Noise and Hearing Damage

in Construction Apprentices

University of Washington
Department of Environmental and Occupational Health Sciences

September 2004

NOISE AND HEARING DAMAGE IN CONSTRUCTION APPRENTICES

Final Report of a Study:

Prospective Hearing of Hearing Damage Among Newly Hired Construction Workers

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September, 2004

Funded by the National Institute for Occupational Safety and Health,
US Centers for Disease Control and Prevention
Grant number OH 03912

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This study would not have been possible without the assistance and generosity of the participating apprentices and contractors, or without the help of Washington Audiology Services, Inc. In addition, the following Western Washington Building Trades Apprenticeship Programs provided invaluable assistance:

Apprenticeship Program	Key Staff
Western Washington Masonry Trades Apprenticeship	Randy Johnson, Coordinator Laird Donaldson, Instructor Terry Hayes, Instructor
Carpenters-Employers Apprenticeship and Training Trust Fund of Western Washington	Steve Baker, Coordinator Guy Astley, Instructor Charlie Blankenship, Instructor Jesse Chute, Instructor
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Puget Sound Electrical Apprenticeship and Training Trust	Bill Bowser, Coordinator Bill McCartan, Assistant Training Director
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Pacific Northwest Ironworkers and Employers Apprenticeship and Training Committee – Local 86	Lee J. Newgent, Coordinator Jeff Butler, Instructor Kevin McGee, Instructor Erich Smith, Instructor Frank Zimmerman, Instructor
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Western Washington Sheet Metal Joint Apprenticeship Committee	Bob Steele, Coordinator Eric Peterson, Assistant Coordinator Bill Kupper, Instructor Brian Lindholm, Instructor Mike Saffer, Instructor
Renton Technical College	Tanya Pellegrino
South Seattle Community College - Duwamish	Betsy McConnell-Gutierrez

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EXECUTIVE SUMMARY

Noise-induced hearing loss, also called noise-induced permanent threshold shift (NIPTS) is among the most common occupational diseases. NIPTS usually progresses unnoticed until it begins to interfere with communication, posing a serious safety hazard and decrease in quality of life. A precise understanding of the relationship between noise exposure and NIPTS – especially for highly variable noise exposures like those found in construction – has not been established. In recent years, the potential for distortion product otoacoustic emissions (DPOAEs, measurable sounds produced by the inner ear) as a screening tool for early hearing damage, and possibly as a marker of susceptibility for hearing loss has been recognized. DPOAEs have been suggested as a far more sensitive measure of early hearing loss than the gold standard hearing test, pure-tone audiometric thresholds. However, prior to this study, no prospective research on DPOAEs in relation to well-characterized noise exposure and standard audiometry has been conducted.

From 1999-2004 the University of Washington Department of Environmental and Occupational Health Sciences conducted a prospective study of noise exposure and hearing loss on a cohort of 456 subjects. Three-hundred ninety-three of these subjects were apprentices beginning their training programs in a number of construction trades: carpenters, cement masons, electricians, ironworkers, insulation workers, masonry workers, operating engineers, and sheet metal workers. The remaining 63 were a control group of non-noise exposed University of Washington graduate students. All subjects completed a baseline evaluation, which consisted of an audiometric evaluation in a mobile test van, DPOAE tests in a quiet room, and a questionnaire concerning demographics, NIPTS risk factors, previous noisy work, military experience, non-occupational noise exposure, and other factors. Follow-up evaluations, which consisted of a similar questionnaire covering the follow-up period and the same set of hearing examinations, occurred roughly annually. Three hundred thirty-six valid first follow-up, 284 second follow-up, and 221 third follow-up evaluations were completed, for an average of 3.4 ±0.8 tests per subject among those subjects with more than one exam.

Full-shift noise dosimetry and hearing protection use data on construction workers were also collected before and during this study. These levels were measured according to both the Occupational Safety and Health Administration (OSHA) standard for noise, and the more protective National Institute for Occupational Safety and Health (NIOSH) standard, which better reflects construction worker's risk of hearing loss. In the more than 700 total measurements made across all the trades, the mean NIOSH L_{EQ} levels were always higher than OSHA L_{AVG} levels (Fig. 1), and exceeded 85 dBA (the level at which risk of hearing loss becomes significant) for all but one trade. Two-thirds of all NIOSH, and one-third of all OSHA, measurements exceeded 85 dBA (Fig. 2). As part of this study, new metrics were developed for noise exposure evaluation. Noise is usually measured only in terms of an average level, but the new metrics allow for better assessment of the variability of noise levels and the degree of impact or high-level noise – two very important issues in construction noise exposure assessment.

In addition to occupational noise, exposures to non-occupational noise were assessed, including everyday activities like commuting and less common events like concerts and riding snowmobiles. Our study found that, for most construction workers, non-occupational activities make little contribution to overall (occupational and non-occupational) annual noise dose (Fig. 6). Only for a small fraction of workers who spend significant amounts of time in noisy activities, and in the quieter trades, would non-occupational noise significantly contribute to overall noise dose. The impact of firearms use on annual noise dose could not be assessed, but the study showed that people who shoot firearms are more likely to participate in other noisy activities. Hearing protection use was found to be even lower during noisy non-occupational activities than it was during occupational activities.

As part of the study, the amount of noise blocked by earplugs worn by construction workers was measured while the protectors were being worn. The protectors provided 20 decibels (dB) of protection on average, slightly less than 70% of the average labeled Noise Reduction Rating of 29 dB for the earplugs. Occupational exposure levels for each of the trades measured without accounting for use of hearing protection were compared with levels that were adjusted to account for both the amount of time that hearing protection was used and an assumed 20 dB of protection when they were used. The average full-shift exposure reduction provided by hearing protectors was estimated to be less than 3 dB. This very small reduction in exposure resulted from the low usage of hearing protectors among construction workers, who on average were found to wear hearing protectors less than 20% of the time they were needed (Fig. 3). Only two trades achieved more than 6 dB exposure reduction on average, and overall less than one in five shifts was brought down to safe levels (below 85 dBA) through the use of hearing protection.

Baseline audiometric thresholds and DPOAEs were analyzed at 2, 4, 6, and 8 kHz, the frequencies most commonly affected by noise-induced hearing loss, in relation to previous noise exposures reported by our subjects. Apprentices reported more noise than students prior to the beginning of the study in both their occupational and non-occupational exposure histories, and had worse audiometric thresholds and DPOAE levels at baseline (Fig. 10). Both age and previous work in the construction industry were found to have strong effects on audiometric thresholds and DPOAEs at 4, 6, and 8 kHz. Each year of construction work prior to baseline was associated with a 0.7 dB increase in audiometric thresholds or a 0.2 dB decrease in DPOAE levels. Overall, the pattern of effects seen in the audiometric and DPOAE data was very similar.

Follow-up test audiometric thresholds and DPOAEs were analyzed to measure changes in the hearing levels of the cohort across the duration of the study. Three noise exposure groups were used: the control group and ‘low’ and ‘high’ exposed groups (the four trades with the lowest and highest mean occupational exposure levels after accounting for HPD use). Factors expected to affect hearing and noise exposure levels, like age, gender, previous noise exposure, and baseline hearing ability, were accounted for. The audiometric thresholds displayed only slight trends toward increased (worse) threshold levels (Fig. 12) with increasing noise exposure. Small but significant noise exposure-related changes in DPOAEs were evident over time, especially at 4 kHz (Fig. 12) at about 0.5 dB decrease each year for the high exposed group, with less clear but similar patterns observed at 3 kHz.

In summary, the results of this study demonstrate that:

- Depending on the trade, construction workers are exposed over 85 dBA in about 70% of work shifts using the NIOSH exposure standard, and in about 30% of shifts using the les-protective OSHA exposure standard.

- Although non-occupational activities occasionally have high noise levels, these exposures make a meaningful contribution to total noise exposure for only a small fraction of construction workers.

- Although construction workers can attain good noise exposure attenuation using hearing protection devices, hearing protection is worn less than 20% of the time when exposure levels are over 85 dBA. As a result of this low use time, workers achieve an average of less than 3 dB of noise reduction in a full-shift exposure.

- Task-based assessment of noise exposure provides a comprehensive approach to estimation of noise levels associated with construction work. Construction workers were able to recall their work tasks with a high degree of accuracy. However, the large degree of variability in noise exposure between individuals doing the same task makes the estimated exposure level for any individual highly imprecise.

- Noise exposure can be summarized in a variety of exposure metrics. Those expressing an average level (including the NIOSH L_{EQ} and OSHA L_{AVG}) are very highly correlated with each other, and use of any of these average metrics probably makes little difference to the exposure-response analysis. Metrics which express the variability and impulse component of noise – exposure parameters which are very important in construction work – are poorly correlated with the average metrics.

- Distortion Product Otoacoustic Emissions (DPOAEs) directly monitor noise induced damage to the cochlea. Although a number of challenges were identified in the use of DPOAEs for monitoring changes in hearing, their test-retest variability is lower than that of pure tone behavioral audiometry, and therefore provides better sensitivity to subtle changes. However, with the particular protocol used for our study, the variability from year to year was slightly higher than previously reported in the literature.

- Construction work experience was associated with worse hearing (higher hearing thresholds and lower DPOAEs) in our baseline cohort of 434 subjects, with the effect seen most clearly at 6 kHz.

- Over an average of about 2.4 years of work in construction (3.4 annual tests) at estimated exposures of 85-90 dBA, there was a measurable decrease in DPOAEs of about 0.5 dB per year at 4 kHz. No measurable change was seen in audiometry.

Further follow-up of this group of construction workers will help determine if the observed changes in DPOAEs are predictive of later changes in audiometric thresholds. If so, DPOAEs may form an important tool for monitoring and preventing hearing damage. In the mean time, increased efforts to reduce noise exposure among construction workers and prevent the development of significant hearing impairment are needed.

BACKGROUND

Noise and Hearing Loss In Construction

Noise induced hearing loss continues to afflict workers in many occupational settings despite the longstanding recognition of the problem and well-known methods of prevention and regulations. Although many industries have noise exposures, construction workers are at particularly high risk. Noise levels associated with heavy construction equipment range from 80 to 120 dBA and power tools commonly used in construction produce exposures up to 115 dBA.

These exposure levels are clearly high enough to necessitate hearing conservation efforts, as noise exposure above 85 dBA is considered hazardous. However, complete and effective hearing conservation programs are rare in the industry for a number of reasons, including the transience of the workforce, extremely variable work conditions and environment, lack of resources, and worker reluctance. The absence of hearing conservation efforts has resulted in very high rates of hearing loss, also called noise-induced permanent threshold shift, or NIPTS, among construction workers.

Previous Hearing Loss Research

The relationship between long-term, high-level continuous noise exposure and NIPTS is well-documented. The scientific literature generally demonstrates that with occupational noise exposures greater than about 85 dBA, hearing thresholds at the 4 kHz frequency decline rapidly within a short time of exposure onset. With continuing exposure, the rate of decline slows, and decrements spread to higher and lower frequencies. Although previous studies shows some differences in the exact progression of hearing loss, general models of NIPTS development have been developed, such as those published by the International Organization for Standardization (ISO 1999:1990) and American National Standards Institute (ANSI S3.44-1996). These models allow for the prediction of NIPTS expected to occur in a population, accounting for age, gender, race, steady state occupational noise exposure level and duration of exposure in years.

Despite the availability of these and other NIPTS estimation models, there are a number of limitations in the existing hearing loss data. These include the lack of prospective studies; a focus on industries with relatively steady-state exposure levels (and not industries like construction with variable noise levels and impulsive noise); use of a variety of noise exposure metrics; the general absence of individual-level information on critical factors such as occupational and non-occupational noise exposures and use of hearing protection devices (HPDs), and the absence of specific exposure activity data (for example, on a task-level, vs. the commonly used but fairly generic job title- or work department-level). The previous studies also provide limited information concerning the rate of change in hearing during the first few years of exposure. In fact, most studies have examined changes only after about 10 years of exposure – the point at which hearing loss generally begins to be clinically noticeable – and have mainly used crude linear extrapolations to estimate changes in hearing during the first 10 years of exposure. Finally, existing studies have measured audiometric thresholds, while more sensitive tests such as DPOAEs, which could potentially play a critical role in the identification and prevention of disabling NIPTS, have not been explored.

Evaluation of Noise Exposure

The appropriate exposure metric for quantifying noise exposure in relation to hearing loss continues to be investigated. The two primary US noise exposure standards are the Permissible Exposure Limit of the Occupational Safety and Health Administration, and the Recommended Exposure Limit of the National Institute for Occupational Safety and Health. Measurements can be made for these standards using either sound level meters or noise dosimeters; however, sound level meters are not nearly as accurate as dosimeters for variable and frequently-changing exposure conditions, such as those found in construction.

The OSHA and NIOSH noise exposure standards differ in several important ways. OSHA allows a full-shift (8-hour) average exposure level of 90 dBA, whereas NIOSH specifies a more protective 85 dBA average level. OSHA also requires that the allowable exposure time be halved for every 5 dB increase above this average level (in other words, 8 hours allowed at 90 dBA, 4 hours at 95 dBA, 2 hours at 100 dBA, and so on). This relationship between allowable exposure time and exposure level is known as the exchange rate. NIOSH specifies a more protective 3 dB exchange rate, which allows shorter exposure durations at high levels than does the OSHA standard. OSHA is one of the few agencies in the world that specifies a 5 dB exchange rate; almost every other scientific and regulatory agency has adopted the more protective 3 dB exchange rate. Average levels measured using the OSHA standard are referred to as L_{AVG} levels, while average levels measured using the NIOSH standard are referred to as L_{EQ} levels. Note that average levels, whether L_{AVG} or L_{EQ}, can be measured over any length of exposure duration – from as short as a minute to more than a full day – using a datalogging noise dosimeter.

The difference in average exposure levels measured using the different OSHA and NIOSH exchange rates, is related to the degree of variability in the exposure levels. Likewise, the difference between the average level – either L_{AVG} or L_{EQ} – and the maximum level experienced in a given period, L_{MAX}, expresses the degree to which impact or impulse noise is present – the ‘peakiness’ of the exposure, in other words. The relative inability of average levels to account for impulsiveness of noise exposure may help explain the fact that high level impulse noise appears to produce a greater degree of hearing damage compared to similar average levels of steady-state noise, and suggests that better evaluation of the variability and peakiness of exposures is needed.

Evaluation of Hearing Ability

It is of particular public health importance that individuals with greater than average susceptibility to noise induced hearing loss be identified at an early stage so that appropriate hearing conservation intervention can be designed. Unfortunately, the gold standard for evaluating hearing ability, pure tone threshold air conduction audiometry, is unable to measure the very early stages of NIPTS loss due to its high variability (±5 dB), the subjective nature of the test (which requires a subject response), and the fact that it tests outer, middle, and inner ear function. Hearing loss resulting from chronic high-level noise exposure is the result of accumulated injury to the cochlea (the inner ear), which contains delicate sensory cells called inner and outer the hair cells, or IHCs and OHCs. There is substantial evidence to suggest that OHCs are the initial location of damage following exposure to high-level sound. Technological advances now allow for direct stimulation of OHCs, which results in otoacoustic emissions

(OAEs), predictable tones produced by active movement of OHCs in the cochlea which are measurable in the ear canal with a sensitive microphone. One common type of OAE test produces distortion sounds in the cochlea; the test is referred to as Distortion Product Otoacoustic Emissions (DPOAEs).

DPOAEs are produced by the normal cochlea when two pure tone signals of different intensity levels (L_1 and L_2) at frequencies f_1 and f_2 (with f_2 always higher) are transmitted to the ear simultaneously. A number of distortion products arise from the two-frequency signal delivered to the ear; however, the most reliable product corresponds to the frequency $2f_1$-f_2. At low stimulus intensity levels, DPOAEs reflect the functional status of OHCs with great sensitivity; they are reduced or eliminated by insults such as occupational noise that damage or destroy OHCs. DPOAEs compare favorably to standard audiometry, as they are completely objective (with no behavioral component), have lower variability (±3 dB vs. ±5 dB), and monitor cochlear OHC status directly. However, no standardized DPOAE test methodologies are available, and to date no study has prospectively documented the sensitivity or susceptibility of human DPOAEs to permanent effects of overexposure to noise, nor have any compared DPOAE and audiometric results in an occupational setting.

METHODS

Overview of Study Design

This prospective study followed a group of construction apprentices and a control group of non-noise exposed University of Washington medical and graduate students over a period of four years (2000-2003), and evaluated noise exposures and changes in hearing ability among all subjects. All subjects were recruited during the first year of their four-year apprenticeship or educational programs. After a brief overview of the study purposes and procedures, volunteers signed an informed consent letter approved by the University of Washington Institutional Review Board (IRB). The construction trades recruited for this study were carpenters, cement masons, electricians, ironworkers, insulation workers, workers from the masonry trades (bricklayers, masonry restoration workers, and tilesetters), operating engineers, and sheet metal workers. All testing was conducted at the apprenticeship training sites or at the University of Washington. Volunteers were paid a small monetary incentive for their participation. All subjects completed a baseline examination and a maximum of three follow-up examinations, with each examination consisting of an exposure and activity questionnaire and several hearing level assessments.

Evaluation of Hearing Ability

Hearing evaluation included pure tone air conduction threshold audiometry delivered by a contract testing company and DPOAE tests delivered by field staff after training by the study audiologists. Otoscopic examination and tympanometry (Grason Stadler Model GSI 38) were used to screen subjects prior to testing. If excessive earwax was present, or if tympanometry revealed middle ear abnormality, subjects were referred for appropriate treatment and asked to return for testing at a later date. Subjects were also asked during screening if they had experienced any substantial noise exposure within the past 16 hours. All hearing test instruments received annual calibrations in accordance with manufacturers' specifications. Prior to each test session, each instrument was checked and calibrated for proper response following recommended protocols.

Audiometric Testing

Pure tone air conduction audiometric threshold testing was conducted in a mobile, acoustically-treated audiometric test van by CAOHC-certified audiology technicians employed by Washington Audiology, Inc., Seattle, WA. Background noise levels in the test van were monitored (Quest Bioacoustics Monitor) throughout each testing session, and met OSHA requirements for audiometric testing during all tests, and the more stringent ANSI requirements (ANSI S3.1-1991) during most tests. Audiometry (Tremetrics RA300 audiometer with TDH-39 headphones) was conducted on up to six subjects at a time using an automated test sequence at the frequencies of 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz. Audiograms with excessive non-noise-related hearing loss at baseline (mean average 500, 1000, and 2000 Hz hearing levels greater than 50 dB) were excluded from the analysis. Audiograms were reviewed by an audiologist and subjects with abnormal findings were referred for follow-up clinical consultations.

Distortion Product Otoacoustic Emissions (DPOAEs)

DPOAEs (Bio-Logic Scout AuDX system) were measured in two ways: as ‘DP-Grams’ (comparable to a conventional audiogram, with DPOAE responses at a single intensity measured across a range of frequencies) and as input/output functions (with DPOAE responses at a single frequency measured across a range of input tone intensities). DP-Grams were measured at twenty-one f_2 frequencies between 1031 and 10,028 Hz using a f_2/f_1 ratio of 1.2, an L_1 intensity of 65 dB SPL, and $L_2 = L_1 + 10$ dB. Input/output (I/O) functions were measured at seven $f2$ frequencies chosen to approximate the audiometric test frequencies, and were recorded as functions of increasing stimulus level, with L_1 ranging from 35 to 80 dB SPL in 5 dB steps, and $L_2 = L_1 + 10$ dB. During DPOAE tests, noise levels in the test room were monitored (Quest Technologies Q-300 dosimeter) at one-minute intervals; the average background L_{eq} levels were adequate (66.7 ± 6.3 dBA).

Exposure and Activity Questionnaires and Activity Cards

An extensive questionnaire concerning demographics, medical and hearing history, family history of hearing loss, and containing detailed questions concerning occupational and non-occupational noise exposure histories was developed and delivered to subjects via computer at baseline. A version of this same questionnaire was given at each follow-up examination, covering the period since the last examination. The work histories included the timing and duration of all construction jobs, involvement with specific construction tasks and tools, use of hearing protection devices, and type of construction environment, in addition to non-occupational exposures from firearms and other activities, military service, and noisy non-construction jobs. In addition to the follow-up questionnaires, subjects in the study were mailed 48-hour duration trade-specific activity cards which listed a number of common activities for each trade, as well as a limited number of non-occupational activities, and allowed workers to report their daily events with approximately a 15-minute time resolution.

Exposure Measurement

Noise exposure data were collected on workers over full workshifts. Workers wore datalogging dosimeters (Quest Technologies Q-300) for a complete workshift. These dosimeters measured workers’ exposures according to the several different average exposure metrics, including the NIOSH and OSHA standards, and logged a number of different exposure levels for each minute of the monitored period, including NIOSH L_{EQ}, OSHA L_{AVG}, and L_{MAX}. While wearing the dosimeters, workers completed a trade-specific activity card describing their tasks, tools, environmental conditions, and hearing protection device (HPD) use throughout the entire workshift. These cards listed a number of common activities for each trade, and allowed workers to report their workshift activities and tools with approximately a 15-minute time resolution. Exposure levels were assessed both with and without consideration of HPD use during the exposure; these levels were referred to as HPD-adjusted and unadjusted exposure levels.

Ancillary Studies

A number of related research efforts were conducted as part of this study. The results from these efforts were used to increase the available noise exposure data, while also addressing specific questions about our data. Very few of the workers participating in these ancillary studies were in the prospective study cohort; rather, subjects were interested construction workers employed at various commercial construction sites around Western Washington state. However, the workers in these ancillary studies were employed in the same trades as those in the longitudinal cohort, and were exposed to similar working conditions.

Comparison of task-based and full-shift exposure estimates (Seixas et al, 2003)
Using a large dataset of noise exposure measurements on construction workers assembled prior to the start of this study, task-based and full-shift exposure levels were compared and analyzed for the sources and magnitudes of error associated with several different exposure estimation techniques. Datalogging dosimeters recorded OSHA L_{AVG} noise levels over 502 workshifts (representing 248,677 one-minute datalogging intervals) on workers from five different trades. These data were combined with information from trade-specific activity cards completed by the monitored subjects, including information on trade, construction site type, location, activity, and tool. Six task-based exposure estimation linear regression models were applied to the one-minute data, and the results were used to estimate daily full-shift exposure levels based on the exposure durations and predicted noise levels of each task reported within a shift. These levels were then compared to the measured full-shift exposure levels. The task-based exposure estimates were derived using task-specific predicted noise levels alone, and also with the inclusion of subject- and shift-specific residual means and variances.

Exposure recall (Reeb-Whitaker et al, 2004)
The validity of the task- and tool-based self-report methodology upon which the baseline and follow-up questionnaires were based was evaluated. Workers from several of the trades in the prospective study were given the baseline questionnaire used in the study. They were then followed over a period of 6 weeks, and about 6 months after initial contact, were given the follow-up questionnaire used in the prospective study. During the 6-week observation period, all workers wore noise dosimeters and were observed by research staff one day per week; most workers were also asked to report their tasks and tools (via the self-report activity cards used in the main study) each day for a period of 6 weeks. Task- and tool-based reporting from the questionnaire was compared to activity card task- and tool-based reporting, and exposure levels were estimated by combining task-specific exposure levels measured using dosimetry with activity card- or questionnaire-derived activity data. These levels were then compared to the full-shift average levels measured with dosimeters. In addition, activity card reports were compared to researcher observations made over the same period. This approach allowed for evaluation of the accuracy of worker reporting, and the effects of this accuracy on estimated noise exposure levels.

Non-occupational exposure (Neitzel et al, 2004a and b)
Non-occupational noise exposures were estimated for subjects in the prospective study. These estimates were made by combining non-occupational activity participation data with non-occupational activity noise levels from several sources. A range of activity-specific routine non-occupational noise levels (10th, 50th, and 90 percentiles) were computed from non-occupational dosimetry and activity card measurements on construction workers, and a range of estimates of episodic non-occupational activity noise levels (“low,” “mid,” and “high”) were calculated from the literature. These estimated noise level ranges were combined with subject-specific non-occupational activity participation data (hours per year spent in each of the activities) gathered in the first follow-up examination of the prospective study, and were used to calculate total noise dose over the 6760 hours of non-occupational exposure time in a year for each subject. These dose estimates were then integrated over an equivalent 2000 hour exposure period, resulting in

an annual non-occupational noise exposure level which could be directly compared to the occupational exposure levels estimated for the cohort. To account for the wide variation in exposure levels, annual exposures were estimated for all possible combinations of routine (10th, 50th, and 90th percentile activity-specific dosimetry exposure levels) and episodic ("low," "mid," and "high" activity-specific literature exposure levels) non-occupational activities.

Attenuation of hearing protection (Neitzel et al, 2004c)
Noise Reduction Ratings (NRRs) for hearing protection devices, which are laboratory estimates of noise attenuation, have been shown to have a poor relationship to the actual attenuation achieved by workers in an occupational setting. To account for this difference between laboratory- and field-based attenuation levels, the attenuation achieved by construction workers employed on 6 different sites operated by 5 contractors was measured using a FitCheck attenuation measurement system. The same subjects also wore dosimeters and completed activity cards during the measured shift. Subjects were tested in a quiet area on site. The FitCheck system was used to measure subjects' audiometric threshold levels with and without use of earplugs; the difference between the two levels indicates the exact amount of attenuation achieved by an individual tested using a specific protector. Measurements were made in five 1/3 octave bands, and the frequency-specific attenuation results were summed into a Personal Attenuation Rating similar to the NRR.

Development and Analysis of Noise Exposure Metrics
A variety of exposure metrics were evaluated for use in estimating noise exposures for the trades and tasks studied, as well as for calculating cumulative exposure levels for individual subjects. These metrics are described in detail in Seixas et al, 2004a. Metrics examined include the commonly-used L_{AVG}, L_{EQ}, and L_{MAX}, along with two novel metrics developed for us in this study: the ratio of L_{EQ} to L_{AVG}, and the ratio of L_{MAX} to L_{EQ} (both calculated in terms of sound pressure, not decibels, to preserve the exponential relationship of noise levels). These ratios metrics function, respectively, as measures of how variable and how 'peaky' noise levels are for a given exposure. The ratios are useful in that they provide additional information about the noise profile associated with a particular exposure that is not available from an average level (L_{EQ} or L_{OSHA}) alone. The five exposure metrics described above were used to estimate exposure levels for each subject in the longitudinal cohort. A number of alternative approaches for estimating exposure levels were considered; ultimately, a combination of trade/task (i.e., tasks occurring within a specific trade) was adopted to develop mean exposure levels.

Annual occupational noise levels were estimated for each subject for the interval between annual hearing tests. The hours per year each subject reported doing a particular trade/task was calculated, and these durations were then combined with the appropriate trade/task mean exposure level to obtain the individual 2000-hour equivalent L_{OSHA}, L_{EQ}, and L_{MAX} exposure levels. By standardizing to 2000 hours, these measures increase with longer durations between examinations or more hours worked per year. Exposure estimates for the two ratio metrics were not standardized to 2000 hours, and therefore represent the average variability of exposure over the whole examination interval.

Baseline Data Analysis
Audiometric hearing threshold levels (HTLs) and DPOAE levels from the baseline examination were evaluated to assess the hearing ability of the cohort at the outset of this study. The analysis

is described in detail in Seixas et al, 2004b. A large number of audiometric and DPOAE frequencies were available for analysis; for simplicity, analyses were restricted to the frequencies 2, 4, 6 and 8 kHz. The analysis addressed the relationships between noise exposure history (including previous occupational, non-occupational, and military noise exposure) and a variety of other demographic and medical risk factors with HTL and DPOAE levels, while controlling for correlation between ears. These relationships were assessed using mixed effect linear regression models.

Longitudinal Data Analysis

Audiometric HTLs and DPOAEs from the follow-up tests were evaluated to measure changes in hearing, including frequency-specific audiometric thresholds and frequency or level-specific DPOAE levels, across the duration of the study. This analysis, which is described in detail in Seixas et al, 2004c, was conducted using mixed effects linear regression modeling, in which the variation between subjects, as well as between ears within a subject, was treated as a random effect. Three noise exposure groups were used: the control group, a ‘low’ exposed group, and a ‘high’ exposed group. The high exposure group consisted of the trades with the four highest mean HPD-adjusted L_{eq} exposure levels, and the low exposure consisted of the remaining four trades.

Adjustments were made for covariates thought to be correlated with both hearing outcomes and occupational noise exposure, including gender, age at baseline, occupational noise exposure prior to baseline, and mean of baseline audiometric thresholds at 3, 4, and 6 kHz. Non-occupational noise exposure was also considered, but because it was highly correlated with occupational noise exposure, and did not further contribute to the model, was excluded from the analysis. Tests for interaction between each of these variables and time since baseline were then performed at all 4 kHz hearing outcomes; only the trade-based exposure groups showed significant evidence of interaction.

RESULTS

Cohort Recruitment

Four hundred and fifty six subjects were recruited between 2000 and 2001, of which 393 were apprentices, and the remaining 63 were student controls. The cohort had a mean age of 27 (±7) years; 84% of subjects were male, and 78% were white. All subjects completed a baseline evaluation, and 350, 296, and 234 completed follow-ups at intervals one, two, and three, respectively. Apprentice subject retention was 74% at follow-up interval one and 46% at follow-up three – remarkably high given the transience of the construction workforce and the high attrition rates common to construction apprenticeship programs. Some examinations were excluded from analysis due to incomplete follow-up questionnaire information, ear infection or other contraindicated condition at the time of evaluation, or poor DPOAE data quality. Four-hundred thirty-four valid baseline examinations were collected, and 221 follow-up three examinations were completed, with the mean number of follow-up examinations 3.4±0.8 among subjects who completed more than one examination.

Occupational Exposure Levels

Table 1 shows the one-minute NIOSH L_{eq} exposure levels measured on nine different trades over 730 workshifts. Means and standard deviations are displayed overall and by trade, as are the percentage of minutes exceeding 85 dBA. The trades are ordered by descending mean one-minute L_{EQ} level. Over 360,000 minutes of exposure were measured; slightly less than half of these data (roughly 172,000 minutes) were collected during the pilot studies conducted prior to the prospective study. All data on cement masons, insulation workers, masonry trades, and sheet metal workers were collected as part of the current study. Although mean one-minute levels were always below 85 dBA, a substantial fraction of the total minutes measured on each trade exceeded 85 dBA.

Table 1. One-minute exposure metrics description by trade

		NIOSH L_{eq} level (dBA)		
Trade	**n minutes**	**Mean**	**SD**	**% minutes >85 dBA**
Operating Engineer	31,296	83.8	8.3	45.8
Ironworker	35,752	82.9	8.5	38.3
Carpenter	66,231	81.3	8.4	31.6
Cement Mason	14,764	80.8	7.8	26.3
Sheet Metal Worker	21,156	80.6	6.4	24.0
Electrician	114,827	80.5	7.6	26.3
Masonry Trades	34,437	80.5	8.9	25.5
Insulation Worker	11,597	77.9	6.2	15.0
Overall	**361,492**	**81.2**	**8.1**	**29.9**

Figure 1 shows the mean full-shift average L_{eq} exposure levels for the same 730 workshifts described in Table 1, by trade and overall. The trades are ordered by descending mean full-shift average L_{EQ} level. The full-shift OSHA L_{AVG} exposure level is presented for the same shifts. Standard deviations are indicated by error bars. Mean full-shift average L_{EQ} levels were always higher than L_{AVG} levels, and exceeded 85 dBA for all but one trade, while only one mean L_{AVG} level was above 85 dBA.

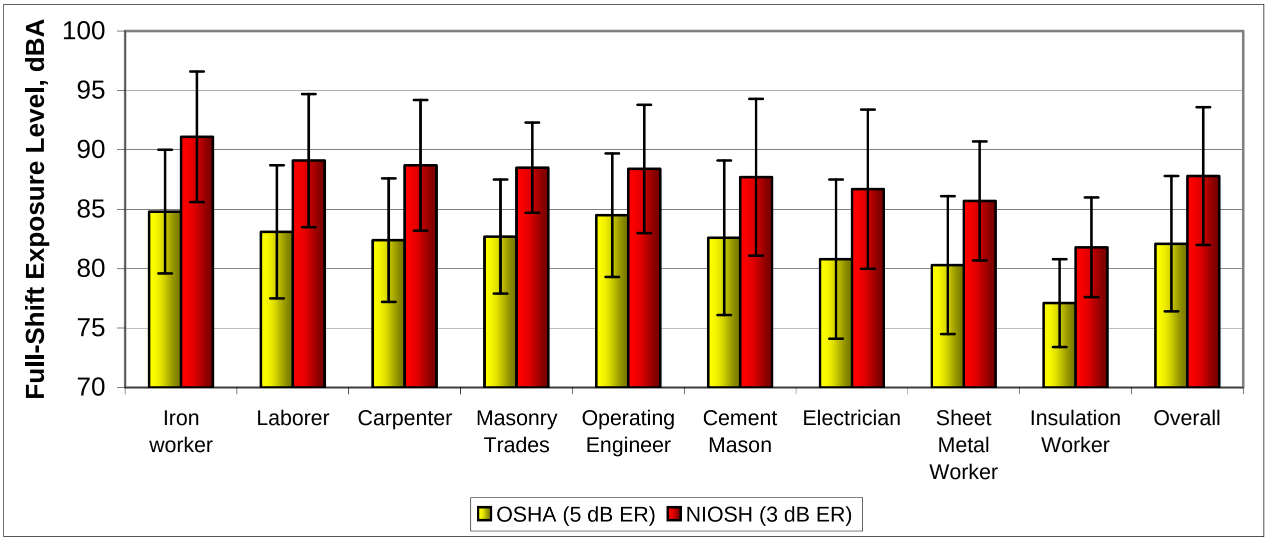


Figure 1. Full-shift average exposure levels by trade

The percentage of the 730 NIOSH L_{EQ} and OSHA L_{AVG} full-shift average levels from Table 1 which exceeded 85 dBA are shown in Figure 2 by trade and overall. The trades are ordered by descending mean full-shift average L_{EQ} level (as in Figure 1). The full-shift average L_{EQ} exceedance percentages were greater than 50% for all but one trade, while the L_{AVG} exceedances ranged from 9%-52%.

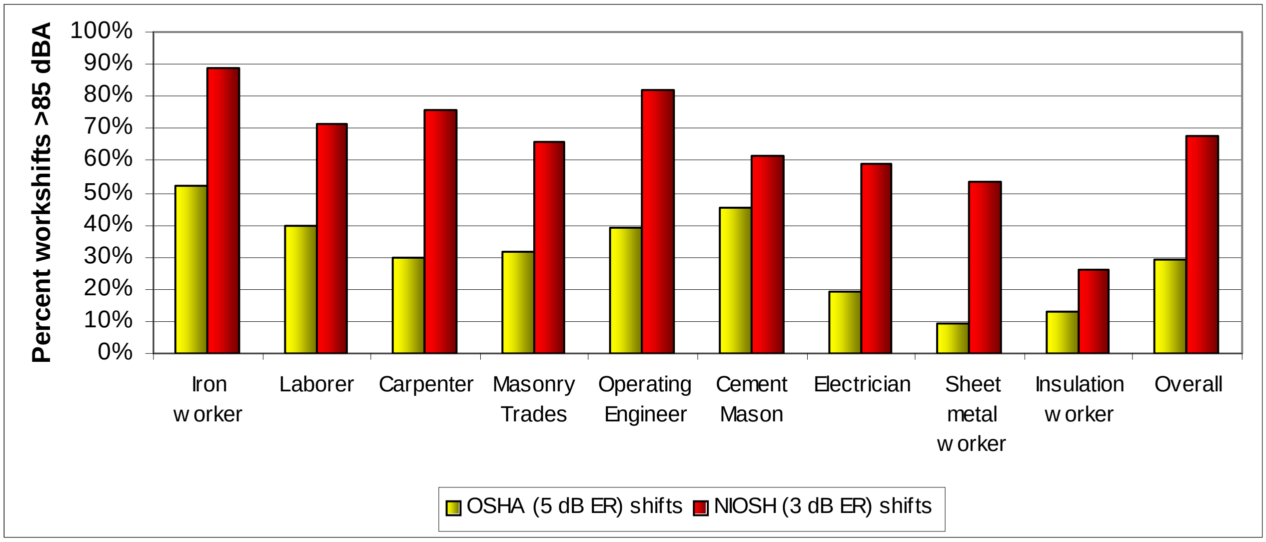


Figure 2. Percentage of shifts exceeding 85 dBA

Table 2 shows the percent of one-minute intervals in which L_{EQ} exposure levels exceeded 85 dBA, and the percentage of these minutes during which hearing protection was used. The mean and standard deviation percent of minutes per shift are included. The mean exposure and HPD use percentages in this table are also displayed graphically in Figure 3. The trades in both the table and figure are shown in the same order as Figures 1 and 2, by descending mean full-shift L_{EQ}. The 557 workshifts covered in this table represent a subset of the 730 workshifts from Table 1 for which both exposure levels and reported hearing protection use data were available. Overall, nearly a third of monitored minutes exceeded 85 dBA (and therefore needed HPD use), but hearing protection was used less than 20% of this time. Note that HPD use above 85 dBA varies widely by trade, and does not correlate very well with the percentage of minutes exceeding 85 dBA.

Table 2. HPD use >85 dBA by trade and overall

			% minutes in shift >85 dBA L_{eq}		**% minutes >85 dBA L_{eq} HPDs were used**	
Trade	**n work shifts**	**n minutes**	**Mean**	**SD**	**Mean**	**SD**
Operating Engineer	33	17,079	49.0	30.9	59.2	49.0
Ironworker	37	18,894	38.8	17.4	8.7	24.9
Carpenter	81	39,027	33.0	14.1	22.0	37.2
Cement Mason	31	14,764	26.3	18.4	16.7	31.5
Electrician	230	114,827	26.3	17.4	4.5	17.9
Masonry Trades	73	34,437	25.5	18.5	25.3	40.5
Sheet Metal Worker	43	21,156	24.0	15.2	43.3	46.8
Insulation Worker	23	11,597	15.0	17.5	4.3	20.7
Overall	**557**	**274,468**	**28.7**	**19.2**	**17.1**	**34.9**

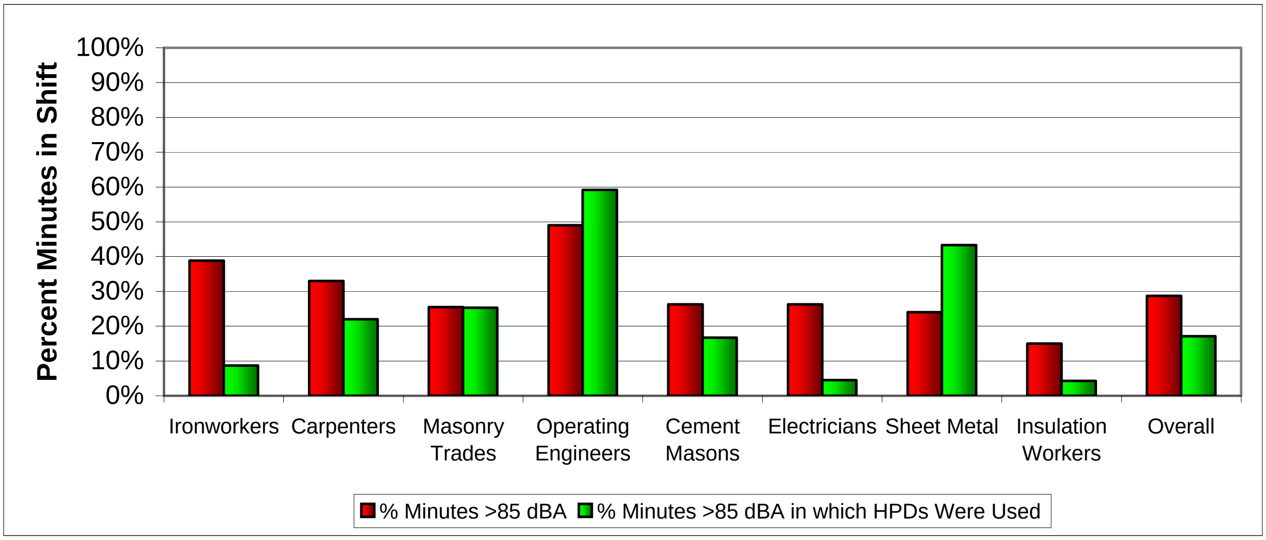


Figure 3. Exposure and HPD use above 85 dBA by trade and overall

Table 3 is based on the same 557 workshifts from Table 2. Full-shift NIOSH L_{EQ} Time-Weighted Average (TWA) exposure levels are shown by trade and overall for both unadjusted exposure levels (which do not account for use of hearing protection devices, HPDs) and HPD-adjusted exposure levels (which account for HPD use time and assume a 20 dB attenuation during use, based on the mean level of the 42 FitCheck field attenuation measurements made on construction workers during this study). Mean and standard deviation L_{eq} TWA levels are shown by trade and overall, as is the percentage of workshifts exceeding 85 dBA. Mean and standard deviation differences between unprotected and protected exposures are also shown. The trades are ordered by descending mean protected L_{EQ} TWA level. The overall protection in full-shift average L_{eq} exposure levels afforded by HPD use was less than 3 dB, resulting from a combination of reasonable attenuation values and very low use time. Only two trades achieved more than 6 dB exposure reduction on average. Using HPD-adjusted levels, the high exposure group consisted of Ironworkers, carpenters, electricians and cement masons, while the low exposure group included masons, insulation workers, sheet metal workers and operating engineers. When unadjusted levels were used, cement masons and electricians dropped to the low exposure group, and operating engineers and masons moved up in rank to the high exposure group.

Table 3. Protected (HPD-use adjusted) vs. unprotected NIOSH TWAs

		Unadjusted NIOSH TWA (dBA)				**HPD-adjusted NIOSH TWA (dBA)**				**Difference (unadjusted – HPD-adjusted) (dBA)**	
Trade	**N work shifts**	**Mean**	**SD**	**% >85 dBA**	**Rank**	**Mean**	**SD**	**% >85 dBA**	**Rank**	**Mean**	**SD**
Ironworker	37	90.7	5.5	83.8	1	89.5	6.3	78.4	1	1.2	4.1
Carpenter	81	89.3	4.5	84.0	2	86.2	6.9	65.4	2	3.1	6.2
Electrician	230	86.7	5.5	59.1	6	86.2	6.2	56.1	3	0.5	2.5
Cement Mason	31	87.7	5.6	61.3	5	85.0	7.8	51.6	4	2.7	5.9
Masonry Trades	73	88.5	6.7	65.8	3	84.4	7.0	43.8	5	4.1	7.0
Insulation Worker	23	81.8	3.8	26.1	8	81.1	4.2	21.7	6	0.7	3.4
Sheet Metal Worker	43	85.7	4.2	53.5	7	78.8	8.0	25.6	7	6.8	8.4
Operating Engineer	33	88.1	6.0	75.8	4	77.3	9.0	24.2	8	10.9	9.2
Overall	**557**	**87.4**	**5.7**	**64.5**		**84.8**	**7.4**	**51.2**		**2.7**	**6.0**

Figure 4 illustrates the difference between the percentage of unadjusted and HPD-adjusted L_{eq} TWA exposures above 85 dBA. Percentages are shown by trade and overall. The trades are ordered by descending mean HPD-adjusted L_{EQ} TWA (as in Table 4). HPD use resulted in dramatic reductions (greater than 50%) in overexposure situations for two trades (operating engineers and sheet metal workers), but produced minimal changes in overexposures for most other trades, with around one in five overexposures being brought below 85 dBA by use of HPDs.

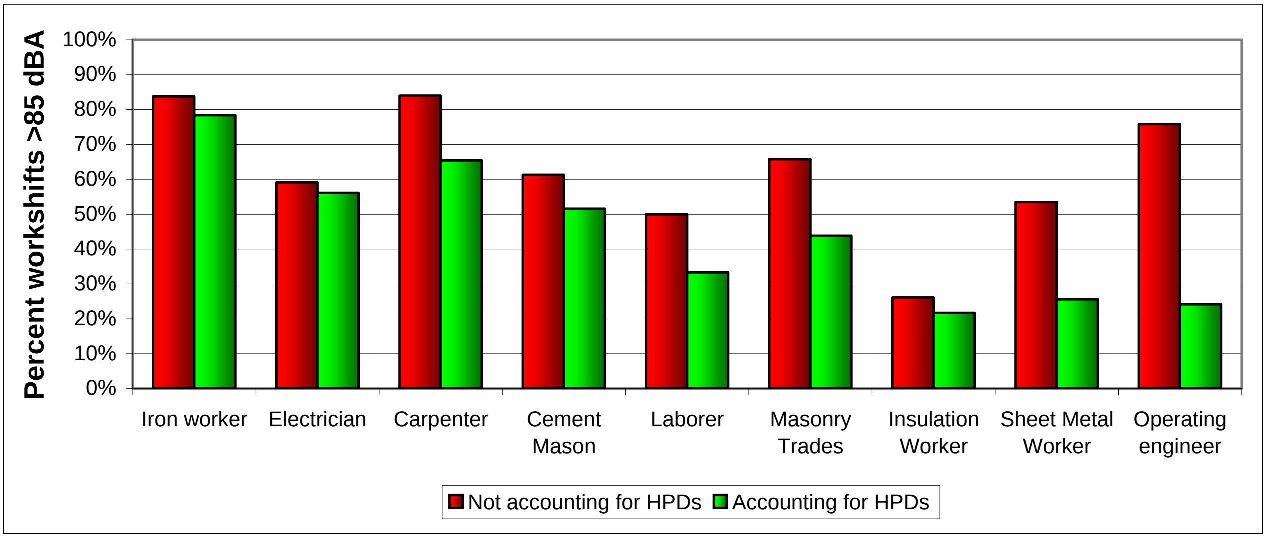


Figure 4. Percentage of shifts above 85 dBA with and without consideration of hearing protection use

Dissemination of Occupational Noise Exposure Results to the Construction Industry

A variety of trade-specific educational materials were developed to help disseminate the results of this comprehensive assessment of occupational noise exposure to the construction industry. These materials were developed with funds from the prospective study and from the Washington state Medical Aid and Accident Funds. The materials include booklets intended for use by safety and health professionals, as well as training brochures for use by trade workers. A website containing links to all these materials has been posted at http://depts.washington.edu/occnoise/.

Non-Occupational Exposure Levels

Activity card data and L_{EQ} noise levels from dosimetry measurements made on subjects during their non-work time were used to assess exposure levels during six routine non-occupational activities. In addition, questionnaire responses from subjects who completed follow up examination one in the prospective study were combined with noise levels from the existing literature to assess exposures resulting from six less-frequent (episodic) activities. These routine and episodic non-occupational activity exposure data were then used to estimate total annual non-occupational noise dose for each subject over the 6,760 nominal non-occupational hours in a year. These 6,760 hour exposure levels were then transformed into an equivalent 2,000 hour exposure level to allow for direct comparison of occupational and non-occupational noise exposures among subjects in the prospective study.

The amount of time spent in six routine non-occupational activities was reported by 148 prospective study subjects who completed the first follow-up examination questionnaire. The six activities assessed were: bar/restaurant/shopping/ theater, home, listen to music, travel in a car/bus, yardwork, and other. A total of 9,724 hours of routine non-occupational activities were reported over 406 subject-days. L_{EQ} noise levels were simultaneously measured during 2,141 of these hours using noise dosimeters. These routine activity L_{EQ} noise level data represent over 128,000 minutes of non-occupational activity dosimetry measurements on 118 subject-days from

31 construction apprentices. The majority of reported and measured non-occupational time (nearly 50%) was spent at home, while nearly 20% of reported time was spent traveling in a car or bus, and 10% of time was spent listening to music. The percentages of time reported in each activity were used to estimate the number of hours spent in each routine non-occupational activity over the 6,760 nominal non-occupational hours in a year.

Episodic non-occupational activity participation was reported by 266 prospective study subjects on the first follow-up examination questionnaire. The seven episodic activities assessed were: light aircraft, loud recreation (including dances, races, concerts, commercial sporting events), loud machinery, motorcycles, power tools, snowmobiles and jetskis, and firearms. Actual *exposures* to firearms noise could not be modeled due to lack of available L_{EQ} exposure level data and insufficient data on firearms use. Nearly 60% of all subjects reported participating in loud recreation activities, and 50% reported using power tools off the job, while less than 25% of subjects reported participating in the other episodic activities. Twenty-two percent of subjects reported using firearms regularly. However, a higher percentage of shooters reported participation in all of these non-occupational activities than did non-shooters, and shooters reported longer exposure durations for the activities than did non-shooters.

Figure 5 shows noise levels assigned to the non-occupational activities examined in this study, with the exception of firearms use. Noise levels for the routine activities are presented as 10th, 50th, and 90th percentile L_{EQ} levels from dosimetry measurements and simultaneous activity reporting done as part of the prospective study. Noise levels associated with the episodic activities were drawn from more than 20 scientific studies in the literature; these levels are reflected as "low" (the average of the lowest associated levels in the literature), "high" (the average of the highest associated levels in the literature), and "mid" (the average of the low and high levels). Routine activity noise levels were always lower than episodic activities, with 90th percentile routine activity levels almost never exceeding the low episodic levels. Exposure durations are inherently shorter for episodic activities than for routine activities.

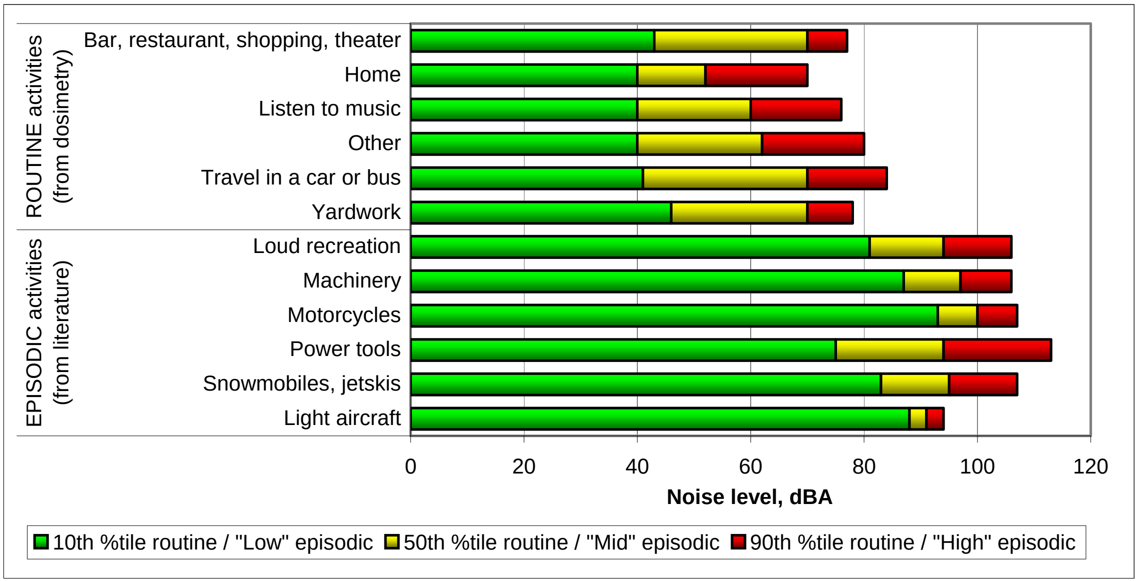


Figure 5. Noise levels of routine (10th, 50th, and 90th percentile L_{EQ} levels from dosimetry) and episodic ("low," "mid," and "high" levels from literature) non-occupational activities

Figure 6 illustrates the differences between "low-," "mid-," and "high-" range estimates of annual non-occupational exposures (integrated over a 2000 hour exposure) for non-shooters and shooters (with no consideration of firearms exposure), as well as the 10th, 50th, and 90th percentile annual occupational exposures for construction workers. The total (occupational plus non-occupational) exposure estimates are also shown. For most construction workers, non-occupational activities make little contribution to overall annual noise dose, as evidenced by the fact that the estimated total levels are essentially identical to the occupational levels. Non-occupational noise significantly increases total noise dose only for the small fraction of workers who spend significant amounts of time in noisy activities and work in the quieter trades. The importance of firearms use could not be assessed, but shooters reported more time in other noisy non-occupational activities, and as a result had higher non-occupational levels than non-shooters.

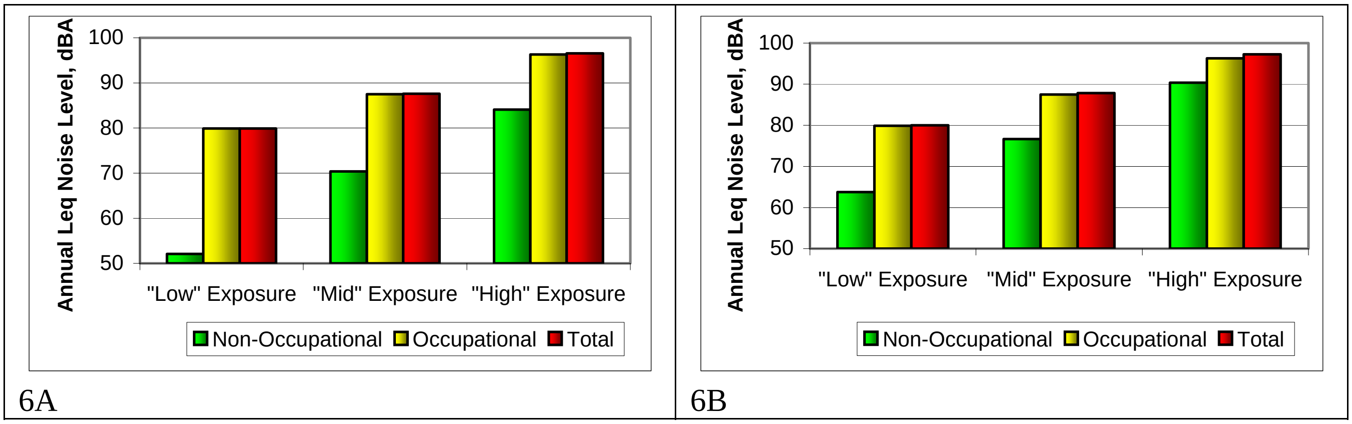


Figure 6. Estimated occupational, non-occupational (sum of episodic and routine activities) and total annual noise exposure for non-shooters (6A) and shooters without firearms (6B)

Comparison of Task-Based and Full-Shift Exposure Estimates

For analysis of task-based versus full-shift exposure levels, a variety of statistical models were developed which regressed task-based estimates on measured full-shift noise levels. Although task and tool data were collected, only the six models for task data are presented here (Table 4). Due to the large number of tasks (53) reported by the monitored subjects, groups of similar activities were devised. Statistical models developed using these task groups are referred to as grouped task models. Individual tasks were also modeled; analyses done using individual tasks are termed individual task models. Single predictor models used only the predicted task-specific noise levels, while more complex multiple predictor models used task-specific noise levels in addition to four other variables (trade, site type, tool type, and location on site). The most complex interaction term models also included the effects of combinations of all possible variables (i.e., trade and site, tool and site, etc). All models were run using predicted task-based noise levels only, using predicted noise levels and subject- and shift-specific residual means, and using predicted noise levels and subject- and shift-specific residual means and variances. Residual mean and variance data (which represent the difference between the predicted and true values) are not normally available for exposure estimation purposes, but were explored in this analysis to evaluate the effects of inclusion of these data on task-based exposure estimates.

The regression models which used only predicted task-based noise level and ignored subject- and shift-specific variability produced a significant negative bias, consistently underestimating the true exposure level due to the nonlinear averaging relationship of decibels. The bias was corrected when residual mean and variance information was utilized. The task-based exposure estimates explained 10 to 60% of the variability (r^2 in Table 4) in measured full-shift levels. Adding the residual data resulted in much better performance, and explained about 90% of the variability. Our analyses indicate that task-based exposure estimates are important for noise exposure estimation when task time varies substantially. However, task-based estimates include a substantial degree of error when there is large variability in exposure levels for a given task for different subjects and workshifts, as is the case in construction work. Methods to improve the prediction of task-associated exposure are needed. In particular, increased specificity in task definitions is required to reduce misclassification, and techniques to estimate exposure differences between subjects and sites must be explored, as these differences have large effects on exposure levels which cannot currently be modeled easily.

Table 4. Task-based exposure estimates using six alternative models and relationships between full-shift measurements and task-based noise exposure levels (dBA) (n=502 workshifts)

	Models					
	Grouped Tasks			Individual tasks		
Task-based L_{AVG} Level	Single predictor	Multiple predictors	Multiple predictors with interactions	Single predictor	Multiple predictors	Multiple predictors with interactions
Predicted only						
Mean	76.0	76.1	76.2	76.2	76.2	76.3
SD	2.1	3.7	4.0	3.5	4.1	4.9
r^2	0.084	0.30	0.38	0.30	0.38	0.55
Predicted + residual variance						
Mean	83.4	83.5	83.6	83.6	83.6	83.6
SD	3.9	4.6	4.8	4.5	4.9	5.4
r^2	0.11	0.33	0.40	0.31	0.41	0.59
Predicted + residual mean/variance						
Mean	83.5)	83.5)	83.6	83.6	83.6	83.6
SD	6.9	6.9	6.9	6.9	6.9	7.0
r^2	0.89	0.90	0.89	0.89	0.90	0.89

Cohort Exposure Analysis – Metrics

The 730 workshifts presented in Table 1, including data on 361,492 minutes of exposure to workers in 9 trades were examined using trade/task mean exposure levels and five different exposure metrics (the commonly-used average metrics of NIOSH L_{EQ}, OSHA L_{AVG}, L_{MAX}, and the variability metrics developed for this study, L_{EQ}/L_{AVG}, and L_{MAX}/L_{EQ}). Figure 7 shows a scatterplot demonstrating the correlation between the average annualized (2000 hour) metrics (L_{EQ}, L_{AVG}, and L_{MAX}) and average variability metrics (L_{EQ}/L_{OSHA} and L_{MAX}/L_{EQ}) for the 700 year-long intervals worked by the cohort. The correlations among all of the average metrics were high (r from 0.79 to 0.95), while the correlations between the average metrics and the ratio metrics were low (r from –0.54 to 0.51), as was the correlation between the ratio metrics (r of 0.48). The high correlation between the average metrics suggests that these measures of noise exposure are very closely related, while the low correlation between the average metrics and the variability metrics, and between the variability metrics, suggests that these newly-developed measures capture aspects of noise exposure that are not adequately conveyed through the use of the average metrics.

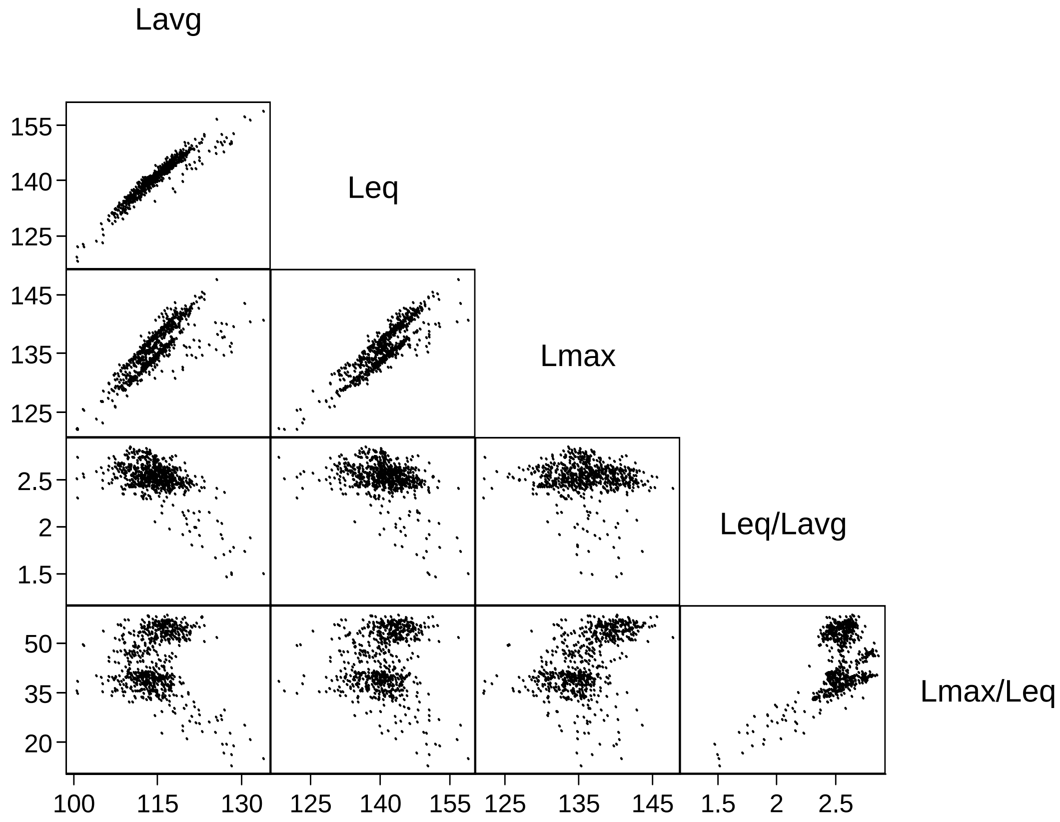


Figure 7. Scatterplot of yearly exposure metrics for the cohort

Exposure Recall Study
Twenty-five subjects participated in the sub-study which assessed the validity of the questionnaires and activity cards used in the prospective study. Twenty of these workers were carpenters or electricians; of the remaining five, only two were from trades not evaluated in the longitudinal study. All 25 completed a baseline questionnaire at enrollment. Seventeen subjects completed daily activity cards over the 6-week observation period, for a total of 389 activity card days. All 25 subjects wore dosimeters once a week during the 6-week observation period, for a total of 130 dosimeter measurements. Twenty-three subjects completed the follow-up questionnaire approximately 6 months after initial contact. Subjects in the study reported a mean of 2.5 tasks per day, with a range of 1-4, and worked at 1.8 ±1.2 sites on average.

Table 5 compares full-shift dosimetry measurements of L_{EQ} noise exposure with task-based L_{EQ} estimates made from simultaneously-collected activity cards and questionnaires administered six months later. The correlations between the various noise exposure measures were generally very good: 0.59 (questionnaire estimates vs. dosimetry measurements), 0.62 (activity card estimates vs. dosimetry measurements), and 0.91 (questionnaire estimates vs. activity card estimates). The accuracy for these exposure estimates was quite high, ranging from 96-99%. In addition, a total of 4775 minutes (from 17 workers) in which matched data from worker reporting and researcher observation were available were analyzed. Kappa statistics of agreement across these matched data were good for task and environment reporting (0.67 and 0.70, respectively), but were low for number of workers nearby (0.24 overall). The results of this sub-study indicate that six months later, construction workers could recall their tasks quite accurately and that exposure estimates made with these data are almost as accurate as task-based estimates from activity card reporting of tasks and simultaneous dosimetry measurements.

Table 5. Comparison of noise estimates from various sources of activity data

		Mean Estimated Exposure L_{EQ} (dBA) ± SE			
Trade	**n**	**Dosimetry**	**Activity Card**	**Bias**	**95% CI of the bias**
All subjects	17	87.2 ± 1.0	88.7 ± 0.8	-1.5*	-2.7 to -0.3
Carpenter	8	89.9 ± 0.7	91.9 ± 0.5	-2.0*	-3.5 to -043
Electrician	5	84.0 ± 1.2	85.0 ± 0.2	-1.0	-4.0 to 2.0
Other*	4	85.6 ± 2.4	86.9 ± 1.1	-1.3	-6.9 to 4.3
		Dosimetry	**Questionnaire**		
All subjects	23	86.3 ± 0.9	87.9 ± 0.9	-1.7*	-2.9 to -0.4
Carpenter	10	89.9 ± 0.6	91.9 ± 0.6	-2.0*	-3.8 to -0.3
Electrician	8	83.1 ± 1.2	85.1 ± 0.3	-2.0	-4.9 to 1.0
Other*	5	84.2 ± 2.4	84.6 ± 2.1	-0.4	-4.4 to -3.5
		Activity Card	**Questionnaire**		
All subjects	16	88.9 ± 0.9	88.8 ± 0.9	0.1	-0.6 to 0.5
Carpenter	8	91.9 ± 0.5	91.7 ± 0.8	0.2	-0.9 to 13
Electrician	4	84.9 ± 0.3	85.4 ± 0.3	- 0.5	-1.7 to 0.8
Other**	4	86.9 ± 1.1	86.5 ± 1.2	0.4*	0.1 to 0.8

*Significantly different from 0 at the 0.05 level, 95% confidence intervals do not include zero.
**Other trades included laborer, sheet metal, sprinkler fitter and operating engineer

DPOAE Variability

In order to evaluate the variability in our DPOAE test results, we estimated the within-test and between test (or year-to-year) variability in DPOAE results. Analysis was conducted using 2491 tests on 664 subject-ears including tests conducted over one to three years of follow-up. For 251 of these tests, DPOAE tests were duplicated within the test session, which allowed for separation of the total variability of the DPOAEs into within-test and year-to-year components. These test-retest repetitions were conducted only for the DP-Gram (L1=65 dB, 1–10 kHz) and the 6 kHz I/O growth function (L1= 35-80 dB). Variance components were estimated using a linear mixed effects model with time after baseline as a fixed effect, and subject, ear within subject, and time within ear within subject as random effects. Analyses were also conducted on subsets of the data excluding tests with a difference between the measured DPOAE intensity and the background noise floor of 0, 3 and 6 dB. To evaluate potential causes of within-test and year-to-year test variability, analyses were stratified by exposure group (apprentices vs. controls), test probe group (DPOAEs consistently measured using the same test probe vs. those measured with different probes at each test), technician group (same vs. changed technician administering the DPOAE test), hearing level at baseline (defined as the mean of audiometric thresholds at 3, 4, and 6 kHz and then stratified into ≤ 10, 10-20, and > 20 dB hearing levels), age group (younger and older than age 30), and whether the subject had reported any noise exposure just prior to the test.

Figure 8 presents the estimated within-test and year-to-year test standard deviations for the DP-Gram and 6 kHz I/O function. Graphs are shown with no data exclusions, and with test with differences between background noise floor and DPOAE intensity less than 6 dB excluded. Results demonstrate relatively consistent within-test variability with standard deviations of about 3 dB, and 2 dB after excluding the fraction of the data below or very close to the background noise floor. At very low primary intensities, the within-test variability is as high as 6 dB, down to about 3 dB at high level intensities, and is lowered an additional 1 dB with exclusions. Year-to-year variability is higher, from 4 dB up to over 6 dB at high frequencies. Stratifying the data by various potential causes of year-to-year variability demonstrated only slight differences. Keeping the probe or technician constant between tests reduced variability by 0.5 dB at most. Exposure group, age and prior reported noise had very little effect on year-to-year variability. Baseline hearing level had a slight effect, as seen in Figure 9, with higher thresholds (worse hearing) associated with slightly higher variability between 2-6 kHz, but only at DPOAE stimulus levels greater than 60 dB.

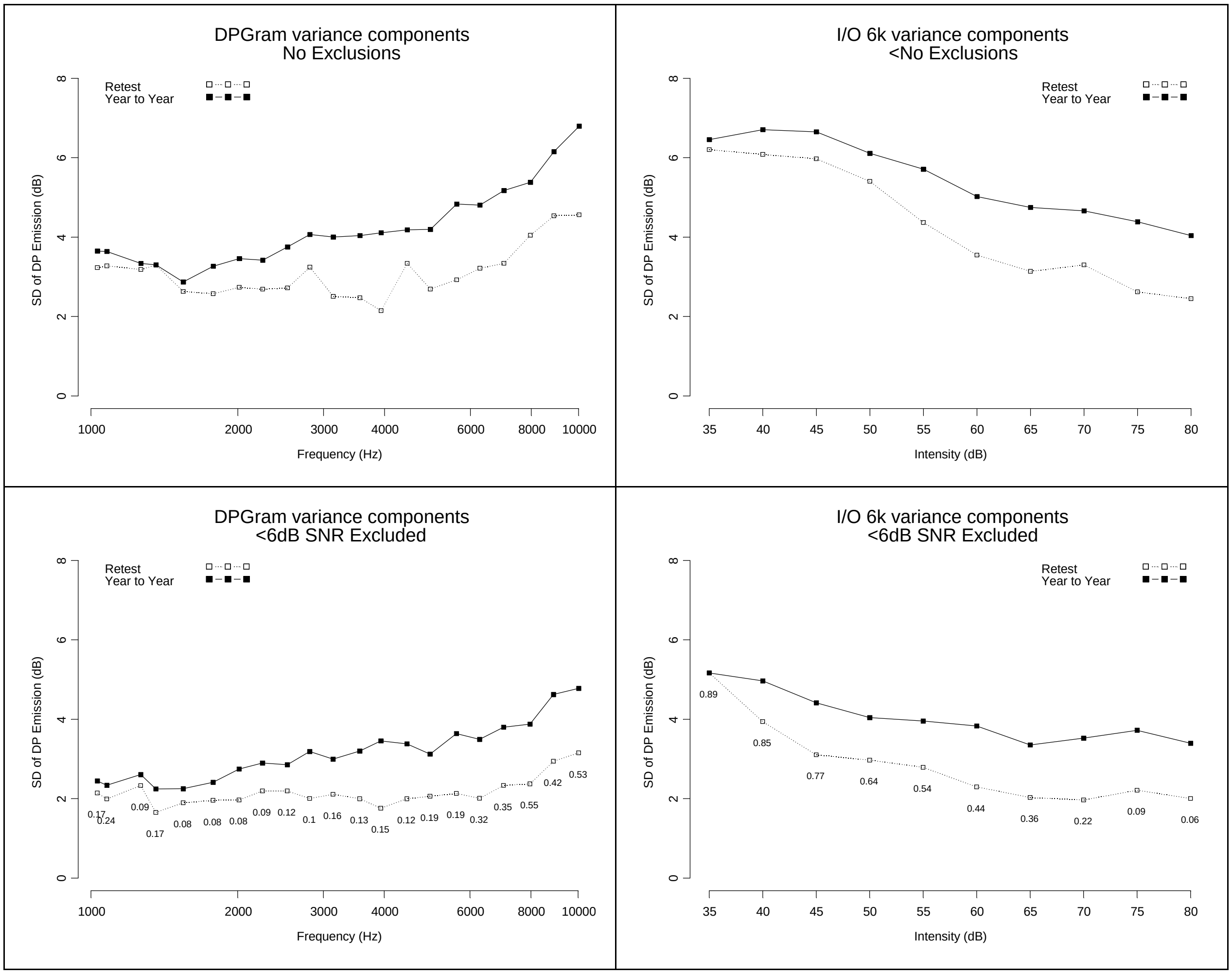


Figure 8. Within-test and year-to-year test variability in DP-Gram (left) and 6 kHz I/O (right) for all data (top) and those with SNR< 6 dB excluded.

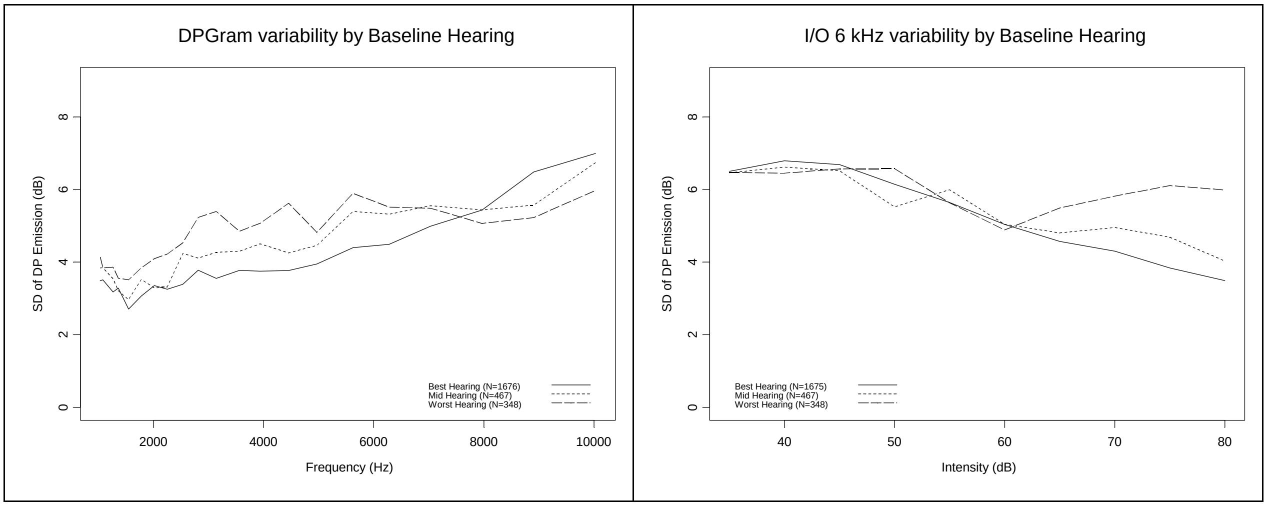


Figure 9. Year-to-year test variability stratified by baseline hearing group

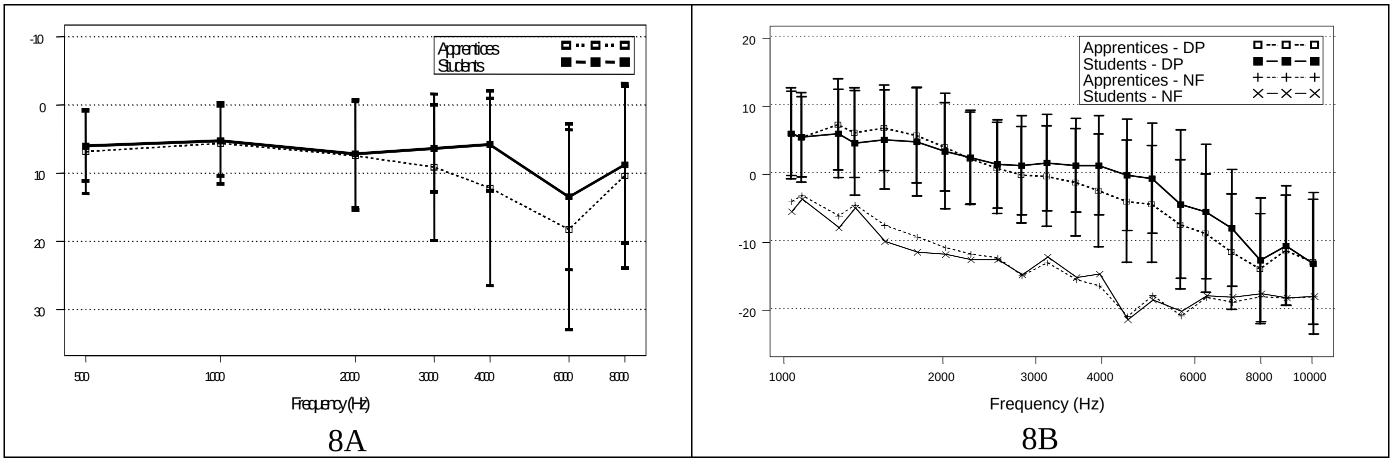
Baseline Analysis

A large number of demographic characteristics and risk factors were collected on the prospective study cohort at the baseline examination. Continuous and categorical data are shown in Table 6 for the 374 apprentices and 62 controls. These data include demographic characteristics, years of previous work experience for several different types of work, previous exposure to a number of noise sources and ototoxic agents. The ages of the two groups were very similar. Apprentices reported more previous noisy work, other noise exposures, and ototoxic exposure than did students. Nearly all apprentices were male, compared to the controls, which were roughly half female. Apprentices were far more likely to smoke and participate in noisy non-occupational activities.

Table 6. Cohort demographics and risk factors

	Apprentices (n=374)	**Controls (n=62)**	**Overall (n=434)**
Continuous Variable	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Demographic Factors			
Age	27.2 (7.0)	27.2 (4.2)	27.2 (6.7)
Noise Exposure Factors			
Construction work (years)	2.2 (3.2)	0.2 (0.8)	1.9 (3.1)
Non-construction noisy work (years)	3.8 (6.0)	3.4 (4.8)	3.7 (5.9)
Regular firearm use (years)	2.2 (5.1)	0 (0)	1.9 (4.8)
Firearms/explosion in military (years)	0.2 (1.0)	0.01 (0.06)	0.2 (0.9)
Power tool use (hours/week)	2.2 (4.1)	0.4 (0.5)	2.0 (3.9)
Home machinery use (years)	0.5 (2.8)	0.1 (0.6)	0.5 (2.6)
Machine use in military (years)	0.4 (1.8)	0.2 (1.0)	0.4 (1.7)
Motorcycle use (years)	2.1 (4.8)	0.1 (0.5)	1.8 (4.5)
Other Exposure Factors			
Solvent exposure (years)	1.3 (3.4)	0.9 (2.1)	1.3 (3.2)
Paint exposure (years)	0.5 (1.6)	0.0 (0.1)	0.4 (1.5)
Categorical Variable	**Number (%)**	**Number (%)**	**Number (%)**
Demographic Factors			
Gender: Male	333 (89)	34 (55)	367 (84)
Race/Ethnicity: White	292 (78)	50 (81)	342 (78)
Cigarette Smoker			
Current	180 (48)	1 (2)	181 (42)
Ex	65 (17)	4 (6)	69 (16)
Never	129 (34)	57 (92)	186 (43)
Family History of HL	83 (22)	18 (29)	101 (23)
Handedness: Right	329 (88)	57 (92)	386 (89)
Eye Color (Brown)	151 (40)	25 (40)	176 (40)
Hair Color (Dark)	282 (75)	48 (77)	330 (76)
Noise Exposure Factors			
Ever Regular Firearms Use	84 (22)	0 (0)	84 (19)
Other Vehicle Use	53 (14)	1 (2)	54 (12)
Loud Recreation	81 (22)	10 (16)	91 (21)
Listen to Music Loud	113 (30)	3 (5)	116 (27)
Other Exposure Factors			
Previous Disease	83 (22)	18(29)	101 (23)
Ear Injury	72 (20)	8 (13)	80 (18)
Ototoxic Therapy	14 (4)	0 (0)	14 (3)
Aspirin Use	36 (10)	2 (3)	38 (9)

Figure 10 shows the baseline audiometric thresholds and DPOAE amplitudes for apprentices and controls. Due to their greater experience with occupational noise and other ototoxic factors, baseline audiometric thresholds and DPOAE levels were significantly worse in apprentices than controls.



8A

8B

Figure 10. Audiometric thresholds (8A) and DPOAE DP-Gram (L2=65 dB) (8B) at baseline for apprentices and controls (error bars shows standard error)

The results of a mixed effects linear regression model on baseline audiometric thresholds at 2, 4, 6, and 8 kHz and baseline DPOAE levels at the test frequencies closest to the 2, 4, 6, and 8 kHz are shown in Table 7. The variables shown are those that were found to contribute significantly ($p<0.05$) to the model. Apprentices reported more noise than students in both their occupational and non-occupational exposure histories. A strong effect of age and years of work in construction was observed at 4, 6 and 8 kHz for audiometric thresholds. Each year of construction work reported prior to baseline was associated with a 0.7 dB increase in audiometric thresholds and a 0.2 dB decrease in DPOAE amplitude. Overall, pattern of effects among audiometric thresholds and DPOAE amplitudes were very similar.

Table 7. Reduced linear mixed models for audiometric thresholds and DPOAE levels***

	Audiometric Frequencies				DPOAE f2 Frequencies			
Characteristic	**2 kHz**	**4 kHz**	**6 kHz**	**8 kHz**	**2014 Hz**	**3936 Hz**	**6279 Hz**	**7965 Hz**
AIC	5690	6475	6593	6567	5369	5601	5832	5853
Intercept	6.6 (±1.2)**	2.6 (2.3)	7.0 (2.7)*	8.2 (2.0)**	6.4 (1.3)**	6.0(1.5)**	-2.8 (1.6)	-10.7 (1.5)**
Age (Baseline < 20 years)								
20 - <30	1.0 (±1.2)	-0.003 (2.0)	3.5 (2.2)	0.4 (2.0)	-0.4 (1.1)	-1.5 (1.3)	-0.03 (1.4)	-0.4 (1.2)
30 - < 40	2.3 (1.4)	1.8 (2.2)	6.8 (2.5)*	3.2 (2.3)	-2.7 (1.2)*	-3.5 (1.4)*	-3.1 (1.5)*	-2.3 (1.4)
> 40	7.3 (1.8)**	14.1 (2.9)**	15.5 (3.2)**	8.1 (2.9)*	-3.7 (1.6)*	-8.4 (1.9)**	-7.5 (2.0)**	-5.7 (1.8)**
Construction Years	-	0.7 (0.2)**	0.7 (0.2)**	0.5 (0.2)*	-	-0.2 (0.1)	-0.4 (0.1)*	-0.2 (0.1)
Gender (Male)	-	6.1 (1.4)**	4.8 (1.6)**	-	-1.9 (0.8)*	-6.0 (0.9)**	-4.4 (1.1)**	-1.6 (0.9)
Dominant Ear	-1.7 (0.4)**	-	-1.5 (0.6)*	-1.2 (0.7)	0.6 (0.3)*	-	0.8 (0.4)*	-
Use Firearms Regularly	-	2.7 (1.4)	-	-	-1.9 (0.7)**	-	-	-
Painting (Years)	-	-0.9 (0.4)*	-	-	0.5 (0.2)*	-	-	0.4 (0.2)
Solvent Exposure (Years)	-	0.6 (0.2)**	-	-	-0.2 (0.1)*	-0.3 (0.1)*	-	-
Family History	-	-	2.8 (1.4)*	-	-	-	-	-
Motorcycle Use	-	-	2.8 (1.3)*	-	-	-	-	-1.4 (0.7)
Power Tool Use (Years)	-	-	-	-	-	-	-0.2 (0.1)	-
Non-White	-	-	-	-	1.9 (0.7)*	-	-	-

* $p < 0.05$

** $p < 0.005$

*** Mixed models including random intercept for subject and adjusted for selected individual outliers.

Longitudinal Analysis

Of the 434 subjects (840 ears) included in the baseline analysis, 336 (652 ears) had one follow-up examination, 284 (553 ears) had two follow-ups, and 221 (432 ears) had all three follow-up tests. Results included in the current analysis are those subjects (or ears) with at least one follow-up, after excluding 8 individuals (20 ears) with middle-ear problems. The final longitudinal analysis dataset thus included 328 subjects (632 ears). Retention rates for at least one follow-up were 72% for apprentices and 97% for controls. Follow-up was very good, with an average of 3.4 (±0.8) exams per subject.

Analyses of change in hearing were conducted at all audiometric and DPOAE frequencies; however, the main effects were hypothesized (and evident) at 4 kHz and are presented here. Audiometric data and DPOAE results at selected levels (L1 = 40 and 65 dB) at 4 kHz are shown in Figure 11 for the three exposure groups (control, low, and high). Note that poor or declining hearing is represented by high or increasing audiometric thresholds, or small or decreasing DPOAE amplitudes. Controls tended to have lower hearing thresholds and slightly higher emissions than the low and high exposure groups, even at baseline. A clear separation in results between the students and controls was observed, although very little meaningful trend over time was seen for audiometric thresholds or I/O DPOAE functions at L1=40 dB. At L1=65 dB, slight downward trends in DPOAEs were seen for the exposed groups, and a slight upward trend appeared to be present in the controls. The large variances in relation to the slight trends underscore the difficulty of observing changes within the period of time studied.

Longitudinal models were run with random effects for subject and ear and fixed effect covariates for gender, age at baseline (≤30, >30), hearing level at baseline (mean threshold at 3, 4 and 6 kHz, ≤10, >10-20, >20 dB), and presence or absence of occupational exposure prior to baseline. Exposure was considered as time (in years) since baseline, exposure group (control, low, or high) and the interaction of time since baseline and exposure group.

The coefficients and 95% confidence intervals for exposure (interaction of time and group) are shown for audiometric thresholds and DPOAE magnitude at 4 kHz across primary intensities (L1=35 to 80 dB) (Fig. 12). Very little change in audiometry over time was observed at 2, 3 and 4 kHz, although the ordering of the coefficients for the three groups suggest a slight worsening of hearing with higher exposures. The high exposure group was statistically significantly increased in comparison to the control group, although it was not significantly greater than 0. At 6 kHz, the control group showed a significantly increased threshold over time.

In the 4 kHz I/O functions, the effect of time in the high exposure group was significantly more negative than in the control group for L1 from 50 to 75 dB, and significantly lower than 0 from 45 to 70 dB. The change in DPOAEs over time for the low exposure group was intermediate between the controls and high exposure group, indicating a relatively consistent exposure-response pattern. The positive coefficient (increase in DPOAE magnitude over time) for the control group was an unexpected result, though it is important to note that it is only significantly greater than 0 at only one level.

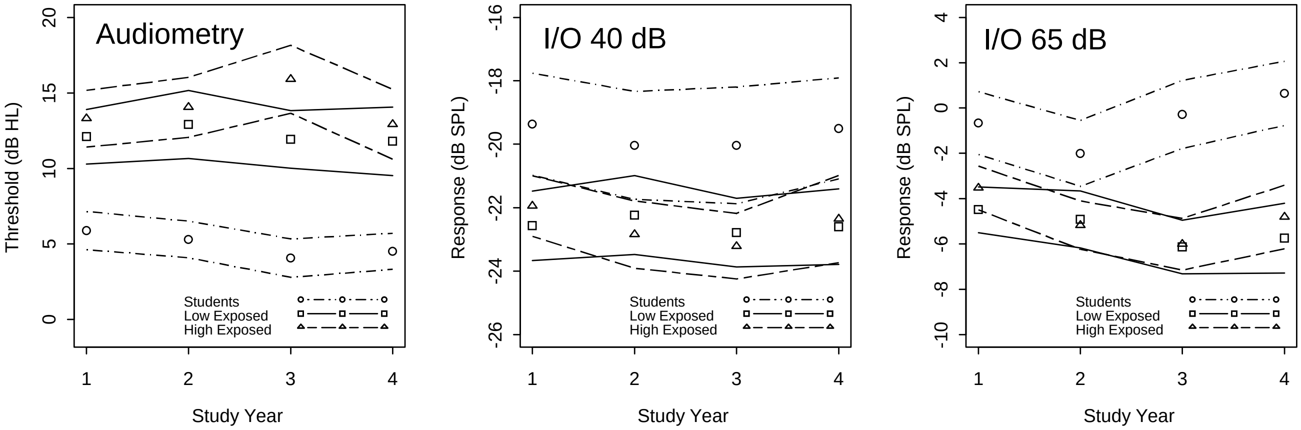


Figure 11. Mean (95% CI) 4kHz outcomes over time comparing controls and low and high exposure groups of apprentices.

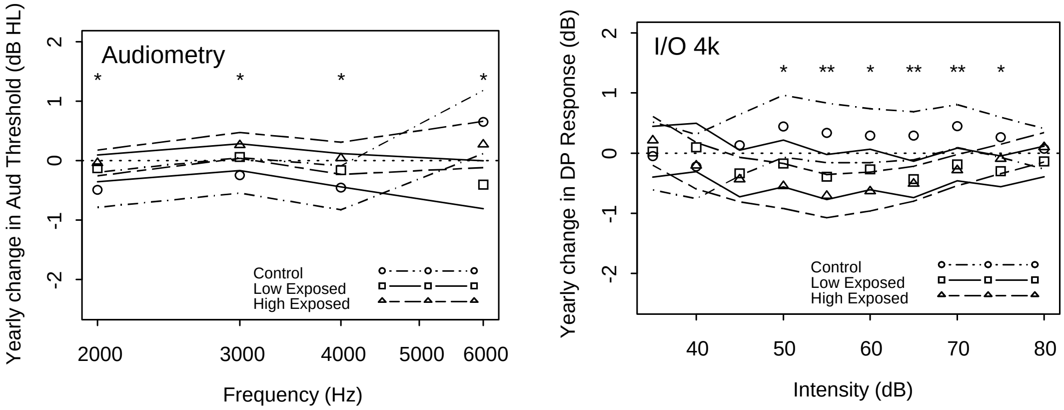


Figure 12. Coefficients (95% CI) for interaction of exposure group (control, low, and high) and time from mixed effects models for audiometric thresholds and 4 kHz DPOAE I/O functions.

Number of asterisks at a particular outcome represents number of exposure groups (1 or 2) significantly different from controls

The full longitudinal mixed effects models for the *a priori* hypothesized 4 kHz effects in audiometric thresholds and DPOAE with (L1=40 and 65 dB) are given in Table 8. The audiometry model indicates higher thresholds for low and high exposure groups in comparison to controls. By combining the modeled effect of years of follow-up with the interaction of follow-up time and exposure group, it is evident that the controls have slightly (non-significantly) decreasing thresholds over time, while there is very little change over time for the two exposure groups. At the low level stimulus (L1=40 dB) there is no discernable change over time at 4 kHz, while at the 65 dB stimulus, there is a significant change over time of about –0.4 and –0.5 dB per year for low and high exposure groups, respectively. These changes are significantly different from 0, and from the modeled change in the control group. The models also indicate that higher audiometric thresholds and lower DPOAEs (worse hearing, in other words) were associated with previous occupational noise exposure, older age, and higher thresholds at baseline. Male gender was also associated with higher thresholds and lower DPs, but not significantly.

Table 8. Model coefficients (95% CIs) at 4 kHz*

Characteristic	Audiometry	I/O 40 dB	I/O 65 dB
Years Since Baseline	-0.46 (-0.83,-0.09)	-0.23 (-0.76,0.30)	0.29 (-0.10,0.68)
Low Exposure Group	2.83 (0.11,5.55)	-1.05 (-2.99,0.89)	-0.46 (-2.32,1.40)
High Exposure Group	3.15 (0.54,5.76)	-0.66 (-2.52,1.20)	0.29 (-1.49,2.07)
Follow-up Years * Low Exposure Group	0.30 (-0.16,0.76)	0.32 (-0.35,0.99)	-0.72 (-1.23,-0.21)
Follow-up Years * High Exposure Group	0.50 (0.04,0.96)	0.02 (-1.86,1.90)	-0.80 (-1.29,-0.31)
Previous Occupational Noise	1.25 (-0.83,3.33)	-1.19 (-2.54,0.16)	-0.88 (-2.25,0.49)
Age >30	3.92 (1.94,5.90)	-1.10 (-2.39,0.19)	-2.64 (-3.93,-1.35)
Baseline Audiometry (0=≤10, 1=10-20, 2=>20)	12.40 (11.32,13.48)	-3.44 (-4.15,-2.73)	-5.22 (-5.89,-4.55)
Male Gender	1.26 (-1.23,3.75)	-2.31 (-3.94,-0.68)	-3.47 (-5.12,-1.82)

* Note that a positive coefficient for the audiometry model indicates association with worse hearing, whereas a positive coefficient for the OAE models indicates association with stronger response, or “better” hearing.

CONCLUSIONS

Demonstration of changes in hearing function over relatively short periods of occupational noise exposure is challenging because significant noise-induced permanent threshold shifts (NIPTS) require sustained exposures over time, and standard audiometric techniques have considerable imprecision. In order to address the development of noise-related changes in hearing, a cohort of construction industry apprentices and non-noise exposed controls was recruited at the beginning of their careers, and followed for four years using annual standard pure-tone audiometry coupled with Distortion Product Otoacoustic Emissions. The primary results of the longitudinal analysis of these data demonstrate that very slight, but statistically significant DPOAE losses over time were evident among the construction trades, with higher exposed trades having a larger decrease than lower exposed trades. The magnitude of the observed change, about -0.5 dB per year, was small but indicative of the potential for long-term damaging effect of noise on hearing, even within the first few years of work in the trades.

Noise exposure estimation is difficult among groups in which the noise levels and use of hearing protection devices are variable between subjects and over time. By combining data-logging dosimetry with individual HPD use self-reporting and a small number of direct measurements of HPD attenuations, trade-specific average exposures could be adjusted to better reflect true exposure levels. The HPD-adjusted exposure rankings demonstrated a much clearer dose-response relationship than was the case when HPD use data were not utilized.

The high-exposure group had estimated HPD-adjusted average NIOSH L_{EQ} exposures between 85 and 90 dBA. According to the ANSI and ISO models for predicting NIPTS, at these levels of exposure, the decrease in median audiometric thresholds at 4 kHz is 0.6-1.4 dB per year, respectively. Our results, indicating almost no change in audiometric thresholds over a three-year period of observation, are not consistent with these models. However, the models depend on extrapolation of changes in hearing thresholds for exposure periods of less than 10 years, and may not correctly represent the true progression of early NIPTS. It is also possible that although average exposure levels were between 85 and 90 dBA, the highly intermittent exposures found in the construction industry alter the course of hearing damage. The only way to explore these early findings is to extend the period of follow-up of this cohort.

Although the results are consistent with our *a priori* hypotheses, a number of issues are evident in the results. Of most concern is an apparent decrease in audiometric thresholds and increase in DPOAEs (e.g., improvement in hearing functions) over time among the control group. This apparent improvement could not be explained by changes in testing technique, equipment, baseline hearing levels, presence of temporary audiometric threshold shifts, an audiometric learning effect among the tested subjects, or other variables. If this improvement in measured hearing were similar between the controls and apprentices, then the noise-related changes among the apprentices have been underestimated, and the damage to their hearing ability is actually greater than presented here.

DPOAEs have shown promise as a sensitive early indicator of NIPTS, and may have potential surveillance applications as part of a hearing loss prevention program. In this study, small but significant decreases in average DPOAE magnitudes were observed in less than three years, and the changes were bigger with increasing noise exposure. However, the application of DPOAEs to identify individual subjects at increased risk of NIPTS is still not clear: while the DPOAEs measured for this study had a higher precision than audiometry, this level of precision still may be inadequate for individual level surveillance over short time periods.

The findings of this study highlight the fact that construction workers continue to suffer hearing damage from exposure to unsafe levels of noise on the job, and that further action is needed to adequately protect construction workers' hearing. In particular, we found that:

- Depending on the trade, construction workers are exposed over 85 dBA in about 70% of work shifts using the NIOSH exposure standard, and in about 30% of shifts using the les-protective OSHA exposure standard.
- Although non-occupational and recreational activities occasionally have high noise levels, these exposures make a meaningful contribution to total noise exposure for only a small fraction of construction workers.
- Although construction workers can attain good noise exposure attenuation using hearing protection devices, hearing protection is worn less than 20% of the time when exposure levels are over 85 dBA. As a result of this low use time, workers achieve an average of less than 3 dB of noise reduction in a full-shift exposure.
- Task-based assessment of noise exposure provides a comprehensive approach to estimation of noise levels associated with construction work. Construction workers were able to recall their work tasks with a high degree of accuracy. However, the large degree of variability in noise exposure between individuals doing the same task makes the estimated exposure level for any individual highly imprecise.
- Noise exposure can be summarized in a variety of exposure metrics. Those expressing an average level (including the NIOSH L_{EQ} and OSHA L_{AVG}) are very highly correlated with each other, and use of any of these average metrics probably makes little difference to the exposure-response analysis. Metrics which express the variability and impulse component of noise – exposure parameters which are very important in construction work – are poorly correlated with the average metrics.
- Distortion Product Otoacoustic Emissions (DPOAEs) directly monitor noise induced damage to the cochlea. Although a number of challenges were identified in the use of DPOAEs for monitoring changes in hearing, their test-retest variability is lower than that of pure tone behavioral audiometry, and therefore provides better sensitivity to subtle changes. However, with the particular protocol used for our study, the variability from year to year was slightly higher than previously reported in the literature.
- Construction work experience was associated with worse hearing (higher hearing thresholds and lower DPOAEs) in our baseline cohort of 434 subjects, with the effect seen most clearly at 6 kHz.
- Over an average of about 2.4 years of work in construction (3.4 annual tests) at estimated exposures of 85-90 dBA, there was a measurable decrease in DPOAEs of about 0.5 dB per year at 4 kHz. No measurable change was seen in audiometry.

Further follow-up of this group of construction workers will help determine if the observed changes in DPOAEs are predictive of later changes in hearing. If so, DPOAEs will form an important tool for monitoring and preventing hearing damage. In the mean time, increased efforts to reduce noise exposure among construction workers and prevent the development of serious hearing impairment are needed.

REFERENCES AND APPENDICES

Neitzel R, Seixas N, Olson J, Daniell W, Goldman B. “Non-occupational noise: Exposures associated with routine activities.” *J Acoust Soc Am*, 115(1): 237-245 (2004a).

Neitzel R, Seixas N, Goldman B, Daniell W. “Contributions Of Non-Occupational Activities to Total Noise Exposure of Construction Workers.” *Ann Occup Hyg* 48(5): 463-473 (2004b).

Neitzel R, Seixas N. “Effectiveness of hearing protection among construction workers.” *J Occup Environ Hyg* (submitted, 2004c).

Reeb-Whitaker C K, Seixas N S, Sheppard L, Neitzel R. “Accuracy of task recall for epidemiological exposure assessment to construction noise.” *Occup Environ Med*, 61(2): 135-142 (2004).

Seixas N, Neitzel R, Sheppard L, Goldman B. “Alternative metrics for noise exposure among construction workers.” *Ann Occup Hyg* (submitted, 2004a).

Seixas N, Kujawa S, Norton S, Sheppard L, Neitzel R, Slee A. “Predictors of Hearing Threshold Levels and Distortion Product Otoacoustic Emissions Among Noise Exposed Young Adults.” *Occup Environ Med* 61: 899-907 (2004b).

Seixas N, Goldman B, Sheppard L, Neitzel R, Norton S, Kujawa S. “Prospective Noise Induced Changes to Hearing Among Construction Industry Apprentices.” *Occup Environ Med* (submitted, 2004c).

Seixas, N, Sheppard L, Neitzel R. “Comparison of task-based estimates with full shift measurements of noise exposure” *AIHAJ*, 64: 823-829 (2003).

Outreach Materials Developed During this Study

University of Washington Construction Trades Noise Booklets and Brochures
http://depts.washington.edu/occnoise/

Chronological List of Student Theses Completed During this Study

Whitaker, C. “Accuracy of construction worker recall of tasks for epidemiological exposure assessment to noise.” University of Washington Department of Environmental and Occupational Health Sciences, 2001.

Parker, L. **“**A new approach to correlating distortion product otoacoustic emissions and audiometric thresholds : area, depth and frequency.” University of Washington Department of Speech and Hearing Sciences, 2001.

Reed, M. “The change in distortion product otoacoustic emissions in subjects at risk for noise-induced hearing loss.” University of Washington Department of Speech and Hearing Sciences, 2002.

Olson, J. “Non-occcupational noise exposure and its contribution to noise dose in apprentice construction workers.” University of Washington Department of Environmental and Occupational Health Sciences, 2002.

Olenchock, T. “Cross Shift Changes in Oto-acoustic Emissions in Relation to Occupational Noise Exposure.” University of Washington Department of Environmental and Occupational Health Sciences, 2003.

Goldman, B. “Use of Segmented Regression for Improved Threshold Estimation in DPOAE Data.” University of Washington Department of Biostatistics, 2004 (expected).