2003	23	13	16	16	532	47	532	40
2001–2003 and 2009–2010	62	35	62	62	203	18	406	30
2009–2010	90	52	22	22	405	35	405	30
Total	175	100	100	100	1140	100	1343	100

[a] Jobs within the DISCO 88, the Danish version of the International Standard Classification of Occupations (ISCO), revision 1988.

of 334 workers filled in a log-book with detailed information on usage of hearing protection devices during the shift. Age and sex were extracted from the civil registration number (Pedersen, 2011).

The study protocol was approved by the local ethics committee (M-20080239) and the Danish Data Protection Agency (2009-41-3072) and participants gave written, informed consent.

Noise exposure measurements

Noise measurements were conducted during 2 subsequent work days. Measurements started throughout the day, and not necessarily when work started, and ended the subsequent day no later than 29 h after the first measurements started. Only measurements during work were included and not necessarily the complete working time. Sampling starting and ending times were defined by the research team according to what was practically feasible during this field study.

We measured noise level as A-weighted equivalent sound level means (L_{EQ}) by personal dosimeters (Brüel & Kjær, model 4443 and 4445) recording every 5 s. In the first measurement campaign in 2001–2003, dosimeters were set to a 50–120 dBA range. In the second campaign in 2009–2010, dosimeters were set to a 70–140 dBA range. Therefore, all 5-s measurements below 70 dBA regardless of campaign (38% in 2001–2003 and 53% in 2009–2010) were set to a value of 50 dBA corresponding with a 70 dBA threshold divided by $\sqrt{2}$ (Hornung and Reed, 1990; Burns *et al.*, 2016). Likewise, measurements over 120 dBA (0.002%) were set to 120 dBA, regardless of campaign.

All measurements were synchronized with questionnaire information, so each 5-s measurement relative to work, off-work, or night time could be identified. All individual noise recordings during work were transformed from dBA to intensity, and a mean was computed before transforming back to dBA yielding personal occupational noise intensity levels, hereafter referred to as noise levels according to the following formula: $10 \times \log\left[\sum(10^{\mathrm{dB(A)}/10} \times T)\right]$. Measurements were obtained on ordinary working days all year round to account for potential seasonal variation in exposure.

Expert assessment

During 2016, four specialists in occupational medicine with at least 10 years of experience evaluating occupational exposures within industries and jobs rated noise levels for jobs included in DISCO 88. In order to qualify ratings, we *a priori* randomly selected approximately half (n = 35) of the jobs with ≥5 noise measurements (mean of 21 measurements per job) in our database to benchmark their assessments. For these jobs, the experts were informed on mean, median, and range of dBA values measured, and the number of underlying measurements. The experts independently rated the expected average exposure intensity for a worker during a standard working day of 7.5 h for each of the remaining 337 jobs (22 jobs with estimated noise exposure level blinded to the experts and 315 jobs with no or <5 measurements (n = 43) and classified each job as low level (<80 dBA), medium level (80–84 dBA), or high level (≥85 dBA) exposed. The experts discussed discrepancies in ratings; based on relevant literature and sound arguments they reached consensus for all jobs. Before discussing discrepancies and reaching final consensus, three or all four experts agreed on the ratings in 85% of the cases, with a kappa of 0.77 for the overall agreements between the experts.

Statistical methods

Noise exposure grouping strategy

In order to examine variance components and predictors of noise exposure intensity, we fitted linear mixed effect models in STATA (mixed-command) using restricted maximum likelihood estimation, with mean noise exposure level as the dependent variable and job and worker as random effects including all measurements.

We checked the adequacy of the models confirming the normal distribution of the residuals by QQ plots and linearity/homogeneity by scatter plots of the residuals versus fitted values.

Statistical model

The model structure was:

$$\begin{aligned} Y = {} & \beta_0 + \beta_{\mathrm{sex}} + \beta_{\mathrm{age}} + \beta_{\mathrm{benchmark \times rating}} \\ & + \beta_{\mathrm{occupational\ class}} \\ & + \beta_{\mathrm{Calendar\ year \times occupational\ class}} \\ & + b_{\mathrm{job}} + b_{\mathrm{worker}} + \varepsilon \end{aligned}$$

The model terms were:
Y: noise level in dB

Fixed effects
β_0: model intercept
β_{sex}: categorical variable for sex (woman used as reference)
β_{age}: continuous variable for age (40-year-old as reference)
$\beta_{\mathrm{benchmark \times rating}}$: categorical interaction term between benchmark (yes, no) and expert rating (low, medium, and high exposed)
$\beta_{\mathrm{occupational\ class}}$: categorical variable for occupational class (blue-, white-collar used as reference)
$\beta_{\mathrm{calendar\ year \times occupational\ class}}$: continuous interaction term between calendar year (continuous with 2010 as a reference) and occupational class (blue-, white-collar)

Random effects
b_{job}: random effect term for job
b_{worker}: random effect term for worker
ε: residual error (within worker)

Information on sampling duration was also assessed but not included in the model because of statistical insignificance (P-value >0.05). P-values were not corrected for model selection or multiple testing.

The random effect terms b_{job} and b_{worker} were assumed statistically independent and normally distributed with means 0 and two different variance components representing the between job variance and the between-workers (within job) variance. We obtained best linear unbiased predictions (BLUPs) of the coefficients for each of the jobs with noise measurements (n = 100). The BLUPs shrink the estimates toward the overall mean exposure of the expert score when there are few measurements and pulls the estimates toward the individual measurements when either there are more measurements available or the exposure variability is low.

We aimed at assessing noise exposure levels for each of the 372 jobs described by the DISCO 88. Jobs without measurements were assigned the weighted mean noise exposure level derived from the model for the corresponding category of the expert ratings. For jobs with exposure measurements available, the job specific prediction from the statistical model (BLUP) was added to the noise exposure estimate. Thus, an exposure level for all 372 jobs, sex, age, benchmark, and year were estimated.

All analyses were performed using STATA 14.1 (StataCorp LP, College Station, TX, USA).

Results

The individual noise recording durations were normally distributed with a mean of 515 min and a SD of 147. Noise levels varied between 56 and 107 dBA with a mean of 81.7 dBA and a SD of 6.6. Noise level increased through the expert ratings and was higher among blue-collar jobs. Mean noise exposure decreased with increasing calendar year and age and was lower among women than men (Table 2).

Table 2. Number of samples and distribution of noise levels (dBA), overall and by level of selected variables.

Variable	N[a]	%[b]	Mean	SD
Overall	1343	100	81.7	6.6
Sex				
Women	323	24	78.3	7.1
Men	1020	76	82.8	6.0
Age (tertiles)				
18–37 years	470	35	82.4	6.8
38–46 years	457	34	81.6	6.3
47–65 years	416	31	81.2	6.5
Rating				
Low exposed	250	19	74.2	7.3
Medium exposed	541	40	81.9	4.4
High exposed	552	41	85.0	5.0
Calendar year				
2001	52	4	84.4	5.4
2002	599	45	82.2	6.5
2003	84	6	82.6	6.7
2009	333	25	81.3	6.4
2010	275	20	80.5	6.7
Occupational class				
White-collar	299	22	75.6	7.5
Blue-collar	1044	78	83.5	5.0

[a] Number of samples.
[b] Relative percentages of samples by level.

Table 3. Variance components for noise level (dBA) from the mixed effects model (*n* = 1343).

Variance components	Null model[a]	Intermediate model 1[b]		Intermediate model 2[c]		Final model[d]	
	Variance (%)	Variance	%[e]	Variance	%[e]	Variance	%[e]
Between jobs	25.4 (54)	24.0	6	7.9	69	7.1	72
Between workers	5.0 (11)	5.0	0	5.1	−2	5.3	−6
Within worker	16.2 (35)	15.9	2	15.9	2	15.5	4
Total	46.6 (100)	44.9	4	28.9	38	27.9	40

[a] Null model includes job and subject id as random effects.
[b] Intermediate model 1 includes in addition to the previous random effects, sex and age as fixed effects.
[c] Intermediate model 2 includes in addition to model 1, the interaction term between benchmark group and ratings as fixed effects.
[d] Final model includes in addition to model 2, occupational class and an interaction term between occupational class and calendar year as fixed effects.
[e] Percentage reduction of variance explained by fixed effects when compared with null model.

Table 4. Fixed effects model parameters for noise levels (dBA) (*n* = 1343).

	β	SE	*P*-value
Intercept	72.88	1.22	<0.001
Sex			
Woman	Ref.		
Man	1.25	0.41	0.002
Occupational class			
White-collar	Ref.		
Blue-collar	2.77	1.08	0.011
Age[a]	−0.04	0.01	0.012
Calendar year × occupational class[b]			0.012
White-collar	0.06	0.07	0.357
Blue-collar	−0.14	0.04	<0.001
Benchmark[c] × rating[d]			0.025
Yes			
Low exposed	Ref.		
Medium exposed	5.99	1.48	<0.001
High exposed	9.48	1.71	<0.001
No			
Low exposed	1.87	1.36	0.172
Medium exposed	4.87	1.74	0.006
High exposed	6.41	1.64	<0.001

[a] Age is standardised to 40 years (continuous).
[b] Interaction term between calendar year standardized to year 2010 (continuous) and occupational class (dichotomous).
[c] Expert rating for no benchmark group (low, medium, and high exposed).
[d] Interaction term between benchmark and ratings.

Table 3 presents variance components for noise level from the mixed effects model. More than 50% (25.4/46.6) of the total variance was between jobs as can be seen from the null model that only included random effects. By including sex and age as fixed effects, we observed a 6% reduction of the variance between jobs. When we added the interaction term between benchmark and expert rating as fixed effect this value increased to 69%, reaching finally a 71% reduction when we added occupational class and the interaction term between occupational class and calendar year as fixed effects in the final model.

The fixed effects model parameters are presented in Table 4. Noise level was higher among men and blue-collar workers. Noise level decreased with increasing age and showed an 0.1 dBA annual decline by increasing calendar year among blue-collar workers while no such trend was apparent for white-collar workers (test for interaction between occupational class and calendar year, $P = 0.012$). While medium exposed benchmark jobs were 1 dBA higher than the medium exposed expert rated jobs (5.99 versus 4.88 dBA), the corresponding difference was 3 dBA for the high exposed jobs (9.48 versus 6.41 dBA) (test for interaction between benchmark and expert rated jobs, $P = 0.025$).

Table 5 shows model-based mean noise levels (dBA) for the 10 highest and the 10 lowest exposed jobs as estimated for 40-year-old male workers in 2010. Metal wheel-grinders, polishers, and tool sharpeners presented the highest level of 88.9 dBA while finance and sales associate professionals showed the lowest noise level of 70.2 dBA.

Among low, medium, and high exposed workers, 12, 24, and 29% used hearing protection according to logbook information (data not shown).

Supplementary Table A presents the number of all 372 jobs as defined at the 4-digit level in DISCO 88 and the number of jobs represented in the dataset for the nine major job categories.

In total, 27% of all jobs were represented in our sample. We prioritized sampling of jobs with expected high noise exposure levels. A total of 46% of all jobs in the major job category 8 ‘Plant and machine operators

Table 5. Model-based noise level (dBA) for the 10 highest and the 10 lowest exposed jobs as estimated for a 40-year-old male worker in 2010 among 100 estimated jobs.

Jobs[a]	Job description	*N*	Mean
Ten highest exposed jobs			
7224	Metal wheel-grinders, polishers, and tool sharpeners	6	88.9
8123	Metal-heat-treating-plant operators	8	88.7
7411	Butchers, fishmongers, and related food preparers	11	88.1
8275	Fruit-, vegetable-, and nut-processing-machine operators	6	86.8
8240	Wood-products machine operators	37	86.3
8271	Meat- and fish-processing-machine operators	20	85.9
7212	Welders and flame cutters	6	85.8
7423	Woodworking machine setters and setter-operators	35	85.7
7211	Metal moulders and core makers	12	85.6
8274	Baked-goods, cereal, and chocolate-products machine operators	8	85.5
Ten lowest exposed jobs			
3419	Finance and sales associate professionals not elsewhere classified	<4	70.2
4212	Tellers and other counter clerks	<4	70.3
2441	Economists	<4	70.7
2419	Business professionals not elsewhere classified	17	71.8
4190	Other office clerks	12	71.9
1227	Production and operations department managers in business services	<4	72.0
3411	Securities and finance dealers and brokers	<4	72.8
3118	Draughts persons	<4	73.0
2351	Education methods specialists	<4	73.6
1231	Finance and administration department managers	<4	74.1

[a] Jobs within the DISCO 88, the Danish version of the International Standard Classification of Occupations (ISCO), revision 1988.

and assemblers' were represented in the data. We also included low and medium exposed jobs. The noise JEM will be made freely available at the DOC-X homepage (http://doc-x.dk/).

Discussion

We created a general population quantitative JEM with estimates of personal occupational noise intensity level specific for sex, age, and calendar year. The model calibrated the expert ratings to a scale (dBA). This enables assessment of job and calendar year specific exposure levels of occupational noise for all jobs represented in Denmark including those with missing quantitative information. The JEM will be applicable to epidemiological studies addressing exposure–response relations between occupational noise exposure and cardiovascular and other health effects hypothesized to be associated with noise exposure in and outside work.

Two JEMs of occupational noise exposure for the general population have previously been described. Sjöström *et al.* developed a Swedish expert based semi-quantitative 3-level JEM for 321 jobs within the Nordic Occupational Classification system based on ISCO 58. The expert assessment was informed on 569 measurements from 129 jobs. Twenty-five percent of the measurements were personal and included both short-time and full-shift measurements from 1970 to 2004, with most measurements collected during 1995–1999 (Sjöström *et al.*, 2013).

Recently, Roberts *et al.* reported a quantitative JEM including 753 702 measurements among 443 broad level standard occupational classification (SOC) groups in the USA (Roberts *et al.*, 2018). The measurements were mainly obtained from the US government occupational exposure databases (85%), private industry (14%), and published literature (1%) and made according to the Occupational Safety and Health Administration's (OSHA) permissible exposure limit of 90 dBA criterion level and threshold, and a 5 dB time–intensity exchange rate. They used imputation statistics for jobs with no available measurements (Roberts *et al.*, 2018) and had previously conducted a meta-analysis to ensure high heterogeneity across different job titles (Cheng *et al.*, 2018). In contrast to this extensive dataset and to the Swedish JEM, we used personal noise measurements collected in accordance with a research protocol, thereby circumventing some problems with hot spot measurements or worst case sampling (Cherrie, 2003).

We observed that women were exposed to less noise than men within the same jobs and we were thus able to capture some of the exposure variation within jobs. Lacking ability to go beyond the job is a major limitation of most JEMs (Kauppinen *et al.*, 1992; Greenland *et al.*, 2016). There have previously been indications of sex differences in occupational exposure levels within the same jobs for assembly workers and janitors (Locke *et al.*, 2014). Some argue that these differences could either be due to differences in either tasks or reporting (Eng *et al.*, 2011; Lacourt *et al.*, 2018), however, this might not always be the case (Heilskov-Hansen *et al.*, 2014). It could be argued that the noise level difference observed is due to sex differences between jobs rather than within jobs, however in 52% of all jobs both men and women are represented. And for up to 62% of blue-collar jobs, measurements on both sexes were available (data not shown).

Interestingly, we also found a decrease of noise exposure by increasing age, which could reflect changes to less exposed tasks over working years within the same job (Cassidy, 2017).

To our knowledge, only few previous JEMs have combined expert ratings with measurements in a statistical model framework (Peters *et al.*, 2011; Friesen *et al.*, 2012; Vested *et al.*, 2019). Applied in epidemiological studies, the use of general population JEMs has recently depicted the shape of the exposure–response relation between low-level asbestos and silica exposure and lung cancer in a population-based case–control study (De Matteis *et al.*, 2012; Olsson *et al.*, 2017).

More than 50% of the total variance of our dataset was between jobs and this is more than often seen in general population or industry specific exposure (Kromhout *et al.*, 1993; Peters *et al.*, 2011; Friesen *et al.*, 2012). Since noise exposure is prevalent in many jobs, this is expected to reflect considerable variation in noise levels across jobs (Kock *et al.*, 2004). Measurements were performed in companies within industries with high reporting of noise-induced hearing loss, which might overestimate noise exposure for the same jobs also represented in industries with lower noise levels and reporting of noise-induced hearing loss.

Adding the fixed effects to the model explained up to 72% of the between job variance, mostly attributed to the expert ratings. This proportion was about 43 and 18% in Friesen's and Peters' studies of benzene and quartz exposure, respectively (Peters *et al.*, 2011; Friesen *et al.*, 2012). Hence, most of the variance could be attributed to jobs.

There is a general concern about lack in consistency for expert rating of occupational exposures, and the agreement between experts can vary from poor to very good depending on the exposure (Teschke *et al.*, 2002; Friesen *et al.*, 2011). In order to improve homogeneity between the different experts' ratings, we selected 35 benchmark jobs with ≥5 measurements that permitted the experts to calibrate their estimates to a common scale. Even if noise level of 1/3 of the benchmark jobs were based on only 5–9 measurements and thus subject to uncertainty, we observed very good agreement between the experts (kappa = 0.77) before discussing discrepancies and reaching final consensus (Teschke *et al.*, 2002). Noise exposure increased monotonically with increasing expert rating, however, we observed that experts and thus our noise JEM were not able to capture the full exposure contrast in noise exposure level by overestimating low and underestimating high noise levels.

A comprehensive study estimated historical levels and long-term trends in occupational exposures, and found that most exposures declined between 4 and 14% per year, with a median value of 8% per year influenced by exposure factors including type of monitoring, historical changes in the threshold limit values, and period of sampling (Symanski *et al.*, 1998). Several other papers have documented the same decreasing trend in occupational noise exposure (Middendorf, 2004; Joy and Middendorf, 2007; Neitzel *et al.*, 2011, 2014; Sayler *et al.*, 2019). Roberts *et al.* also reported decreasing occupational noise exposures in 40.9% of the major classification groups (Roberts *et al.*, 2018). Parallel results have also been seen by others. Likewise, we observed a linear 0.1 dB annual decline of noise level among blue-collar workers. This finding provides the possibility to evaluate exposure changes over time that could be an important source of exposure misclassification if left unaccounted. Our dataset only included noise recordings made between 2001 and 2010. Extrapolating noise levels several years back in time based on the linear trend observed within this rather brief period is however not warranted.

Our elaborated final model provides estimates of personal ambient noise exposure levels that may be significantly attenuated by hearing protection (Stokholm *et al.*, 2014; Arlien-Søborg *et al.*, 2016; Frederiksen *et al.*, 2017). Based on questionnaire information, about 74% of highly exposed workers used hearing protective devices in our cohort. Neitzel *et al.* reported that workers exposed above 85 dBA who reported always using hearing protective devices, actually only wore them one-third of the time (Neitzel and Seixas, 2005), which was also the case in our population according to the log-book reporting. With information on the usage of hearing protection across jobs, it is possible to adjust exposure assessment. Mean noise level declined about 2 dBA when accounting for the use of hearing protection devices in a subsample of this population assuming a reduction of an average 10 dBA when wearing protection (Stokholm *et al.*, 2014).

This study was performed in random samples of small and large companies within a range of selected industries with high reporting of noise-induced hearing loss. Some of the reasons for declining participation (such as time lag or organizational changes) may not be related to noise levels, but there is a risk of bias if companies with high noise levels due to limited resources declined to participate, resulting in underestimation of actual noise levels. Still, it is plausible that companies that successfully have solved a noise problem would be less interested in participating. However, neither the participation rate at the industry nor the number of workers per industry was related to the measured noise levels. Workers were mainly selected by foremen and managers so as to have at least one employee from each work area, and this selection might have resulted in bias in an unpredictable direction. Nevertheless, we expect the measurements to be representative of these industries.

Each noise recording represented a sample of working hours during 2 subsequent working days and not a full shift. Sampling duration (mean 8.5 h) was not defined by the participants or shift length but by the research team and we regard the included measurements to be representative of full-shift noise levels. For that reason, it was not relevant to normalize levels to full-shift duration.

We only had repeated measurements from a few workers. This could bias the results if only highly motivated workers chose to participate in both measurement campaigns. Still, about 50% of workers agreed to participate in the second campaign when reinvited. However, only 36% (18% of all participants) had operational measurements, as the remaining were either performed during days off, or from unemployed or pensioned workers (Frederiksen *et al.*, 2017).

Some non-differential misclassification could also affect the results as 1-min resolution questionnaire information was synchronized with 5-s resolution noise level data.

It is problematic to compare these model-based noise levels with the two previous published JEMs on noise exposure. In Europe, we use a stricter noise exposure standard than in the USA (85 dBA level and a 3 dB time–intensity exchange rate). Thus, US levels are expected to be higher(Roberts *et al.*, 2018). Furthermore, Roberts *et al.* used 443 jobs according to the broad SOC and Sjöström *et al.* used 321 jobs classified according to the Nordic Occupational Classification system (NYK) (Sjöström *et al.*, 2013), which likewise makes comparability difficult. However, it is possible to compare few jobs across the three JEMs. In the Swedish JEM most measurements were collected during 1995–1999, and based on this assumption butchers, for example, are exposed to a median of 90 dBA, a mean of 90.6 dBA according to Roberts *et al.* and a mean of 90.3 dBA for a 40-year-old male in 1995 according to this JEM. The latter estimate reflected a 2.2 dBA increase from 2010 back to 1995. An increase of 3 dB was observed for the major SOC group in the same period in the American JEM. Likewise, workshop mechanics are exposed to a mean of 82.7 dB in 2010 (reference year), corresponding to 85.0 dBA in 1995 according to this JEM, a median of 88 dBA in the Swedish JEM and 83.7 dBA according to the American JEM.

Conclusion

The noise estimates of this JEM can guide future preventive efforts, not only focussing on specific jobs but also targeting age and sex. Additionally, this occupational noise exposure matrix can be used in epidemiological studies to investigate exposure–response relations between occupational noise exposure and health effects. This quantitative JEM is designed for epidemiological studies of the general population as noise exposure is ubiquitous and not restricted to specific industries. The JEM provides exposure levels by calendar year which is highly relevant for estimating duration of and cumulative contemporary noise exposure retrospectively, which may predict otological, cardiovascular and other non-contagious diseases. Furthermore, we showed the usefulness of applying benchmarks for the calibration of expert assessment.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of Interest

The authors declare no conflict of interest relating to the ma presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

References

Arlien-Søborg MC, Schmedes AS, Stokholm ZA *et al.* (2016) Ambient and at-the-ear occupational noise exposure and serum lipid levels. *Int Arch Occup Environ Health*; **89**: 1087–93.

Burns KN, Sun K, Fobil JN *et al.* (2016) Heart rate, stress, and occupational noise exposure among electronic waste recycling workers. *Int J Environ Res Public Health*; **13**: 140.

Cassidy H. (2017) Task variation within occupations. *Ind Relat*; **56**: 393–410.

Cheng W, Roberts B, Mukherjee B *et al.* (2018) Meta-analysis of job-exposure matrix data from multiple sources. *J Expo Sci Environ Epidemiol*; **28**: 259–74.

Cherrie JW. (2003) The beginning of the science underpinning occupational hygiene. *Ann Occup Hyg*; **47**: 179–85.

De Matteis S, Consonni D, Lubin JH *et al.* (2012) Impact of occupational carcinogens on lung cancer risk in a general population. *Int J Epidemiol*; **41**: 711–21.

DISCO. (2011) Available at https://www.dst.dk/en/statistik/dokumentation/nomenklaturer/disco-88. Accessed 14 May 2019.

Eng A, 't Mannetje A, McLean D *et al.* (2011) Gender differences in occupational exposure patterns. *Occup Environ Med*; **68**: 888–94.

Eurofound. (2016) Sixth European working conditions survey—overview report. Luxembourg: Office of the European Union. Available at http://www.eurofound.europa.eu/sites/default/files/ef_publication/field_ef_document/ef1634en.pdf. Accessed 14 May 2019.

Frederiksen TW, Ramlau-Hansen CH, Stokholm ZA *et al.* (2017) Noise-induced hearing loss—a preventable disease? Results of a 10-year longitudinal study of workers exposed to occupational noise. *Noise Health*; **19**: 103–11.

Friesen MC, Coble JB, Katki HA *et al.* (2011) Validity and reliability of exposure assessors' ratings of exposure intensity by type of occupational questionnaire and type of rater. *Ann Occup Hyg*; **55**: 601–11.

Friesen MC, Coble JB, Lu W *et al.* (2012) Combining a job-exposure matrix with exposure measurements to assess occupational exposure to benzene in a population cohort in shanghai, china. *Ann Occup Hyg*; **56**: 80–91.

Greenland S, Fischer HJ, Kheifets L. (2016) Methods to explore uncertainty and bias introduced by job exposure matrices. *Risk Anal*; **36**: 74–82.

Heilskov-Hansen T, Svendsen SW, Frølund Thomsen J *et al.* (2014) Sex differences in task distribution and task exposures among Danish house painters: an observational study combining questionnaire data with biomechanical measurements. *PLoS One*; **9**: e110899.

Hornung RW, Reed LD. (1990) Estimation of average concentration in the presence of non-detectable values. *Appl Occup Environ Hyg*; **5**: 46–51.

Joy GJ, Middendorf PJ. (2007) Noise exposure and hearing conservation in U.S. coal mines—a surveillance report. *J Occup Environ Hyg*; **4**: 26–35.

Kauppinen TP, Mutanen PO, Seitsamo JT. (1992) Magnitude of misclassification bias when using a job-exposure matrix. *Scand J Work Environ Health*; **18**: 105–12.

Kock S, Andersen T, Kolstad HA *et al.* (2004) Surveillance of noise exposure in the Danish workplace: a baseline survey. *Occup Environ Med*; **61**: 838–43.

Kromhout H, Symanski E, Rappaport SM. (1993) A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Ann Occup Hyg*; **37**: 253–70.

Lacourt A, Labrèche F, Goldberg MS *et al.* (2018) Agreement in occupational exposures between men and women using retrospective assessments by expert coders. *Ann Work Expo Health*; **62**: 1159–70.

Locke SJ, Colt JS, Stewart PA *et al.* (2014) Identifying gender differences in reported occupational information from three US population-based case-control studies. *Occup Environ Med*; **71**: 855–64.

Middendorf PJ. (2004) Surveillance of occupational noise exposures using OSHA's Integrated Management Information System. *Am J Ind Med*; **46**: 492–504.

Neitzel RL, Galusha D, Dixon-Ernst C *et al.* (2014) Methods for evaluating temporal trends in noise exposure. *Int J Audiol*; **53** (Suppl. 2): S76–83.

Neitzel R, Seixas N. (2005) The effectiveness of hearing protection among construction workers. *J Occup Environ Hyg*; **2**: 227–38.

Neitzel RL, Stover B, Seixas NS. (2011) Longitudinal assessment of noise exposure in a cohort of construction workers. *Ann Occup Hyg*; **55**: 906–16.

Olsson AC, Vermeulen R, Schüz J *et al.* (2017) Exposure-response analyses of asbestos and lung cancer subtypes in a pooled analysis of case-control studies. *Epidemiology*; **28**: 288–99.

Pedersen CB. (2011) The danish civil registration system. *Scand J Public Health*; **39** (7 Suppl.): 22–5.

Peters S, Vermeulen R, Cassidy A *et al.*; INCO Group. (2011) Comparison of exposure assessment methods for occupational carcinogens in a multi-centre lung cancer case-control study. *Occup Environ Med*; **68**: 148–53.

Peters S, Vermeulen R, Portengen L *et al.* (2011) Modelling of occupational respirable crystalline silica exposure for quantitative exposure assessment in community-based case-control studies. *J Environ Monit*; **13**: 3262–8.

Prince MM. (2002) Distribution of risk factors for hearing loss: implications for evaluating risk of occupational noise-induced hearing loss. *J Acoust Soc Am*; **112**: 557–67.

Roberts B, Cheng W, Mukherjee B *et al.* (2018) Imputation of missing values in a large job exposure matrix using hierarchical information. *J Expo Sci Environ Epidemiol*; **28**: 615–48.

Rubak T, Kock S, Koefoed-Nielsen B *et al.* (2008) The risk of tinnitus following occupational noise exposure in workers with hearing loss or normal hearing. *Int J Audiol*; **47**: 109–14.

Sayler SK, Roberts BJ, Manning MA *et al.* (2019) Patterns and trends in OSHA occupational noise exposure measurements from 1979 to 2013. *Occup Environ Med*; **76**: 118–24.

Selander J, Albin M, Rosenhall U *et al.* (2016) Maternal occupational exposure to noise during pregnancy and hearing dysfunction in children: a nationwide prospective cohort study in sweden. *Environ Health Perspect*; **124**: 855–60.

Sjöström M, Lewné M, Alderling M *et al.* (2013) A job-exposure matrix for occupational noise: development and validation. *Ann Occup Hyg*; **57**: 774–83.

Skogstad M, Johannessen HA, Tynes T *et al.* (2016) Systematic review of the cardiovascular effects of occupational noise. *Occup Med (Lond)*; **66**: 10–6.

Stokholm ZA, Hansen ÅM, Grynderup MB *et al.* (2014) Recent and long-term occupational noise exposure and salivary cortisol level. *Psychoneuroendocrinology*; **39**: 21–32.

Symanski E, Kupper LL, Hertz-Picciotto I *et al.* (1998) Comprehensive evaluation of long-term trends in occupational exposure: Part 2. Predictive models for declining exposures. *Occup Environ Med*; **55**: 310–6.

Teschke K, Olshan AF, Daniels JL *et al.* (2002) Occupational exposure assessment in case-control studies: opportunities for improvement. *Occup Environ Med*; **59**: 575–93; discussion 594.

The Danish Working Environment Authority. (2019) Arbejdstilsynet - is working for a safe and healthy working environment in all companies in Denmark. Available at https://at.dk/en/about-us/about-the-wea/. Accessed 14 May 2019.

Thygesen LC, Daasnes C, Thaulow I *et al.* (2011) Introduction to Danish (nationwide) registers on health and social issues: structure, access, legislation, and archiving. *Scand J Public Health*; **39** (7 Suppl.): 12–6.

Vested A, Schlünssen V, Burdorf A *et al.* (2019) A quantitative general population job exposure matrix for occupational daytime light exposure. *Ann Work Expo Health*; **63**: 666–78.

Wild P, Sauleau EA, Bourgkard E *et al.* (2002) Combining expert ratings and exposure measurements: a random effect paradigm. *Ann Occup Hyg*; **46**: 479–87.