Noise induced hearing loss: Screening with pure-tone audiometry and speech-in-noise testing
Leensen, M.C.J.

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Longitudinal changes in hearing threshold levels of noise-exposed construction workers

M.C.J. Leensen
W.A. Dreschler
Abstract

Purpose: Longitudinal analysis of audiometric data of a population of noise-exposed workers provides insight in the development of noise-induced hearing loss (NIHL) over a period of 4 years, as a function of noise exposure, and age.

Methods: Over a period of approximately 4 years after the measurements reported in Chapter 2, 17,930 construction workers of this baseline cohort had one or more follow-up assessments. Their pure-tone audiometric thresholds obtained during these periodic occupational health examinations were available for analysis. Linear mixed models were fitted to explore the relationship between the annual rate of change in hearing and noise intensity, exposure duration, and age. The audiometric data of a subset of 3,111 workers who were tested on three occasions, were used to investigate the pattern of hearing loss development.

Results: The mean annual rate of change in this study population was about 0.56 dB/yr and this became larger with increasing noise intensity and increasing age. The duration of noise exposure did not affect the annual shift in hearing loss. During the first decade of noise exposure, mean rate of change again deviated from ISO-1999 predictions, in that hearing thresholds improved. The change in hearing over of three measurements showed a concave development of hearing loss as a function of time, corresponding to NIHL development.

Discussion: The deviation from ISO-1999 predictions observed in Chapter 2 is probably the result of the higher average normal-hearing levels in survey data. Because hearing threshold levels obtained at follow-up were better than those obtained at baseline, no statement can be made about the NIHL development during the first decade of exposure. This improvement in hearing threshold levels is likely the results of measurement variation in occupational screening audiometry, rather than an actual improvement in hearing ability.
Introduction

Noise is one of the most prevalent occupational hazards. Despite the widespread recognition of the impact of noise on hearing, occupational noise exposure remains a significant problem, especially in the construction industry (Suter, 2002), where the majority of the workforce is exposed to daily noise levels exceeding 80 dBA (Neitzel et al, 2011). As a result, noise-induced hearing loss (NIHL) is the most commonly reported occupational disease in the Netherlands (Van der Molen & Lenderink, 2012). Averaged over the past five years, 39% of occupational disease reports concerned NIHL, the majority of which derived from the construction industry (Van der Molen & Lenderink, 2012).

Indeed, the cross-sectional data analysis reported in Chapter 2 showed that noise-exposed construction workers had greater hearing losses compared to the reference population reported in ISO-1999 annex A (1990), as well as to their non-noise-exposed colleagues.

The ISO-1999 standard combines data from numerous cross-sectional studies into a widely used model to predict hearing loss for a noise-exposed population. This model assumes that a subject’s hearing threshold level (HTL) is composed of two additive elements: an age-related component estimating the age-related hearing loss (ARHL) in annex A, and an estimation of the noise-induced permanent threshold shift (NIPTS) resulting from on-the-job noise exposure.

However, the relationships of hearing threshold and noise exposure found in Chapter 2 deviates from the relationship described in ISO-1999 in two important aspects. First, there was only a weak relationship between noise intensity and hearing threshold levels. When the daily noise exposure level rose from 80 dBA towards 96 dBA only a minor increase in hearing loss was shown (0.18 dB increase per dB increase in noise level). The duration of noise exposure seemed a better predictor than noise exposure level, probably because of limited accuracy of noise exposure estimates (Seixas et al, 2004; Seixas et al, 2012) and the confounding effect of hearing protection usage (Rabinowitz et al, 2007).

Second, despite the stronger relationship of hearing loss and exposure time, it only corresponded to ISO-1999 predictions for durations between 10 and 40 years, whereas the observed thresholds in the first decade of exposure were higher than predicted by ISO. ISO-1999 presents an algorithm, to calculate NIPTS for exposure durations between 10 and 40 years. However, previous research showed that most NIHL arises during the first 10 to 15 years of noise exposure (Taylor et al, 1965; Rösler 1994; Prince et al, 2002). ISO-1999 designs this steep increase in HTL by an extrapolation of 0 dB NIPTS at the start of noise exposure to the NIPTS predicted after 10 years. Instead of this progressive increase in hearing loss during the first decade of exposure,
the retrospective analysis in Chapter 2 showed an increase in HTLs with increasing exposure duration, which was similar to the relationship found for longer exposure durations. Hearing loss was higher than ISO-1999 predicted, and more importantly, workers employed for less than one year showed average age-corrected hearing losses of about 10 dB HL. Other studies focusing on the first effects of occupational noise exposure also showed deviations from the ISO-1999 interpolation, in that their observed elevation of baseline hearing thresholds was similar to the findings in Chapter 2 (Henderson & Saunders, 1998; Seixas et al, 2004). This poses the question whether the interpolation proposed by ISO-1999 for the first decade of noise exposure is applicable to occupationally exposed employees, or whether employees may have some pre-existing hearing loss when entering the workforce, probably due to recreational noise exposure.

The data analysis described in Chapter 2 was based on cross-sectional data collection, and so estimations of hearing loss over time were done across subgroups of the total study population, rather than obtained individually. Considering the pattern of hearing loss development during the first decade of exposure, the preferred approach to study the development of early losses is using longitudinal studies, especially since this may follow a nonlinear history (Johnson, 1991). Longitudinal analyses combining baseline data with follow-up measurements of the same study population could give more insight into the development of hearing loss over time.

However, the ability to observe small threshold shifts over time requires that the measurement procedure is sufficiently sensitive to detect relatively small changes. Small threshold shifts for an individual employee cannot easily be distinguished from normal test-retest variability of standard pure tone audiometry (Royster & Royster, 1986), which is about 5 dB (Dobie, 1983; Hall & Lutman, 1999; Helleman & Dreschler, 2012). Nevertheless, on group level pure-tone audiometry can establish overall hearing trends for noise-exposed employees by longitudinal analysis of a large audiometric database (Royster & Royster, 1986). Analysing repeated measurements over time within the same individuals may reduce variability in threshold determinations and by averaging over large groups, small changes can be identified.

Of the original group of 29,644 construction workers that were studied by cross-sectional analysis in Chapter 2, 17,930 performed one or more follow-up audiograms in the 4-year period following baseline assessment. Industrial data provide an immediate source of practical knowledge concerning effects of noise on hearing, and longitudinal analysis of hearing threshold levels over time can provide insight in development of NIHL.

Aim of this study was to describe the change in hearing threshold levels of noise-exposed workers as measured during regular periodic audiometric screening over time, and to estimate the typical rate of change in hearing sensitivity per year. The
relationship of this rate of change in hearing with both occupational noise exposure and age is examined, and compared to ISO-1999 predictions. Particular interest is in workers exposed for less than 10 years in order to establish the amount of hearing loss growth during the first decade of exposure. In addition, the association of demographic or work-related variables with the development of NIHL is studied, because this may identify specific risk groups. Finally, the audiometric data of the employees having more than one follow-up measurement are investigated, to analyse the course of hearing loss development.

**Methods**

The study of longitudinal changes in hearing threshold levels was based on data collected by Arbouw, the Dutch national institute on occupational health and safety in the construction industry. These data were extracted from medical records of periodic occupational health examinations (POHE) that were performed as part of regular occupational healthcare. This POHE consisted of an extensive self-administered questionnaire and a physical examination, including standardized audiometric testing. POHEs are offered to all construction employees, irrespective of occupational exposure to noise. Every employee is invited to participate once every four (age < 40) or two (age ≥ 40) years. Participation is completely voluntary.

**Data collection**

The starting point for the data collection in this study was the dataset used for the cross-sectional data analysis described in Chapter 2. That study population, referred to as the baseline cohort, consisted of 29,216 employees examined between 1 November 2005 and 20 July 2006. All additional records of follow-up POHEs of this baseline population performed until July 2010, as well as data from their baseline records, constituted the current dataset of investigation. In total, 22,575 follow-up records were available for analyses.

Of the these records, 4,645 were from the same individuals who had two follow-up examinations during the measurement period. The three measurements available for this subset were kept in a separate dataset, in order to investigate the pattern of hearing loss development over three measurement occasions. For the main analyses, the baseline data and the most recent measurement of this subset were kept, and thus the final dataset consisted of two measurements of 17,930 unique subjects.

**Audiometric measurement**

The core of the data collection was formed by the hearing threshold levels as obtained by regular screening audiometry. Pure-tone audiometry was assessed in accordance
with ISO-8253.1 (2010). Audiometers were annually calibrated according to ISO-389.1 (1998). POHEs were usually conducted during the work shift and at workplaces. If this was possible a mobile unit equipped with a soundproof booth was used. Pure tone air-conduction thresholds were determined at frequencies 0.5, 1, 2, 3, 4, 6, and 8 kHz in both ears, in 5-dB steps ranging from -15 dB HL to a maximum of 90 dB HL. A HTL of 90 dB HL was the upper limit of the test equipment and a hearing threshold level was marked as 95 dB HL if the participant did not respond to this maximum sound signal. Because of this ceiling effect, only hearing threshold recordings of 90 dB HL and lower were preserved in this analysis.

**Questionnaire**

Prior to the physical examination, the POHE participants completed an extensive self-administered questionnaire. Relevant demographic, occupational, and health-related data were extracted from these questionnaires. This included information regarding job title, use of hearing protection devices (HPDs) (yes/no), the number of years employed in both the construction industry and the current occupation, presence of hearing complaints, and whether employees were troubled by noise at work. In addition, cigarette smoking status, alcohol intake and blood pressure were recorded. Hypertension was defined as systolic blood pressure ≥ 140 mmHg combined with diastolic blood pressure ≥ 90 mmHg (De Moraes Marchiori, 2006).

**Noise exposure estimation**

To estimate daily noise exposure, workers were classified by the time weighted average (TWA) noise exposure levels estimated for standardized job titles. These TWA exposure levels were extracted from a database of Arbouw (Arbouw, 1998) that reported data of measurements of TWA noise levels based on personal dosimetry sampling for several job titles. Exposure levels for remaining job titles were based on sound level measurements during specified activities and on group data recorded in previous POHEs. For more information on these noise exposure level estimations, see Chapter 2. All noise exposure levels were expressed as equivalent 8-h, A-weighted sound-pressure levels \( L_{A,eq(8h)} \) calculated using an exchange rate of 3 dB. The reported years of employment in construction industry were used to estimate the duration of noise exposure. The correspondence between reported years employed in construction and years worked in the current job was used to determine whether an employee has had a change in job history. If the number of years employed in construction sector exceeded the number of years on current job, it was assumed that the former job has had equivalent exposure levels.

The workers that were employed in non-noise exposed jobs could function as a reference group. Since this study focuses on the change in hearing threshold levels over time, the 1,077 subjects that reported no occupational noise exposure during
the intermediate measurement period were defined as the reference population.

**Exclusion criteria**

In some cases a medical record could not be used for analysis. Whole employee records were removed for the following reasons:

- Insufficient follow-up period; the interval between measurements should be at least 1 year. In total 475 employees that had their follow-up examination within 11 months after baseline were excluded from analysis.
- Incorrect data collection; 410 workers were omitted for having either demographic discrepancies or missing hearing threshold levels. Similar exclusion criteria as in the baseline cohort were applied (see Chapter 2).
- Lack of correspondence between successive datasets; after merging medical records of each individual, 2,623 cases showed discrepancies between repeated measurements of variables of noise exposure could not be used for current analysis.
- Audiometric discrepancies; 2,160 audiograms that did not correspond with signs of NIHL or presbyacusis, or demonstrated changes (either positive or negative) that showed major deviations from expected values were also excluded.

In the appendix, more details on the specific exclusion criteria are described.

As a result, 12,269 subjects were considered to have reliable data and were kept for further analysis.

**Statistical analyses**

The data were analysed using SPSS (version 19.0) and R software (R Foundation 2008, from http://www.R-project.org).

Linear mixed effect models can be used to fit longitudinal data in which the number and spacing of observations vary among participants. So these models were fitted to current data to assess the longitudinal changes in this study sample, in both ears and across all frequencies, while accounting for the effects of repeated measurements within each individual. Fixed effects in these models were fitted to estimate of the average intercept and the effect of different factors and covariates on hearing threshold levels or change in hearing loss. Random effects accounted for individual variation in individual thresholds, ear, and differences in thresholds among the frequencies. Additionally, these random effects accounted for the autocorrelation due to repeated measurements within each individual and allowed for unbalanced data due to missing values.

First step in data analysis was that the average hearing threshold levels of the total study population collected at two measurement occasions were examined using mixed effects modeling. For this general analysis, longitudinal change was represented by a fixed linear effect of ‘time’, and the audiometric configuration was represented
by the term ‘frequency’. A term representing the tested ‘ear’ also was included. In addition, two-way interactions among these fixed factors were incorporated. After this first analysis, the change in HTLs, and the effect of different parameters on this change were examined, using the rate of change in dB/year as dependent variable. By dividing the difference in HTLs by time between baseline and follow-up measurements in years, effects of different interval periods were eliminated, reducing the amount of parameters in the model. To further reduce the number of parameters, analyses focused on the change in hearing loss in the pure-tone average of the noise-sensitive frequencies 3, 4, and 6 kHz (PTA \(_{3,4,6}\)). Again, these longitudinal analyses of changes in hearing were conducted using mixed effects modeling, with variation between subjects, ears within subject, and measured frequency treated as random effects. The predictors of primary interest were, besides frequency and ear, baseline age, noise intensity, noise exposure duration, and HPD usage. Adjustments were made for covariates thought to be correlated with either HTLs and occupational noise exposure: baseline hearing status (PTA \(_{3,4,6}\)), change in job history, duration of the follow-up interval, smoking status, hearing complaints, and noise disturbance at work.

Only factors and interaction terms that showed a significant contribution to the fitted model, tested with conditional F-tests at the 0.05 level, were investigated for significant coefficients at each level. When coefficients proved to be significant, the term was retained in the model. The results of the models are displayed as the estimated effects for the fixed factors and interaction terms retained in the model, and coefficients and corresponding 99% confidence levels are presented for each term. In case of an interaction between two variables, the difference between a certain condition and the reference is obtained by summing up the coefficients obtained for each term contributing to that interaction.

Results

Characteristics of study population

In total, hearing threshold levels of 12,269 male construction employees were collected. This population can be divided into a large group of noise-exposed employees (n = 11,192) and an internal reference group that was not exposed to noise during the measurement interval (n = 1,077). Mean age of both groups was similar (p = 0.095), but the distribution over age groups differed slightly (p < 0.001) (Table 3.1). Noise-exposed workers were on average 3.8 years longer employed in the construction industry (p < 0.001). Based on their job title, the majority of the exposed group, 75.5%, was estimated to work in average daily noise levels of 90 dBA or higher. Of the exposed employees, 76.9% reported to use hearing protection, 21.8% had complaints of worsened hearing, and 39.0% is bothered by noise during work. Baseline hearing of
the reference group was slightly better than hearing levels observed in the exposed workers (p < 0.001) in both ears (Table 3.1).

Hearing threshold levels
The mean HTLs of the study population at both measurement occasions are shown in Figure 3.1, for both ears separately. Mean hearing levels are plotted against the HTLs of the reference group and the predicted hearing levels by ISO-1999 annex A, based on individual median age-related hearing loss calculated for each employee in the noise-exposed group.

Linear mixed effect models were run with random effects for ‘subject’ and ‘ear’, and fixed effects for ‘ear’ (left, right), ‘frequency’ (0.5 – 8 kHz), and ‘measurement time’ (baseline, follow-up). Two-way interactions between the fixed effects were also included in the model.

Figure 3.1. Mean HTLS of the noise-exposed workers, the non-exposed references and ISO-1999 predictions, for both baseline (dashed line) and follow-up (solid line) measurements.
All fixed factors in the model showed significant effects, and the coefficients and corresponding 99% confidence intervals for all terms of the full model are displayed in Table 3.2. The main effect of ‘frequency’ ($F[1,141468] = 10764.24, p < 0.001$) indicated that hearing threshold levels differed over the frequencies at which they had been
Longitudinal changes in hearing threshold levels obtained. Mean baseline HTLs in the right ear ranged from 12.2 dB HL at 0.5 kHz to 31.3 dB HL at 6 kHz, and were highest in the higher frequency region. Also, ‘frequency’ showed a significant interaction with both ‘measurement time’ (F[6,141468] = 68.48, p < 0.001) and ‘ear’ (F[6,165054] = 377.75, p < 0.001) indicating that the mean HTL difference between both ears or measurements differed between the tested frequencies (Table 3.2).

Table 3.2. Coefficients and 99% confidence intervals for the different terms in the linear mixed model predicting hearing threshold levels of the study population.

<table>
<thead>
<tr>
<th>Model terms</th>
<th>Coefficient</th>
<th>99% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTL right at 0.5 kHz</td>
<td>12.18</td>
<td>11.83 – 12.54</td>
</tr>
<tr>
<td>HTL right at 1 kHz</td>
<td>12.19</td>
<td>11.83 – 12.55</td>
</tr>
<tr>
<td>HTL right at 2 kHz</td>
<td>13.30</td>
<td>12.94 – 13.66</td>
</tr>
<tr>
<td>HTL right at 3 kHz</td>
<td>20.45</td>
<td>20.09 – 20.81</td>
</tr>
<tr>
<td>HTL right at 4 kHz</td>
<td>27.46</td>
<td>27.11 – 27.82</td>
</tr>
<tr>
<td>HTL right at 6 kHz</td>
<td>31.32</td>
<td>30.96 – 31.68</td>
</tr>
<tr>
<td>HTL right at 8 kHz</td>
<td>24.73</td>
<td>24.37 – 25.08</td>
</tr>
<tr>
<td>Left * 0.5 kHz</td>
<td>-0.54</td>
<td>-0.89 – -0.19</td>
</tr>
<tr>
<td>Left * 1 kHz</td>
<td>-0.01</td>
<td>-0.51 – 0.48</td>
</tr>
<tr>
<td>Left * 2 kHz</td>
<td>1.49</td>
<td>1.00 – 1.99</td>
</tr>
<tr>
<td>Left * 3 kHz</td>
<td>2.64</td>
<td>2.14 – 3.13</td>
</tr>
<tr>
<td>Left * 4 kHz</td>
<td>2.58</td>
<td>2.08 – 3.08</td>
</tr>
<tr>
<td>Left * 6 kHz</td>
<td>2.00</td>
<td>1.51 – 2.50</td>
</tr>
<tr>
<td>Left * 8 kHz</td>
<td>2.12</td>
<td>1.62 – 2.62</td>
</tr>
<tr>
<td>Follow-up * 0.5 kHz</td>
<td>-0.28</td>
<td>-0.44 – -0.11</td>
</tr>
<tr>
<td>Follow-up * 1 kHz</td>
<td>-0.18</td>
<td>-0.41 – -0.05</td>
</tr>
<tr>
<td>Follow-up * 2 kHz</td>
<td>0.53</td>
<td>0.30 – 0.76</td>
</tr>
<tr>
<td>Follow-up * 3 kHz</td>
<td>1.66</td>
<td>1.42 – 1.89</td>
</tr>
<tr>
<td>Follow-up * 4 kHz</td>
<td>2.54</td>
<td>2.31 – 2.77</td>
</tr>
<tr>
<td>Follow-up * 6 kHz</td>
<td>0.71</td>
<td>0.48 – 0.95</td>
</tr>
<tr>
<td>Follow-up * 8 kHz</td>
<td>3.00</td>
<td>2.77 – 3.24</td>
</tr>
</tbody>
</table>

The coefficients reflect mean baseline HTLs of the right ear, the difference in baseline HTLs in the left ear relative to the right ear, and the difference in HTLs obtained in the follow-up measurement relative to baseline, for each frequency.
‘Measurement time’ showed a significant main effect (F[1,165054] = 19.09, p < 0.001), indicating that the thresholds obtained at follow-up showed poorer hearing at 2 to 8 kHz. However, at 0.5 and 1 kHz a small but significant improvement of hearing levels was observed (Table 3.2). These effects are also shown in Figure 3.1. The main effect of ‘ear’ (F[1,11323] = 15.47, p < 0.001) showed that across the frequencies measured, hearing sensitivity was slightly poorer in the left ear than in the right, with differences ranging from 1.49 to 2.64 dB HL.

The focus of this study is on change in hearing loss over time. Thus, in order to reduce the number of variables in the model, the successive analyses concerned the rate of change in dB per year, rather than absolute hearing threshold levels. A linear mixed effect model with random effects for ‘subject’ and ‘ear’, and fixed effects for ‘ear’ and ‘frequency’ showed that the rate of change differed across test frequencies (F[6,141474] = 357.55, p < 0.001); hearing was significantly worsened at higher frequencies, varying from 0.19 dB/year at 2 kHz to 0.99 dB/year at 8 kHz (Table 3.3). The negative coefficient obtained for a change in hearing at 0.5 kHz reflected an improvement in hearing of 0.08 dB/year at this frequency. There was no significant effect of ‘ear’ (F[1,11322] = 3.33, p = 0.068), indicating that, although baseline HTLs were different, the rate of change was similar in left and right ears.

<table>
<thead>
<tr>
<th>Model terms</th>
<th>Coefficient</th>
<th>99% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTL change right at 0.5 kHz</td>
<td>-0.08</td>
<td>-0.16 – -0.01</td>
</tr>
<tr>
<td>HTL change right at 1 kHz</td>
<td>-0.05</td>
<td>-0.13 – 0.03</td>
</tr>
<tr>
<td>HTL change right at 2 kHz</td>
<td>0.19</td>
<td>0.11 – 0.27</td>
</tr>
<tr>
<td>HTL change right at 3 kHz</td>
<td>0.58</td>
<td>0.51 – 0.66</td>
</tr>
<tr>
<td>HTL change right at 4 kHz</td>
<td>0.87</td>
<td>0.79 – 0.95</td>
</tr>
<tr>
<td>HTL change right at 6 kHz</td>
<td>0.38</td>
<td>0.30 – 0.46</td>
</tr>
<tr>
<td>HTL change right at 8 kHz</td>
<td>0.99</td>
<td>0.91 – 1.07</td>
</tr>
<tr>
<td>HTL change left</td>
<td>0.03</td>
<td>-0.01 – 0.08</td>
</tr>
</tbody>
</table>

The coefficients reflect mean annual change in HTL for each frequency, and the overall difference in the left ear relative to the right. Since this term is not significant, mean annual changes displayed are similar in the left ear.
Relationship of noise exposure and rate of hearing loss

NIHL affects the high-frequency region, so the greatest change in HTLs of noise-exposed employees was expected in this region (Table 3.3). In order to investigate the effect of age, noise exposure, and covariates on hearing loss development, the rate of hearing loss is defined as the annual rate of change in the pure tone average of hearing threshold level at 3, 4 and 6 kHz (PTA\textsubscript{3,4,6}). The mean rate of hearing loss observed for the total study population was 0.54 dB/year (SD = 3.04).

The relationship between annual rate of change in hearing and noise exposure, was investigated by fitting a linear mixed effect model for fixed effects of ‘noise intensity’ and ‘exposure duration’, and random effects for ‘subject’ and ‘ear’. Since hearing thresholds deteriorate with increasing age, the effect of ‘baseline age’ was also investigated as a covariate in this model. All three parameters showed a significant bivariate relationship with PTA\textsubscript{3,4,6}. The complete mixed model showed both a positive association of annual shift in hearing with noise intensity (F[1,12253] = 11.51, p < 0.001) and with baseline age (F[1,12253] = 123.73, p < 0.001). The main effect of ‘exposure duration’ did not significantly contribute to the model (F[1,12253] = 0.004, p = 0.946). This variable was highly correlated with baseline age, which already explained most of the variance associated with age and/or duration and change in hearing. There were no significant interaction terms between the three fixed factors. The coefficients of the model are shown in Table 3.4. A positive coefficient means a deterioration in hearing ability, a negative coefficient indicates an improvement in hearing thresholds. The intercept value of -1.08 indicated that an improvement in PTA\textsubscript{3,4,6} was observed for workers in the reference condition that the intercept represented. This reference condition concerned workers of 16 years old, exposed to daily noise levels not exceeding 80 dBA and employed in construction for less than 1 year at baseline. The positive coefficients for noise intensity and baseline age showed that the deterioration in PTA\textsubscript{3,4,6} became larger with increasing noise exposure level and increasing age; with every dB increase in intensity of the noise exposure above 80 dBA, the change in

<table>
<thead>
<tr>
<th>Model terms</th>
<th>Coefficient</th>
<th>99% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.08</td>
<td>-1.338 – -0.822</td>
</tr>
<tr>
<td>Noise level</td>
<td>0.024</td>
<td>0.006 – 0.043</td>
</tr>
<tr>
<td>Exposure duration</td>
<td>0.000</td>
<td>-0.009 – 0.010</td>
</tr>
<tr>
<td>Age</td>
<td>0.048</td>
<td>0.037 – 0.059</td>
</tr>
</tbody>
</table>
PTA$_{3,4,6}$ increased with 0.024 dB/yr, and with every year increase in baseline age exceeding 16 years, the change in PTA$_{3,4,6}$ was 0.048 dB greater. Overall, these model coefficients meant that, for example, worker aged 45 years who was exposed to a daily noise level of 90 dBA, would show an average annual deterioration in PTA$_{3,4,6}$ of 0.55 dB/yr.

**Comparison to the ISO-1999 model**

To gain more insight into the relationship between noise exposure and hearing threshold changes, the impact of both parameters was investigated further. These analyses concerned the annual rate of change in PTA$_{3,4,6}$ as a function of either noise intensity or noise exposure duration. These observed relationships were compared to ISO-1999 predictions for threshold changes due to NIHL.

For exposure times between 10 and 40 years the median value of expected NIPTS could be calculated. For exposure times shorter than ten years, median expected NIPTS values were interpolated from the value of NIPTS for ten years. For each participant predicted median NIPTS was calculated, both at baseline and at follow-up, based on their noise exposure history. The same was done for ARHL, and both components of hearing loss were added according to the formula described in ISO-1999. The annual rate of change in hearing predicted was assessed by subtracting the predicted hearing loss at baseline from the prediction at follow-up, divided by the duration of the measurement period in years. The relationship between predicted

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**Figure 3.2.** Observed versus ISO-1999 predicted annual rate of change in PTA$_{3,4,6}$ as a function of noise exposure duration at baseline
Longitudinal changes in hearing threshold levels

and observed annual rate of hearing loss as a function of exposure duration is shown in Figure 3.2. Again, a positive change indicates a deterioration of hearing ability, a negative change indicates an improvement in hearing threshold level.

In general, the growth of the hearing loss predicted by ISO-1999 was dominated by NIHL in the first years of exposure and reduced with increasing noise exposure duration; the predicted rate of NIPTS was highest for the shortest exposure duration, ranging from 1.9 dB at start of exposure to 0.4 after 10 years. In the consecutive period of 10-40 years of exposure, the yearly growth rate due to noise exposure was only low and the increase in hearing thresholds was dominated by the ageing effect. The observed rate of hearing loss showed a quite different pattern. In general, hearing thresholds showed an improvement in the workers that were exposed to noise for the shortest duration (<10 yrs). For longer durations, indeed a deterioration in hearing was observed, and this rate of hearing loss tended to increase with increasing exposure duration due to effects of aging rather than effects of NIHL. For exposure durations exceeding 30 years the observed rate of hearing loss was reasonably consistent with ISO-1999 predictions. For workers exposed to noise for less than 30 years ISO-1999 tended to overestimate the degree of hearing loss increase (Figure 3.2).

![Graph showing observed versus ISO-1999 predicted annual rate of change in PTA as a function of noise exposure level during measurement interval. Error bars represent one SE.](image)

**Figure 3.3.** Observed versus ISO-1999 predicted annual rate of change in PTA as a function of noise exposure level during measurement interval. Error bars represent one SE.

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1 These values concern NIPTS only, therefore deviate from the values displayed in Figure 3.2 that reflect total predicted hearing loss based on both NIPTS and ARHL.
Similarly, PTA\textsubscript{3,4,6} values as function of daily noise exposure level were examined (Figure 3.3). PTA\textsubscript{3,4,6} values were almost evenly distributed over the range of noise intensities, except for the small group of participants exposed to average daily noise levels of 84 dBA. Both curves showed a similar pattern of increasing rate of hearing loss, although only slightly, with higher noise exposure level. This corresponds to the findings obtained in the linear mixed model described above.

**Effects of covariates**

The data collection also provided information about various demographic and work-related variables that could interact with NIHL development, such as the use of hearing protection. These variables may affect the degree of NIHL, as they may be associated with hearing damage or may increase a participant’s susceptibility to noise. To investigate the relationship of these variables with change in hearing loss change a linear mixed effect model was fitted containing all these variables (see Table 3.1) as fixed factors. After initially fitting this full model, factors with non-significant terms as assessed by conditional F-tests, were eliminated from the model. The final model contained 7 fixed effects, as well as a random effect for ‘subject’. Coefficients are presented in Table 3.5.

<table>
<thead>
<tr>
<th>Model terms</th>
<th>Coefficient</th>
<th>99% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.481</td>
<td>-0.796 – -0.166</td>
</tr>
<tr>
<td>Ear: left</td>
<td>0.144</td>
<td>0.079 – 0.208</td>
</tr>
<tr>
<td>Baseline age</td>
<td>0.079</td>
<td>0.073 – 0.086</td>
</tr>
<tr>
<td>Noise level</td>
<td>0.029</td>
<td>0.008 – 0.049</td>
</tr>
<tr>
<td>HPD use: yes</td>
<td>0.216</td>
<td>0.061 – 0.371</td>
</tr>
<tr>
<td>Baseline hearing</td>
<td>-0.055</td>
<td>-0.059 – -0.051</td>
</tr>
<tr>
<td>Hearing complaints: yes</td>
<td>1.007</td>
<td>0.846 – 1.167</td>
</tr>
<tr>
<td>Interval</td>
<td>-0.226</td>
<td>-0.295 – -0.156</td>
</tr>
</tbody>
</table>

The variables that remained significant in the model, in addition to the shown effects of age (F[1,11636] = 990.90, p < 0.001) and noise intensity (F[1,11636] = 12.39, p = 0.004), included tested ear, use of hearing protection, baseline hearing level, presence of complaints about hearing and interval duration. Noise exposure duration did not
show a significant contribution to this multivariable model either (F[1,11636] = 2.54, p = 0.111).

This multifactorial model showed that the annual rate of change in hearing loss was 0.14 dB greater in the left than in the right ear (F[1,11636] = 28.71, p < 0.001). Also, baseline hearing level, expressed in PTA$_{3,4,6}$ showed a significant effect (F[1,11636] = 1166.79, p < 0.001). The use of hearing protection showed a positive association with change in PTA$_{3,4,6}$ (F[1,11636] = 12.50, p = 0.003) indicating that employees using hearing protection showed a 0.21 dB greater annual change in PTA$_{3,4,6}$ than those who did not. Participants having subjective complaints about poor hearing showed a change in hearing level that was significantly larger (0.99 dB) than participants without hearing complaints (F[1,12162] = 250.56, p < 0.001). There was a strong association between rate of hearing loss and duration of the intermediate measurement interval (F[1,12162] = 9.75, p < 0.001); the negative coefficient of -0.23 dB indicated that the annual rate of change in hearing loss became smaller with increasing interval duration.

**Pattern of hearing loss development**

Finally, the subgroup with three audiograms was analysed to investigate the pattern of hearing loss development. Hearing loss deteriorates over time, due to both exposure to noise and aging effects. In the majority of the employees that were tested twice, the extent to which noise and the extent to which ageing were responsible for this reduction in hearing sensitivity over time could not be established. In case of three measurement occasions, a distinction between both causes of hearing loss could be made based on the pattern of hearing loss development, albeit only at group level rather than individually. The ISO-1999 model showed that NIHL steeply increases during the first decade of noise exposure, followed by a slowing rate of growth with prolonged exposure to noise. This should result in a logarithmic progression, or concave form of hearing loss growth over time rather than a linear relationship. Presbyacusis on the other hand is known to be a progressive hearing loss over time, which is manifested as a convex rate of growth, especially in the higher-frequencies.

The complete linear mixed effect model containing all significant covariates showed that interval duration was negatively associated with annual rate of hearing loss in PTA$_{3,4,6}$ (Table 3.5). This indicated that the rate of hearing loss became smaller with increasing interval length, which corresponded to a concave course of hearing loss development over time. In order to verify this pattern of development, the rate of hearing loss as a function of interval level was investigated in the subgroup of 3,111 workers that were tested at three occasions. To do so, individual baseline PTA$_{3,4,6}$ was subtracted from the PTA-values obtained at both follow-up measurements to obtain the difference in hearing relative to baseline. Then a linear interpolation between
baseline PTA\textsubscript{3,4,6}, which was set at 0 dB, and the difference in PTA\textsubscript{3,4,6} obtained at the last follow-up measurement was fitted. When hearing loss develops linearly over time, the differences obtained at the intermediate follow-up measurement should fall onto this linear interpolation line. Figure 3.4 shows this linear interpolation against mean shifts in hearing as a function of interval length (presented as percentage of total interval time, in bins) and the average difference in PTA\textsubscript{3,4,6} established at the intermediate measurement.

A paired Student’s t test comparing the observed difference at the intermediate measurement occasion and the shift predicted by linear interpolation showed significant differences; observed differences in PTA\textsubscript{3,4,6} were significantly higher (\(p < 0.001\)) in both ears than those based on linear interpolations (0.80 dB in the right and 0.94 dB in the left ear). This demonstrated the concave course of hearing loss growth that corresponds to NIHL predictions.

**Discussion**

The aim of this study was to describe the change in hearing threshold levels in a large group of noise-exposed male construction workers, as monitored by regular periodic audiometric screening over a period of approximately 4 years. Overall, a small average deterioration of hearing threshold levels was observed, ranging from 0.5 to 3.0 dB HL depending on tested frequency. Although baseline HTLs of left ears were slightly poorer than those of the right ears, hearing loss development in both ears was similar.

The annual rate of change in hearing over time ranged from 0.2 to 1.0, and was highest at the high frequencies that are sensitive to noise. Analysis of of change in hearing over time in a subgroup with three audiometric assessments showed a concave pattern of hearing loss development, which corresponds to NIPTS development. So, the pattern of hearing loss development indicates that the high-frequency hearing loss observed in this population is mainly attributable to noise exposure, rather than to presbyacusis that also begins to play a significant role in these middle-aged noise-exposed workers.

The average annual rate of hearing loss in PTA\textsubscript{3,4,6} was 0.56 dB/yr for the total population. This is lower than the annual shift in total HTL of 0.94 dB/yr predicted by ISO-1999 (1990). This can also be observed from Figures 3.2 and 3.3, displaying ISO-1999 predictions for the total change in hearing loss that are higher than the observed rates of change in hearing thresholds. The finding that noise-exposed workers did not lose hearing ability as fast as expected, was observed in previous studies as well (Seixas et al, 2005; Clark & Bohl, 2005; Rabinowitz et al, 2011). It might indicate a smaller NIHL development in this study, due to beneficial effects of hearing
conservation interventions that result in less NIHL. In addition, the noise exposure levels used in this study were only rough estimations of actual exposure levels based on job titles, which might have introduced differences between observed and predicted hearing loss (Rabinowitz et al, 2007).

Nevertheless, the observed rate of change in hearing was also smaller than predicted for age-related hearing loss alone, which was on average 0.86 dB/yr for the total study population. This indicates that the total change in hearing is less than the sum of the effects predicted for noise exposure and age. Albera et al. (2010) observed that the progression of presbyacusis in noise-exposed listeners with NIHL was less than predicted for non-exposed individuals according to ISO-1999. The cochlear structures already damaged by exposure to noise, cannot be significantly damaged by age-related effects anymore (Albera et al, 2010). The results of the total linear mixed effect model predicting annual rate of change in hearing demonstrates this as well; baseline hearing was negatively associated with the degree of hearing loss development, indicating that subjects with higher PTA-values, thus more hearing loss, showed a reduced increase in hearing loss compared to normal-hearing subjects.
Change in hearing and noise exposure

When looking at the relationship between annual rate of change in hearing and noise exposure, hearing loss develops faster with increasing noise exposure and increasing age, which was expected from the ISO-1999 model predictions. However, fitted coefficients were small and exposure duration, as assessed at baseline, did not significantly affect hearing loss development when adjusted for age and noise level. This also corresponds to ISO-1999 predictions, which show that the rate of NIHL in exposed workers decelerates after the first 10-15 years of noise exposure (ISO-1999, 1990; Rösler, 1994). Effects of covariates were also assessed using a linear mixed effect model. The variables available in the data collection showed similar effects on the relationship between the annual shift in hearing and noise and age as was found for absolute hearing in Chapter 2, except for job change and noise nuisance during work. Participants having complaints about their hearing at follow-up show a larger increase in hearing loss over the measurement period than their colleagues without complaints. Workers that indicated to have used hearing protection during the measurement period showed larger annual shifts in hearing than those who did not use hearing protection. Although this contradicts an expected protective effect of HPDs, it corresponds to the positive association of using HPDs and hearing loss that was observed in Chapter 2. As was observed there, in the current study workers reported to use HPDs were exposed to higher noise intensities than those who report not to use HPD. Moreover, the binary variable of self-reported HPD usage is much less informative than data on actual consistency of usage, which would be a more accurate predictor of hearing loss.

In addition, tested ear, baseline hearing, and interval duration showed a significant effect on the rate of change in hearing. When adjusting for all other significant covariates, the left ear showed a slightly larger change in hearing loss than the right ear. This may be related to the significant effect of baseline hearing status, which was negatively associated with annual shift in hearing. Finally, interval duration negatively affected change in hearing; the annual rate of hearing loss decreased for increasing intervals, which corresponds to the concave pattern of hearing loss development caused by exposure to noise.

Development of hearing loss during the first decade of exposure

Although duration of noise exposure showed no significant effect on rate of hearing loss when adjusted for age, noise level, and available covariates, their relation is of interest, particularly for workers with baseline exposure for less than 10 years. The cross-sectional data of Chapter 2 showed a strong deviation from ISO-1999 predictions; mean age-corrected PTA of the noise-exposed workers was 10 dB HL at the beginning of employment, which increased slightly with increasing exposure duration. This was in contrast to the predicted steep increase in hearing loss from 0 dB HL at the beginning of
employment. Hearing loss at the start of employment was also found by others (Seixas et al, 2004; Rabinowitz et al, 2006; Seixas et al, 2012) and might be the result of a pre-existing hearing loss when entering the workforce, due to previous educational, occupational, and recreational noise exposure. However, the finding could not be explained by the available cross-sectional data in Chapter 2, and longitudinal analysis of follow-up data of this subgroup was thought to enlighten this deviation.

Yet, it is known that screening audiometry applied in a survey, as was the case during the POHEs in this study, yield poorer hearing threshold levels than laboratory methods (Dobie, 1983; Schlauch & Carney, 2012). Data from a public health survey in the USA conducted between 1935 and 1936 (Glorig, 1956) were used to derive the reference thresholds described in the first standard defining average normal hearing by ASA (1951). The currently used ISO standard of audiometric zero (ISO-389.1, 1998) is derived from data obtained in several laboratory studies. Differences between both standards are known to be about 10 dB HL in favor of ISO reference levels. These differences reflect the differences in survey and clinical audiometry. Using the clinically obtained ISO-398.1 reference as audiometric zero leads to mean normal-hearing thresholds obtained from group survey data that fall at values near 10 dB HL (Schlauch & Carney, 2012).

Actually, this is seen in the audiometric data obtained during POHEs that are presented here, as well as in Chapter 2. All mean or median low frequency HTLs presented in these studies are around 10 dB HL (see Figures 2.1 & 3.1), indicating that reliable measurements up to 0 dB HL could not be established in an occupational audiometric survey. The observation in Chapter 2 of a 10 dB HL loss at the start of employment was suggested to be a result of pre-existing hearing loss when entering the workforce. Although this theory still may be valid, the limited ability of screening audiometry to accurately assess normal hearing threshold levels up to lower values than 10 dB HL might be an alternative explanation for this finding. In that case, the age-corrected PTA value of 10 dB HL reflects the average normal hearing threshold in survey observations rather than pre-existing hearing loss.

Although survey methods yield poorer average normal thresholds levels than laboratory methods, useful conclusions about trends in hearing loss over time can still be drawn from group survey data (Royster & Royster, 1986). Therefore these longitudinal analyses, instead of cross-sectional evaluation, were used to investigate the development in hearing loss during the first decade of exposure. Unfortunately the workers exposed to occupational noise for a period of 10 years or less showed a negative mean rate of hearing loss (Figure 3.2), suggesting an improvement in hearing ability instead of the noise-induced deterioration that was expected (ISO-1999, 1990; Rösler, 1994). This finding is rather unfortunate, because it blurs any detrimental effects of noise exposure on hearing during the first years of exposure.
More so, the improvement in hearing is also reflected in both models predicting the annual rate of change in $\text{PTA}_{3,4,6}$ which have a negative intercept, indicating that subjects in the reference condition experience an improvement in hearing. To gain more insight in this finding, average hearing threshold levels of baseline and follow-up measurements were plotted, for 5 age groups (<25, 25-34, 35-44, 45-54 and ≥55 years) separately in Figure 3.5.

The youngest age groups show better HTLs at follow-up compared to baseline at the majority of the tested frequencies. For the group with a mean age of 40 years, hearing thresholds of both measurements seem similar, whereas the older age groups show the expected deterioration in hearing at follow-up at 2 kHz and higher. However, a small but significant improvement at 0.5 kHz was shown in all age groups except for the oldest workers. Clearly, some degree of HTL reduction was expected in all age groups in this study population, either due to progressive NIHL in the shorter exposed young workers or to presbyacusis in the older groups. Whereas the absence of a significant decrease in hearing ability of the younger workers would indicate that hearing conservation effectively prevented the development of NIHL, an average improvement in hearing across a group of workers is highly unexpected. The most probable explanation for such a change would be alterations in test equipment or

\[ \text{Figure 3.5. Mean hearing threshold levels obtained at baseline (dashed lines) and follow-up (solid lines), separated for five age groups.} \]
measurement procedures. However, standardized audiometry was conducted according ISO-8253.1 (2010) and no systematic changes in this standard or in equipment and test characteristics could be identified during this follow-up period.

Behavioral audiometric thresholds vary somewhat from one test to the next, because of tester and patient experience and motivation (Schlauch & Carney, 2012). Clinical audiometry reports small test-retest variability, varying from 2.1 to 6.8 dB depending on frequency (Hétu, 1979; Dobie, 1983; Hall & Lutman, 1999), which slightly increases with increasing interval length. When audiometric testing is applied in occupational screening this variability increases even more due to various sources of systematic and random errors (Hétu, 1979). The control of most of these sources is specified in occupational standards for adequate screening (ISO-8253.1, 2010). However, in the practice of industrial screening these requirements cannot always be met. Given the fact that there have been no changes in the procedure for calibration, and that there has not been an systematic change in the type of audiometers and/or the method of audiometry, the most important factors that could have influenced the results in the current study are:

- Influence of background noise levels in the testing room; because audiometry requires determination of the lowest signal level that a person can hear, ambient noise in the audiometric test environment should be under the maximum permissible ambient noise levels specified by ISO-6189 (1983). Test rooms calibrated according to this standard will make it possible to test to 0 dB HL for persons whose hearing is that sensitive (Franks, 2001). Nevertheless, these levels are rarely achieved without an audiometric soundproof booth, which is not always available in occupational assessments. In that case, tests are performed in a quiet room, introducing possible interference of background noise. If the availability of a test booth and/or the quality of the sound isolation improved over the years, this is the most likely explanation for the improvement of hearing ability, especially for subjects with hearing in the normal range. Also, the use of different types of supra-aural headphones might have introduced differences in the amount of background noise levels caused by headphone attenuation (Franks, 2001).

- Residual TTS at the time of testing; hearing screening is regularly performed during a working day. Exposure to noise prior to audiometric testing could result in temporary threshold shifts in hearing. Consequently, employees need to be advised to have a period without noise exposure of 14-16 hours preceding the hearing test (May, 2000; Franks 2001; NVAB, 2006). In practice, this is difficult to accomplish, and temporary effects of noise exposure, either occupational or
non-occupational, on HTLs cannot be ruled out completely, hence the observed improvement could reflect a reduction in the degree of TTS (Seixas et al, 2005; Rabinowitz et al, 2011). There is a constant effort to better meet the criteria for a noise-free period and if this has been successful in the past years, this is a second potential explanation for the improvement of hearing ability, especially for the high frequency thresholds in noise-exposed participants.

- Familiarization with the examination procedure; it is possible that familiarity with the examination procedure might lead to an improvement in performance (Hétu, 1979). Royster et al. (1980) observed an improvement of 0 to -1 dB/yr in HTLs at 3, 4 and 6 kHz with respect to baseline, over the first 3 to 4 annual audiometric tests. They consider this attributable to a learning effect.

In addition, other factors such as differences in earphone placement, partial or complete obstruction of the external auditory canal by cerumen, interfering signals from the test equipment, bias introduced by the tester or the examination procedure, the instruction and the presence of tinnitus influence test variability (Hétu, 1979). All above-mentioned sources of error may have influenced the obtained thresholds to some extent, and the improvement in HTLs indicates that these might have been more prominently present during the baseline assessments than during follow-up. However, specifications of test conditions were not available in current data collection. Consequently, above-mentioned suggestions can only be offered as likely and not a certain explanations.

This makes it also unclear whether the causes of the improvement in HTLs are restricted to examinations of the younger workers only, or that these affect the entire cohort. Because the young workers do not show any aging effects yet, measurement variation is reflected more clearly in this subset than in older workers who additionally show some degree of age-related hearing loss (Figure 3.5). The consistent improvement in HTL at 0.5 kHz in all but the oldest age groups, as well as the observed rate of change that is smaller than predicted, indicate however, that measurement variability concerned the entire study population, underestimating the rate of hearing deterioration due to NIHL.

**Quality of the survey data**

Data from audiometric survey of the entire Dutch workforce of the construction industry has the advantage of its large size. Despite the rather high measurement variability, longitudinal analysis on group level can demonstrate trends in hearing loss over time. In addition, by analysing this large amount of data, a judgment on the quality of the collected data can be given.
First of all, by merging baseline and follow-up data sets, inconsistencies between data from multiple measurements of the same individual were revealed. In 15% of the cases there was a lack in correspondence between baseline and follow-up data concerning demographic variables, such as gender and date of birth, or work-related variables, such as job title or employment years that are used to estimate noise exposure. Because correct data could not be recovered, these cases were excluded from further analysis. Most of this data derived from the self-administered questionnaire, hence may be the result from recall bias of individual workers completing it. Also typographical errors when entering questionnaire responses may have induced these deviations.

Another 15% of the cases in this study was excluded because any of their audiometric assessments suggested evidence of hearing loss due to other than noise-induced or age-related causes, since including these cases would disturb the assessment of the relationship between noise exposure and hearing loss. Several criteria were defined to exclude cases with flat and/or conductive losses that do not result from exposure to noise. In screening audiometry, only air conduction thresholds can be reliably obtained, omitting bone conduction and thereby the possibility of correcting for the conductive component of the hearing losses. Instead, more information about the otologic and medical history in the data collection would be helpful in interpreting audiometric abnormalities.

In addition, cases showing a large unilateral difference between baseline and follow-up, either deteriorations or improvements, were excluded. In general NIHL develops more of less bilaterally, and only small difference between ears are expected. The excluded cases showed an unexpectedly large change in hearing ability over the 4-year time period, in only one ear. This reflects bias in audiometric measurements rather than an actual change in HTLs.

Like many surveys conducted in ‘real world’ environments, some information in this study is poorly quantified or absent. Analyses as those conducted in this study would give more accurate results when information of otologic and medical history, exposure to non-occupational noise, individual noise dosimetry, actual attenuation from HPDs and the consistency of their usage, and test conditions was available.

**Conclusion**

Over an interval period of 4 years, an overall deterioration of hearing threshold levels of construction workers was established on group level. The annual rate of change in hearing loss was positively associated with both age and noise intensity. Analysis of the pattern of hearing loss development indicates that the observed change in PTA\textsuperscript{3,4,6} was in correspondence with predicted NIHL development.
Current longitudinal analyses could provide only limited relevant information on the development of hearing loss during the first decade of noise exposure; instead of a sheer deterioration in hearing, an improvement of hearing threshold levels was found. Our hypothesis is that this was rather the result of measurement variability in screening audiometry than an actual improvement of hearing ability. In addition, average HTLs reflecting normal-hearing, such as those of the youngest workers and low-frequency HTLs of the total study population, are 10 dB HL. This increased value for normal hearing in this audiometric survey is a likely explanation for the hearing loss present during the first decade of noise exposure observed in Chapter 2, although some degree of pre-existing hearing loss could not be ruled out completely.

These analyses showed that a large data collection of audiometric survey data can be used to assess group effects in hearing over time. Inconsistencies in data and measurement factors affecting the stability of the database showed that small shifts in individual hearing threshold levels cannot easily be distinguished from normal measurement variability. Additional data collection and a better specification of the test conditions and procedures might improve this.
Appendix: details on exclusion criteria used

In some cases a medical record could not be used for analysis. Of the 17,390 subjects that were examined twice, 5,128 were excluded from further analysis. In addition, of the subset of 4,645 subjects with three measurements, 1,434 cases were omitted. Reasons for exclusion were briefly mentioned in the methods section. Below, the specific definitions and reasoning for the used exclusion criteria are described.

Insufficient follow-up period
Although POHEs are offered once every two or four years, depending on employee’s age, some medical records were collected with a different frequency. To ensure that the interval between baseline and follow-up measurements was sufficiently long to establish a change in hearing loss, this period should be at least one year.

Incorrect data collection
To make sure analysis were performed on actual audiometric thresholds, and that accurate data on noise exposure was available, similar exclusion criteria were defined as those used for the baseline cohort in Chapter 2. 222 subjects of current study population had no recorded audiometric data and 84 participants showed HTLs exceeding 90 dB HL at either one or more frequencies measured in both ears (referred to as code ‘95’). In addition, 526 subjects showed missing or immeasurable HTLs exceeding 90 dB HL in one ear and thresholds of 90 dB HL or better at all frequencies in the contralateral ear. For these subjects, only the contralateral ear was preserved in the dataset, and 240 left and 286 right ears were excluded from analyses. Finally, 81 female workers were discarded because of their concentration in non-noise-exposed jobs.

In addition, criteria were defined to check for incorrect of missing data regarding noise exposure estimations. 415 workers had insufficient noise exposure data missing either information on job title or duration of employment. In case the data of these workers were available in the baseline data collection, missing follow-up data can be adopted from the baseline set after merging both databases, so these subjects were not excluded yet.

Lack of correspondence between successive datasets
The merge of the baseline and follow-up data provided an opportunity to control the quality of the data, by checking the data obtained during two examinations for correspondence. When there was no correspondence between data, subjects were excluded from analysis since it could not be revealed which of the two data collections contained accurate data.
First, date of birth was compared, and in 23 subjects different values were reported. These cases were excluded from the dataset. In addition, factors important for noise exposure estimation, such as reported job title and years employed in construction were also compared. Reported job title was used to estimate the workers’ daily noise exposure levels. For 4,178 worker there was no correspondence between reported job titles, and, more importantly, estimated noise exposure intensity deviated for 1,762 subjects. According to the information in the medical records, 453 of these workers recently changed their jobs. Correct daily noise exposure could thus not be salvaged for the remaining 1,309 worker, hence they were not included in analyses.

The reported amount of years worked in construction, which defines the duration of noise exposures, is also checked for correct correspondence. The difference in reported years is calculated, accounting for the interval between measurements. 1,314 records reported different data for employment duration, showing a deviation between both measurements that exceeded five years. Because correct data for exposure duration could not be recovered, these records were omitted.

In total, 15.5% of the data collection is excluded based on the lack of correspondence between both datasets.

Audiometric discrepancies
Participants were excluded from present study if an audiometric assessment at any measurement occasion suggested evidence of hearing loss due to other than noise- or age-related causes. The following exclusion criteria were defined:

- Diagnosed hearing loss due to other etiologies than noise and age; each medical record reported the diagnosis of an otological disease if present. Eighty participants were diagnosed with hearing loss due to another cause than noise or aging. Since the focus of this study was on the development of hearing loss caused by noise exposure, these subjects were excluded.

- Audiometric configuration; based on previous research regarding NIHL, the study population was divided into subgroups according audiometric configuration (Jansen et al, 2008; Helleman et al, 2010). Five groups and a rest group were defined: normal hearing, subnormal hearing, mild notch, profound notch, and sloping audiogram. Normal hearing was defined as having every threshold at 20 dB HL or better, and the subnormal hearing group showed a flat loss with every threshold at 30 dB HL or better. The notching audiograms indicating NIHL had an elevation in hearing threshold at 3, 4, or 6 kHz when compared to the average of 0.5, 1, and 2 kHz and the better threshold of 6 and 8 kHz, which was small in the mild notch group and larger in the profound notch group. Finally, the sloping audiogram was defined to have similar thresholds at 3 and 4 kHz as the notcht
Longitudinal changes in hearing threshold levels

groups, but without showing an improvement at the higher frequencies, indicating age-related high-frequency hearing loss. 215 participants having both audiograms defined as ‘rest’ showed audiometric configurations likely to correspond to causes of hearing loss beyond the scope of this article. Therefore, these subjects were excluded from analysis. In addition, data of 794 ears defined as ‘rest’ were discarded.

- Conductive hearing loss; NIHL is sensorineural, hence no conductive loss was expected as a result of noise exposure. Since bone-conduction thresholds cannot be adequately assessed in a hearing screening program, an alternative criterion concerning conductive hearing loss was defined using ISO-1999 predictions; low-frequency hearing loss caused by age or noise exposure was expected not to exceed 40 dB HL. So 50 subjects, and additionally 31 ears, having a pure-tone average of 0.5 and 1 kHz > 40 dB HL were considered to have conductive losses, and were excluded.

- Large unilateral change in hearing ability compared to the change in the contralateral ear; a rough analysis of the differences in hearing thresholds over the 4-year measurement period showed that there were both very large deteriorations as well as improvements in hearing ability. So, a confidence criterion should be composed to define the limits of reliable differences. To do so, the observed change in one ear is compared to the observed change in the contralateral ear. Since NIHL is mostly symmetrical, these differences should be more or less similar. A confidence interval of change was calculated by the median difference ± 3 * standard deviation of the difference, and rounded to 5 dB intervals. This way an interval of change of -25 to 25 dB HL was defined for the lower frequencies up to 4 kHz, and an interval of change of -45 to 45 dB HL for 6 and 8 kHz. Participants having differences in HTL change between ears that lie outside this interval were considered outliers. Based on this criterion, 1,783 subjects were excluded from the dataset.

- Large change in low frequency hearing thresholds; after the exclusion of the above-mentioned cases, still very large differences in hearing thresholds existed, which were much greater than expected to occur over a 4-year period. Low frequency hearing thresholds are affected by noise and age only in a minor extent. So, in order to reduce the large unreliable differences observed, ears that showed a change in HTLs at 0.5 or 1 kHz that exceeded the confidence interval of change of -25 to 25 dB HL for change in hearing were also excluded from analysis. 32 participants that showed this in both ears were excluded, and another 133 ears were discarded for this reason as well.