Original Article

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A longitudinal study of changes in evoked otoacoustic emissions and pure-tone thresholds as measured in a hearing conservation program

Estudio longitudinal de cambios en las emisiones otoacústicas evocadas y los umbrales tonales Medidos en un programa de conservación de la audición

Abstract

Non-linear transient-evoked otoacoustic emissions (TEOAEs) at 74 dB pSPL, distortion-product otoacoustic emissions (DPOAEs) at 65/45 dB SPL and pure-tone audiometry were used to detect noise-induced, inner ear changes in a longitudinal study. Repeated-measures ANOVAs were made on the Noise ($n=69$) and Quiet ($n=42$) groups. The Noise group's hearing thresholds increased by 1.2 dB and DPOAE amplitude decreased by −0.9 dB. For both groups, TEOAE amplitude decreased by approximately −0.6 dB. Eight of 12 ears with permanent threshold shift (PTS) and 10 of 13 ears with temporary threshold shift (TTS) showed TEOAE decrements or low baseline TEOAE amplitudes. Fewer TTS and PTS ears also showed DPOAE decrements, and there was never a DPOAE decrement without a corresponding TEOAE decrement or low TEOAE baseline. Some TTS ears showed permanent emission decrements. Although otoacoustic emissions show promise in detecting noise-induced inner ear changes, it is premature to use them in hearing conservation programs.

Sumario

En un estudio longitudinal se utilizaron emisiones otoacústicas evocadas por transitorios (TEOAE) a 74 dB pSPL, productos de distorsión (DPOAE) a 65/45 dB SPL y audiometría por tonos puros para detectar los cambios inducidos por ruido en el oído interno en un estudio longitudinal. Se realizaron mediciones ANOVA en repetidas ocasiones en los grupos de ruido ($n=69$) y silencio ($n=42$). Los umbrales del grupo de ruido aumentaron en 1.2 dB HL. En ambos grupos la amplitud de las emisiones disminuyó aproximadamente 0.6 dB SPL. Ocho de los 12 oídos con aumento permanente del umbral (PTS) y 10 de los 13 oídos con aumento temporal del umbral (TTS) mostraron decremento de las TEOAE o disminución de la línea basal de su amplitud. Menos oídos con TTS y PTS también mostraron decremento en las DPOAE, y nunca hubo un decremento de DPOAE sin la correspondiente disminución en TEOAE o en la línea basal de TEOAE. Algunos oídos con TTS mostraron decremento permanente de las emisiones. Aunque las emisiones otoacústicas son prometedoras en la detección de cambios por ruido en el oído interno, es prematuro utilizarlas en los programas de conservación de la audición.

Monitoring hearing thresholds with pure-tone audiometry has been successful in reducing and preventing noise-induced hearing loss (NIHL) in at-risk adults, but there is still much room for improvement. By the time a permanent threshold shift (PTS) has been recorded in a hearing conservation program, there is significant damage to the inner ear (LePage & Murray, 1993). Evoked otoacoustic emissions (EOAEs) may provide a more direct and reliable measurement of early changes and damage to the inner ear than audiometry. They have the potential to play an important role in increasing the effectiveness of hearing conservation programs.

The outer hair cells in the inner ear generate EOAEs in response to acoustic stimulation. These hair cells are among the first structures in the inner ear to be damaged by noise (Davis et al, 1989; Liberman et al, 1986; Nordmann et al, 2000; Probst et al, 1991). Most healthy, normal-hearing ears have EOAEs (Kapadia & Lutman, 1997); most noise-damaged ears have fewer, smaller or no EOAEs (Attias et al, 1995; Avan et al, 1996; Probst et al, 1991). By measuring if, when and how EOAEs change after exposure to noise, it may be possible to better monitor the health and status of the inner ear in individuals who are at risk for NIHL.

It needs to be established which EOAE types are best for this purpose; in particular, what happens to them as hearing loss develops, and which are most sensitive to inner ear changes due to noise. If EOAEs change before hearing changes, appropriate interventions could halt permanent hearing loss. If EOAEs change concomitantly with hearing, they would represent a useful confirmation, especially in cases where patient cooperation is an issue. Furthermore, it needs to be established if EOAEs change in the same way for PTS and temporary threshold shifts (TTSs), and in response to different types of hazardous noises. Laboratory

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and longitudinal field studies that are designed to systematically answer these questions are needed to develop a valid and sensitive protocol for the use of EOAEs in hearing conservation programs. This paper reports on our first attempt to use EOAEs in a hearing conservation program to find if, when and how EOAEs change with hearing thresholds. Transient-evoked otoacoustic emissions (TEOAEs) and distortion-product otoacoustic emissions (DPOAEs) were used, because they are the ones most commonly used clinically (see Avan et al (1996) and Probst et al (1991) for an overall description of EOAEs).

Considerations for best EOAE

Choosing the best EOAEs for use in hearing conservation programs requires the establishment of validity, reliability and measurability in a group of people who have not been recently exposed to noise.

A valid EOAE measurement consists primarily of the otoacoustic emission, with little contribution from measurement artefact. Artefacts can come from the EOAE hardware (e.g. probe crosstalk, transducer ringing), from the environment (e.g. correlated and deterministic noise), and from signal processing (e.g. frequency spread from windowing). People in hearing conservation programs often have very low emission levels. It is important to ensure that these low-level emissions are still well above any artefact level. As well as looking for artefacts in an artificial ear (acoustic coupler), it is also useful to look for artefacts in hearing-impaired ears. If there is a measurable response in a hearing-impaired ear, it is more likely to be an artefact than an EOAE—even if there was no artefact seen in a coupler.

When monitoring individuals for noise-induced changes in hearing thresholds and EOAEs, minimizing within-subject variability is crucial, because any change must be greater than the test–retest variability to be reliably detected. Test–retest reliability may be estimated from repeated measurements on ears that have not been exposed to noise. Although there are some published reliability figures for various EOAEs, it is important to verify reliability for each population, EOAE system, measurement protocol, and environment. The published figures may be used as a benchmark (e.g. Beattie & Bleech, 2000; Franklin et al, 1992; Marshall & Heller, 1996; Murray et al, 1997).

EOAE measurability is defined here as the proportion of emissions present above the noise floor in a sample from the population of interest. If an emission type is measurable in only a small percentage, then it is unlikely to be of much use in a hearing conservation program (unless the low-level emission can be shown to be predictive of susceptibility to NIHL). Optimizing measurability requires consideration of the stimulus level, the frequency range, and the time available for measurement. For high stimulus levels, an emission may become unmeasurable because of high artefact levels, but for low stimulus levels, the emission may not be distinguishable from the noise floor or artefact level. An emission may be more difficult to measure at low and high frequencies due to equipment limitations. If too few averages are taken, the higher noise floor may mask measurable emissions. There can be good reasons, however, to choose a lower stimulus level, even if the emission becomes less measurable. For instance, there is evidence that emissions evoked by lower-level stimuli are more sensitive to noise-induced changes (e.g. Marshall & Heller, 1998; Sutton et al, 1994). A trade-off among these factors is usually necessary, particularly with regard to optimizing the measurability of an emission versus the time available for testing.

Noise-induced changes in EOAEs and hearing

The next step in determining the best EOAE protocol for hearing conservation programs is to establish whether the EOAE type(s) with the best validity, reliability and measurability are also sensitive to noise-induced inner ear changes. Both TTS and PTS need to be considered, because their underlying damage mechanisms may be different (Nordmann et al, 2000), and thus the effect on EOAEs may also be different.

Only small TTSs can be studied in the laboratory, because, obviously, it is unethical to purposely induce a PTS. PTSs and large TTSs can be studied only in people already occupationally or recreationally exposed to noise. Unfortunately, this usually means that measurements must be made in the field on large numbers of subjects (because it is unknown *a priori* which people will get a threshold shift in response to a given noise exposure), with much shorter testing times, and over a much longer duration (hearing loss can take many years to develop). Further limitations come about because there is usually not enough time to do more thorough testing, which would occur in a laboratory study.

A moderate relationship between TTS and temporary emission shift (TES) exists for TEOAEs in laboratory settings (Attias & Bresloff, 1996; Marshall & Heller, 1998). TTS and TES measured with DPOAEs are also related when some outliers are removed from the data (Engdahl, 1996; Marshall & Heller, unpublished data). TES magnitude is generally smaller than TTS magnitude. For example, the magnitude of the TES is less than one-half the magnitude of the TTS (in dB) for TEOAEs (74 dB pSPL stimulus level) and DPOAEs (65/45 dB SPL stimulus levels) (Marshall & Heller, 1998; Marshall et al, 2001). The recovery functions for TEOAEs and DPOAEs are similar, indicating that either could be a viable method for measuring inner ear changes associated with TTS.

It is difficult to study PTS in humans, because the development of hearing loss tends to be slow and insidious, and can only be studied quasi-experimentally in natural settings. Animal studies have shown an association between change in EOAEs and PTS (Hamernik et al, 1996; Hamernik & Qiu, 2000; Lonsbury-Martin et al, 1987; Schmiedt, 1986; Zurek et al, 1982). These studies tend to focus on large changes in hearing thresholds, whereas in hearing conservation programs we are interested in detecting small changes in hearing thresholds. Furthermore, anatomic differences between humans and other animals (except for, perhaps, primates) make it difficult to predict how EOAEs change with noise exposure in humans, especially when comparing the efficacy of different EOAE stimulus types (e.g. Kemp, 1986, 2002; Probst et al, 1991; Shera & Guinan, 1999; Whitehead et al, 1992, 1996). Most have approached the problem by comparing EOAEs and hearing thresholds among groups of people who have experienced different degrees of noise exposure. Although this helps to establish the relationship between hearing thresholds and EOAEs, the onset of PTS and EOAE changes in humans is still unknown.

EOAEs and PTS: between-subject/cross-sectional approaches

LePage's group at the National Acoustic Laboratories in Australia is one of the few to look systematically at EOAEs and hearing loss on a large scale. Their approach is to look at one type of emission (non-linear TEOAEs at 80 dB pSPL using the ILO88 system) and make measurements on a very large number of people. To date, they have measured the TEOAEs of over 15 000 people. LePage et al (2001) reported that the average emission level in the population decreased at an earlier age than the decrease in hearing thresholds. They suggested that low-level emissions, along with normal hearing thresholds, indicated damage to the inner ear, which had not shown up in an audiogram. Furthermore, they suggested that TEOAEs might be used to monitor the early stages of hearing loss in populations.

Cross-sectional research such as LePage's has shown that ears with hearing loss have low, or no, measurable EOAEs, and that EOAEs may diminish before hearing thresholds (Attias et al, 1995, 2001; Desai et al, 1999; Lucertini et al, 2002; Mansfield et al, 1999; Veuillet et al, 2001).

EOAEs and PTS: within-subject/longitudinal approaches

Although cross-sectional research has shown that there should be a predictive relationship between changes in hearing and changes in EOAEs, few studies have looked at the progression of EOAE and hearing change resulting from noise exposure in individuals.

Hotz et al (1993) measured non-linear TEOAEs (probably at the default value of around 82.5 dB pSPL) in 147 young noise-exposed men before and after a 17-week military training course. During the course, they were exposed to weapons noise while wearing hearing protection. A previous study on the same population had found no change in hearing thresholds. Hotz et al found a −1.8-dB to −3.2-dB reduction in TEOAE levels, especially in the 2–4-kHz band. The bigger reductions were found in the more noise-exposed group.

More recently, Sliwinska-Kowalska & Kotylo (2001) reported that TEOAE amplitude decreased over 2 years in two groups of noise-exposed industrial workers, compared with a control group (they did not report the magnitude of the decrements). DPOAEs and hearing thresholds, on the other hand, did not show any change. Radomskij et al (2002) also found a decrease in non-linear TEOAEs (82 dB pSPL, ILO288) after magnetic resonance imaging (MRI) of −1.84 dB, which was greater than the change seen in a control group, even though the subjects used hearing protection during the procedure. They did not measure EOAE recovery or hearing thresholds, but they stated that people were at risk for TTS from MRI if they did not wear hearing protection.

In contrast, Murray & LePage (2002) found no consistent permanent changes in TEOAEs in 39 of their subjects where repeated measurements had been made over 9 years. These subjects were members of the Australian Opera and Ballet Orchestra. Changes may not have been seen because the subjects may not have received enough noise exposure, and possibly because the orchestra implemented an effective hearing conservation program that reduced the occurrence of TTS (N. M. Murray, personal communication). The changes in TEOAEs that were seen did not consistently increase or decrease with hearing.

Most of these longitudinal studies showed some change in EOAEs after noise exposure. However, conclusions about the use of EOAEs in hearing conservation programs are limited, because too few subjects were tested, hearing thresholds were not necessarily measured in the same group of people, and/or emission types and parameters were not compared. The incidence of hearing loss is low even in noise-exposed groups, so many subjects are needed to see how emissions change with PTS. Multiple emission types should also be compared to find which are most suitable for monitoring individuals over time in hearing conservation programs.

To study the development of PTS in humans, we need subjects who are already occupationally or recreationally noise-exposed. Because these noise exposures are uncontrolled, it is much more difficult to determine what type of noise exposure may have led to the changes in hearing, or to get enough people with similar exposures to allow determination of whether different exposures affect EOAEs differently. It is also difficult to gain access to large, noise-exposed populations that can be monitored for long enough for us to see the development of NIHL.

Here we consider how changes in EOAEs relate to changes in hearing thresholds, within individuals, in a noise-exposed population. We were fortunate to have access to a population comprising mainly noise-exposed, active-duty, US Navy personnel stationed at the Naval Submarine Base in Groton, Connecticut. This group was augmented with noise-exposed and non-noise-exposed ('quiet') people from the surrounding community. With regard to the inherent trade-off between number of subjects and number of tests, we decided to explore more EOAE types and levels per subject than most other studies, because it was not clear which EOAE would be the best indicator of inner ear damage. Therefore, we chose a medium-sized (rather than large) sample.

Methods

Subjects

Four hundred and seventy-four subjects, aged 14–49 years, with varying degrees of noise exposure, were enrolled in the study. The attrition rate was 17% in Year 2 and 25% in Year 3. In Year 4, only 47 of the most and least noise-exposed people were asked back for follow-up (the Year 4 data were used only for analyses on individuals, due to this selection bias). Subjects were required to have no known audiological pathology and hearing thresholds at 2, 3, and 4 kHz no worse than 25 dB HL at enrollment. At enrollment, subjects were classified into groups based on their anticipated noise exposure from their occupations and hobbies. Over the course of the study, many subjects became more or less noise-exposed. Therefore, at the end of the study, subjects were reclassified based on their actual (self-reported) noise exposures. Final subject groupings are reported in the Results section.

Stimuli and equipment

Middle ear status was assessed using a Grason Stadler (GSI-33, version 2) middle ear analyzer. Audiograms were taken using a Grason Stadler (GSI-16) audiometer and TDH-50 earphones with Telephonics P/N 5100017-1 rubber cushions. A test battery consisting of TEOAEs, DPOAEs and synchronized spontaneous otoacoustic emissions (SOAEs) was run using the Otodynamics ILO88 system, running the ILO92 (version 4.2) software.

In order of presentation, the EOAE test battery was: linear TEOAEs (80, 74, 68, and 62 dB pSPL; 540 averages acquired per level), non-linear TEOAEs (80 and 74 dB pSPL; each stimulus ensemble consisted of three positive clicks and one negative click with three times the amplitude; 540 averages acquired per level), synchronized SOAEs using the ILO default, DPOAEs as a function of frequency (31 frequencies, $f_2 = 1001–7996$ Hz, spaced evenly in $\log_2$ coordinates; L_1/L_2 levels of 70/60 and 65/45 dB SPL, and $f_2/f_1 = 1.22$), and DPOAEs as a function of level ($f_2 = 1001$, 2002, 4004, 6006 and 7996 Hz; L_1/L_2 levels of 55/45, 60/50, 65/55 and 70/60 dB SPL where $L_2 - L_1 = 10$ dB, and L_1/L_2 levels of 55/35, 60/40 and 65/45 dB SPL where $L_2 - L_1 = 20$ dB, and $f_2/f_1 = 1.22$). Initially, only linear TEOAEs, SOAEs and DPOAEs were measured. The non-linear TEOAE 74 dB pSPL level was added 5 months into the study, and the non-linear TEOAE 80 dB pSPL level was added 16 months into the study. Therefore, not all subjects had all emission tests for all years. The DPOAE probe was used for all emission measurements. It was covered by an acoustic-immitance probe tip, which had been enlarged using a grinding tool, to allow better placement and manipulation in the ear canal. All audiometric and EOAE tests were run in a double-walled, sound-attenuating chamber (Industrial Acoustics Company, Inc.), with ambient noise levels below the maximum permissible for audiometric threshold testing according to ANSI S3.1 (American National Standards Institute, 1991). All audiological equipment was calibrated in accordance with standard procedures. The EOAE probes were checked regularly in a cavity using the ILO probe-check procedure.

Procedure

Subjects were tested approximately annually up to four times by certified hearing conservation technicians or audiologists. Subjects were given an otoscopic examination (with cerumen removal if necessary), followed by middle ear testing. An audiogram was administered manually using ANSI S3.21 (American National Standards Institute, 1978) audiometric procedures (Hughson–Westlake modified method-of-limits procedure, with 5 dB HL step size). Test frequencies were 0.5, 1, 2, 3, 4, 6 and 8 kHz. Subjects were also instructed about hearing conservation and were fitted with hearing protection.

Subjects were required to have middle ear pressure between −30 and +15 daPa for EOAE testing (Marshall et al, 1997). Subjects with middle ear pressure outside this range who could not equilibrate were rescheduled (all testing was redone). EOAE testing commenced with the ILO92 in-the-ear calibration procedure. Every effort was made to ensure a flat spectrum in the ear canal, without significant ringing, but this was not always possible.

Subjects were questioned extensively about their audiological histories. In the first (baseline) year, subjects were asked about auditory events from their entire life. In subsequent years, only events since the last test were noted. Subjects were asked about (1) years of noise exposure, (2) most recent exposure, (3) type of hearing protection used and percentage of time for which it was used, (4) medical history concerning their ears and hearing, (5) medication, smoking and caffeine use that day, (6) long-term medication usage, (7) military experience, and (8) itemized noise exposures, including duration and hearing protection usage, for both occupational and recreational exposures (e.g. power tools, guns, machinery, music).

In subsequent tests, each subject's audiograms were compared to their baseline audiogram. If the subject had experienced a significant threshold shift (STS) based on the Navy hearing conservation criteria (a shift at 1, 2, 3 or 4 kHz $\geq$ 15 dB, or an average shift at 2, 3 and 4 kHz $\geq$ 10 dB (Navy Occupational Health and Safety Program, 1999)), the subject was asked to come back for a noise-free follow-up (separate from the annual test) to determine if the STS was temporary or permanent.

The experimental protocol was approved by the Navy Bureau of Medicine and Surgery Institutional Review Board.

Results

The validity and measurability of each emission type was used to make a principled selection of portions of the test battery for further analysis. Subgroups of subjects were chosen for detailed analysis, based on noise history and completeness of data set. Group-average hearing and emissions were examined for changes from year to year. Then individuals with TTS and PTS were examined closely to see if there were accompanying changes in their EOAEs.

Criteria for EOAE presence

An EOAE was defined as present if the measurement was (relatively) free of artefact and the emission amplitude was above a criterion based on the noise floor. If the emission was less than or equal to the criterion, then it was considered unmeasurable (this does not necessarily mean that the emission was absent). During data analysis, it became apparent that much of the test battery was affected by calibration problems, artefacts, and unmeasurable emissions. Preliminary analyses also indicated that the DPOAEs and TEOAEs at the higher stimulus levels showed smaller, less consistent changes in subjects with hearing threshold shifts. Therefore, after careful consideration, only results for non-linear TEOAEs at 74 dB pSPL and half-octave DPOAEs at 65/45 dB SPL are reported here.

Linear TEOAEs were eliminated because they evoked responses in a separate group of nine hard-of-hearing ears (Heller & Marshall, unpublished data). These responses were considerably larger than artefacts seen in a coupler, but were unlikely to be true emissions. The response of the hard-of-hearing ears increased with stimulus level, and particularly affected the 2- and 2.8-kHz half-octave frequency bands. Many of the DPOAE measurements were affected by calibration problems and artefacts. DPOAE stimulus levels were consistently below the target levels across the group for $f_1 \geq 4041$ Hz and $f_2 \geq 4919$ Hz (from −2.4 to −7.8 dB for the group average). All measurements at these frequencies were therefore dropped from further analyses on all subjects. Furthermore, DPOAE amplitudes were occasionally elevated for one of the three blocks in the DPOAE measurement series (the 31 measurements were taken in blocks of 10 or 11 contiguous frequencies), perhaps indicating probe movement. In some cases, this occurred along with stimulus levels that were higher or lower than the target level, but there was no overriding, consistent pattern that allowed those cases to be identified and removed from the data set. Our policy is to not remove such outliers for group analyses unless we can explain the phenomenon and identify affected cases in an objective fashion. When we examined individual cases, Year 2 data were used as the baseline if a DPOAE measurement in Year 1 was suspicious, provided that the TTS or PTS did not occur until Year 3 or Year 4. In summary, we decided not to include any linear TEOAEs or single-frequency DPOAEs in further analyses, because they were not measurable at enough frequencies or levels, especially across individuals (this particularly affected the planned analysis of the DPOAE input–output functions).

The TEOAE spectra were partitioned into half-octave bands centered at 0.7, 1.0, 1.4, 2.0, 2.8 and 4.0 kHz. A TEOAE was considered to be present in each half-octave band if its amplitude was greater than the noise floor. A DPOAE was considered to be present if its amplitude was greater than two standard deviations above the average noise floor. To enable comparison with TEOAEs, the DPOAEs within each half-octave band (1–4 kHz) were averaged. There were five DPOAE measurements, equally spaced in frequency, in each half-octave averaged frequency band at 1.4– 4 kHz, but only three DPOAEs in the average at 1 kHz. If a DPOAE was not present at a particular frequency, it was not included in the average, and nor did that particular noise floor contribute to the average noise floor. If there were no DPOAEs present in a half-octave band, it was treated as missing data.

Subject subgroups

Subgroups of subjects were selected, as follows, for the analyses reported here (demographics are given in Table 1). To help avoid confusion among the groups, the number of subjects in each group is used as a subscript: $Noise_{69}$, $Quiet_{42}$, $Quiet_{53}$, TTS_{12}, and PTS_{9}.

First, for group analyses, a relatively noise-exposed group ($Noise_{69}$) and a relatively quiet group ($Quiet_{42}$) were selected as follows:

1. For both groups, subjects must have completed at least three annual tests (baseline and at least two annual follow-ups) with noise-free baseline measurements. (The military subjects participated in our study in lieu of their annual hearing conservation test. Some of these subjects had been exposed to noise within 14 h of their test, sometimes even in their baseline year. Subjects exposed in their baseline year were not included if an audiologist considered that the noise exposure was at a level to potentially give a TTS.)
2. For both groups, there must be complete EOAE data sets for both ears of the subject at 2, 3 and 4 kHz for half-octave non-linear TEOAEs (74 dB pSPL) and half-octave averaged DPOAEs (65/45 dB SPL). This subgroup of three frequencies was chosen to maximize the number of subjects with complete data sets. Quantifying missing data for unmeasurable emissions is difficult. If data sets with missing data are eliminated, then some of the most interesting cases are eliminated too. If the noise-floor criterion is substituted indiscriminately for the missing emissions, changes may be detected that are due only to noise-floor fluctuations. Here, unmeasurable emissions were estimated from the noise floor under only some circumstances (see also Lapsley Miller & Marshall (2001a)). If there was no baseline emission, then no change could be measured, so it was treated as missing data. If an emission was present at baseline, but not at follow-up, the follow-up noise-floor criterion was substituted for the unmeasurable emission if it was lower than the baseline *emission* (this may miss some changes or underestimate the magnitude of a change, but allows us to detect more changes than if these data sets were just eliminated); otherwise, the unmeasurable emission was treated as missing data. Estimating missing follow-up emissions, but not estimating missing baseline emissions, may result in a small bias towards finding decreasing emissions. This is because emissions that decrease into the noise floor are accounted for, but emissions that rise out of the noise floor are not.
3. The $Noise_{69}$ group consisted of those subjects who had been exposed to more than 350 h of non-impulse noise or more than 100 rounds of gunfire per year.
4. The $Quiet_{42}$ group consisted of those people exposed to less than 50 h of non-impulse noise and no gunfire per year.

Table 1. Numbers and average ages of male and female subjects in the subgroup of $Noise_{69}$ and $Quiet_{42}$ subjects used for the ANOVA, and the $Quiet_{53}$ subjects used to calculate criteria for significant emission and threshold shifts

Group	*Sex*	*Subjects*	*Age (years) Mean (SD)*
$Noise_{69}$	Female	12	24.5 (5.1)
	Male	57	25.8 (5.9)
$Quiet_{42}$	Female	30	37.1 (7.4)
	Male	12	38.1 (7.2)
$Quiet_{53}$	Female	37	37.8 (7.0)
	Male	16	36.8 (8.1)

Second, a larger group of quiet subjects ($Quiet_{53}$), which included all $Quiet_{42}$ subjects, was used to calculate criteria for significant emission shifts for all EOAE stimulus types (not just the ones reported here). These subjects were selected using criteria 1 and 4 above. They did not need to have complete EOAE data sets.

Third, 12 subjects with confirmed noise-induced TTS and nine subjects with confirmed noise-induced PTS were identified (criteria specified later). Six TTS_{12} and five PTS_{9} subjects were in the $Noise_{69}$ group. One PTS_{9} subject was in the $Quiet_{42}$ group. Some of these subjects had incomplete data sets and some had participated in only 2 years of the study. Given the low numbers of TTS and PTS subjects, all were included regardless of how complete their data sets were. However, they were analyzed only as individual ears, rather than as groups.

Group differences

Six three-way repeated-measures ANOVA (by year, frequency, and ear) were used to ascertain whether there were any changes in hearing thresholds (2, 3 and 4 kHz), DPOAE amplitude (2, 2.8 and 4 kHz), or TEOAE amplitude (2, 2.8 and 4 kHz) over time for the $Noise_{69}$ and $Quiet_{42}$ groups. The two groups were analyzed separately. It was hypothesized that the $Quiet_{42}$ group would show little to no change over time and that the $Noise_{69}$ group would show elevated hearing thresholds and decreased emission amplitudes, especially at higher frequencies. Differences were investigated only between Year 2 and Year 3, because there were very few data for non-linear TEOAEs in Year 1 and only a subset of subjects was tested in Year 4.

Average hearing thresholds for each group, by frequency, year, and ear, are illustrated in Figure 1. (Standard errors of the mean bars are not plotted in Figures 1–3, because they were smaller than the symbols.) Hearing thresholds for both the $Noise_{69}$ and $Quiet_{42}$ groups showed a characteristic noise notch at 6 kHz, perhaps indicating prior noise-induced hearing damage (it could also indicate a selection bias, because subjects were chosen for normal hearing at 2–4 kHz, but not at 6–8 kHz).

The $Quiet_{42}$ group showed no significant changes in hearing thresholds (for frequencies 2, 3 and 4 kHz) on any factor.

Hearing thresholds for $Noise_{69}$ subjects rose by 1.2 dB between Year 2 and Year 3 ($F_{1,68} = 15.3$, $p < 0.05$). There were

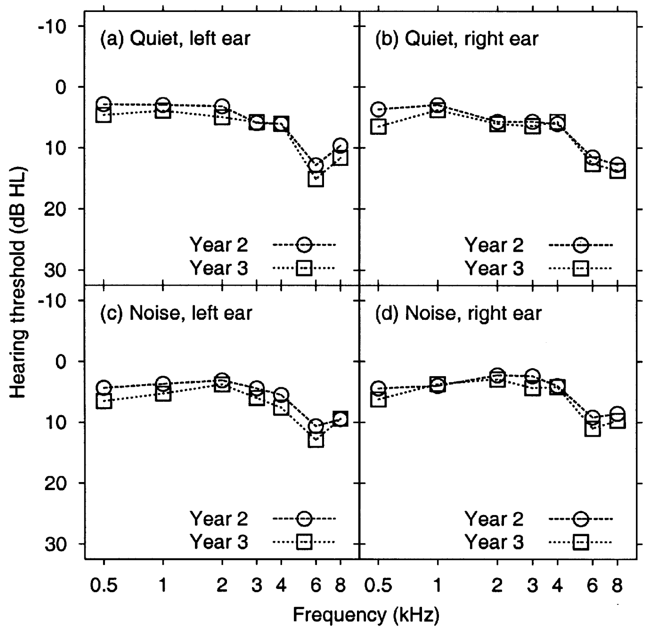

Figure 1. Group average hearing thresholds (dB HL) for the subgroup of *Quiet*$_{42}$ and *Noise*$_{69}$ subjects used in the ANOVA, for Years 2 and 3, for each ear and frequency. Frequency is plotted in $\log_2$ coordinates.

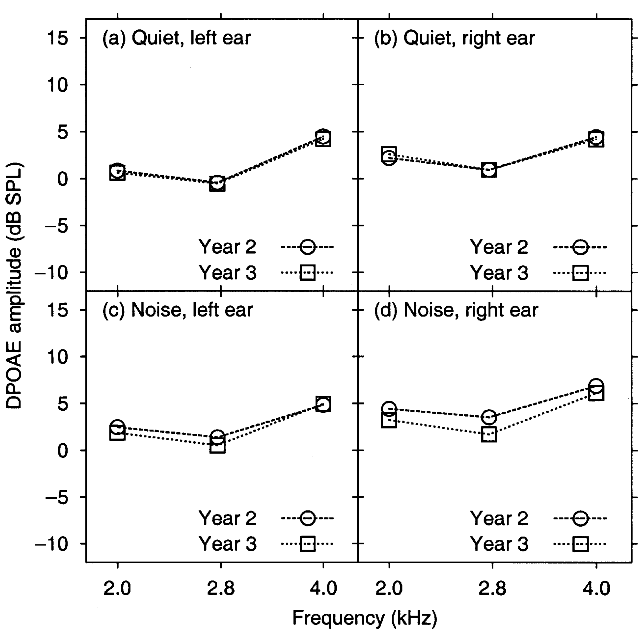

Figure 2. Group average DPOAE amplitudes (dB SPL) for the subgroup of *Quiet*$_{42}$ and *Noise*$_{69}$ subjects used in the ANOVA, for Years 2 and 3, for each ear and frequency. Frequency is plotted in $\log_2$ coordinates.

also significant main effects for frequency ($F_{2,136} = 6.4$, $p < 0.05$) and ear ($F_{1,68} = 13.8$, $p < 0.05$), and a significant three-way interaction ($F_{2,136} = 3.2$, $p < 0.05$). Bonferroni post hoc *t*-test comparisons were done to see which, if any, on-frequency changes between Years 2 and 3 were contributing to the three-way interaction.

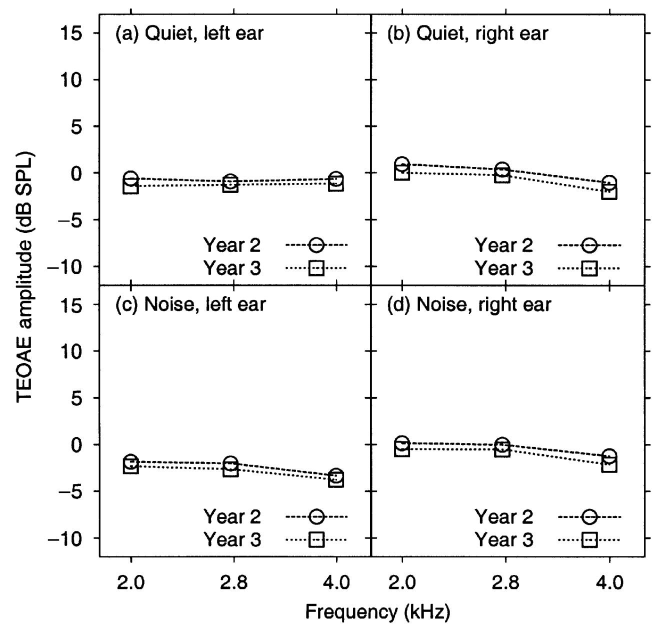

Figure 3. Group average TEOAE amplitudes (dB SPL) for the subgroup of *Quiet*$_{42}$ and *Noise*$_{69}$ subjects used in the ANOVA, for Years 2 and 3, for each ear and frequency. Frequency is plotted in $\log_2$ coordinates.

The family-wise significance level was $p < 0.05$, so the significance level used for each of the six post hoc comparisons (three frequencies and two ears) was $p < 0.0083$. The post hoc tests indicated a significant 2.1-dB increment in the left ear at 4 kHz and a significant 2.0-dB increment at 3 kHz in the right ear.

Average DPOAE amplitudes for 2, 2.8 and 4 kHz for each group, year and ear are illustrated in Figure 2. *Quiet*$_{42}$ subjects showed no DPOAE amplitude changes, but there were significant differences between ears ($F_{1,41} = 5.7$, $p < 0.05$) and among frequencies ($F_{2,82} = 24.3$, $p < 0.05$), and a two-way interaction for ear-by-frequency ($F_{2,82} = 4.3$, $p < 0.05$). In comparison, *Noise*$_{69}$ subjects showed a −0.9-dB decrement in DPOAE amplitude between Year 2 and Year 3 ($F_{1,68} = 14.4$, $p < 0.05$). There were also significant differences among frequencies ($F_{2,136} = 75.3$, $p < 0.05$) and ears ($F_{1,68} = 38.0$, $p < 0.05$), and significant two-way interactions for ear-by-year ($F_{1,68} = 5.8$, $p < 0.05$) and frequency-by-year ($F_{2,136} = 5.4$, $p < 0.05$). Bonferroni post hoc *t*-test comparisons were used to establish which on-frequency changes contributed to the frequency-by-year, two-way interaction. The family-wise significance level was $p < 0.05$, so, for three comparisons, $p < 0.017$ was used. The only significant change was a − 1.3-dB decrement at 2.8 kHz.

Average TEOAE amplitudes for 2, 2.8 and 4 kHz for each group, year and ear are illustrated in Figure 3. *Quiet*$_{42}$ subjects showed a −0.7-dB decrease in TEOAE amplitude between Year 2 and Year 3 ($F_{1,41} = 11.8$, $p < 0.05$). *Noise*$_{69}$ subjects showed a similar decrement in TEOAE amplitude of −0.6 dB, but, unlike the *Quiet*$_{42}$ group, also showed significant main effects for frequency ($F_{2,136} = 6.4$, $p < 0.05$) and ear ($F_{1,68} = 31.5$, $p < 0.05$).

The decrement seen in the *Quiet*$_{42}$ group's TEOAE amplitude between Year 2 and Year 3 may have been due to aging effects in this older group. A three-way, repeated-measures ANOVA was done on a subsample of subjects with similar average age (*Noise*$_{69}$ group, $n = 32$, average age 29.3 years; *Quiet*$_{42}$ group, $n = 20$, average age 31.7 years). A significant effect for year was still found for both groups (*Quiet*$_{42}$ group, $F_{1,19} = 6.4$, $p < 0.05$; *Noise*$_{69}$ group, $F_{1,30} = 18.3$, $p < 0.05$), but the decrement was slightly greater for the *Noise*$_{69}$ group (− 1.0 dB versus − 0.6 dB).

It is also possible that the decrease in TEOAE amplitudes between Year 2 and Year 3 was due to off-frequency changes in hearing that may have affected the older *Quiet*$_{42}$ group more than the younger *Noise*$_{69}$ group (Pearson et al, 1995). Therefore, further three-way repeated-measures ANOVAs were done over all measured hearing thresholds (0.5–8 kHz) for the *Quiet*$_{42}$ and *Noise*$_{69}$ groups. Hearing thresholds for *Quiet*$_{42}$ subjects rose by 1.1 dB between Year 2 and Year 3 ($F_{1,41} = 8.37$, $p < 0.05$). There was also a significant main effect for frequency ($F_{6,246} = 31.6$, $p < 0.05$). There were also significant two-way interactions for frequency-by-ear ($F_{6,246} = 2.4$, $p < 0.05$) and frequency-by-year ($F_{6,246} = 2.4$, $p < 0.05$). Hearing thresholds for *Noise*$_{69}$ subjects rose by 1.3 dB between Year 2 and Year 3 ($F_{1,68} = 21.0$, $p < 0.05$). There were also significant main effects for frequency ($F_{6,408} = 24.3$, $p < 0.05$) and ear ($F_{1,68} = 12.2$, $p < 0.05$), and a significant two-way interaction for frequency-by-year ($F_{6,408} = 2.2$, $p < 0.05$).

The interaction of interest is frequency-by-year, so Bonferroni post hoc *t*-test comparisons were done (separately for the *Noise*$_{69}$ and *Quiet*$_{42}$ groups) to find which, if any, changes between Year 2 and Year 3 were contributing to the interaction. The family-wise significance level was $p < 0.05$ for each ANOVA, so the significance level used for each of the seven post hoc comparisons was $p < 0.007$. None of these comparisons was significant. Nevertheless, because the original ANOVA for hearing thresholds over 2–4 kHz showed no change for the *Quiet*$_{42}$ group, it is likely to be change at higher and/or lower frequencies that contributed to the overall increase in hearing thresholds.

Changes between Year 2 and Year 3 in hearing thresholds (for 2, 3 and 4 kHz) and DPOAEs were consistent with noise exposure, because they were seen only in the *Noise*$_{69}$ group. Changes between Year 2 and Year 3 in hearing thresholds (for 0.5–8 kHz) and TEOAEs, however, were not consistent with noise exposure, because changes were seen in both the *Quiet*$_{42}$ and *Noise*$_{69}$ groups. A different approach is to look at emission shifts in individuals with PTS or TTS. By the use of criteria that compensate for the mean shift in the *Quiet*$_{53}$ group, the relationship, if any, between changes in hearing and EOAEs due to noise may be made clearer.

Significant audiometric and EOAE shifts for individual ears

Although there were small group changes in hearing thresholds and EOAEs over time, hearing conservation programs are ultimately concerned with measuring changes in individuals rather than in groups. Therefore, individuals who had experienced TTS or PTS were identified to see if they had significant changes in their EOAEs that were consistent with the changes in hearing thresholds. These individual cases were identified using a criterion of significance based on the test–retest variability seen in the *Quiet*$_{53}$ group. If an ear had an audiometric or EOAE shift that exceeded this criterion, and if its noise history was consistent with the possibility of damage from noise, then it was concluded that the ear experienced a noise-induced change.

During data collection, a threshold shift was considered significant if it met the Navy hearing-conservation program criteria (Navy Occupational Health and Safety Program, 1999). If a subject had an STS, they were requested to come back for a noise-free follow-up. After the data collection phase was completed, we defined our own criteria, based on the test–retest variability of the *Quiet*$_{53}$ group. The aims were to (1) verify that our reliability was at least as good as that assumed by the Navy criteria, (2) establish STS criteria for 6 and 8 kHz, which tend to be more variable than lower frequencies, and (3) establish STS criteria for the average of 2 and 3 kHz, 3 and 4 kHz, and 2, 3 and 4 kHz.

An STS was defined as an increase (worsening) in hearing threshold that was greater than the group mean *plus* three times the standard error of measurement (SE_{MEAS}) for the *Quiet*$_{53}$ group. Year 2 and Year 3 data from the 106 ears in the Quiet group were used to generate criteria for STSs and significant emission shifts (SESs), because not all emission levels were tested in Year 1. Emissions had to be present in an ear in both years for the data from that ear to contribute to this calculation. For individual ears, the resolutions of the audiogram were 5 dB for single frequencies, and, due to averaging, 2.5 dB for 2–3 kHz and 3–4 kHz, and 1.66 dB for 2–4 kHz. Therefore, each STS criterion was adjusted accordingly by rounding up to the next largest step. Since STS criteria are usually specified as inclusive (i.e. $\geq x$ dB, rather than $> x$ dB), another resolution step was added to give the STS criteria reported in Table 2. The SE_{MEAS} is a within-subjects measure of variability that can be used to specify the magnitude of a statistically significant change within an individual (Ghiselli, 1964). It is defined as $SE_{MEAS} = \sqrt{\frac{1}{2}(s_1^2 + s_2^2)(1 - r)}$ where s_1^2 and s_2^2 are the variances of test 1 and test 2 respectively and r is the correlation between test 1 and test 2. The identification of an STS says only that the shift is statistically unlikely to be due to test–retest variability; it does not convey any further meaning. Interpretation of an STS as a noise-induced PTS or TTS must be done in conjunction with the subject's noise and medical history.

The criteria were set relative to the group mean for consistency with our usage elsewhere (in situations where audiometric results were affected slightly by subjects' practice and motivation). A more lax criterion would identify more shifts, but would also identify many more shifts that are false positive, particularly when considering shifts across a number of frequencies.

Table 2. Significant threshold shift (STS) criteria calculated from the *Quiet*$_{53}$ group (106 ears); shown is the group average threshold shift, the standard error of measurement (SE_{MEAS}), and the resulting STS criteria, for each single- and multiple-frequency band

Frequency (kHz)	*Average shift (dB)*	*SE_{MEAS} (dB)*	*STS (dB)*
0.5	2.1	3.6	20
1	0.7	3.0	15
2	0.9	2.7	15
3	0.2	2.9	15
4	0.0	3.3	15
6	1.1	4.5	20
8	1.2	4.8	25
2–3	0.3	2.1	10
3–4	0.1	2.4	10
2–4	0.4	2.0	8.3

For frequencies from 1 to 4 kHz, an STS was 15 dB. This is consistent with the criteria used in the US Navy hearing conservation program (Navy Occupational Health and Safety Program, 1999). The criterion for the average of 2, 3 and 4 kHz was slightly smaller than that used by the US Navy and Occupational Health and Safety Administration (OSHA), indicating that smaller, wideband shifts could be reliably detected. The larger STS criteria at 0.5, 6 and 8 kHz are possibly due to slight differences in headphone placement from year to year (Shaw, 1966), as well as to subject movement during testing for 0.5 kHz.

All STSs were identified using the STS criteria in Table 2. A shift could occur between any years, not just from the baseline. The audiograms for the shifting ears, including any follow-up audiograms and noise history, were assessed by two audiologists who made a clinical determination as to whether the STS was temporary (13 ears, 12 subjects) or permanent (12 ears, 9 subjects). (There were 108 ears with STSs that remained unclassified because the STS occurred in Year 1 (so there was no baseline for classification), because of inconsistency with noise history, or because of no follow-up audiogram to confirm the shift. Subjects were identified for follow-up using the Navy STS criteria, so subjects who shifted using our post hoc criteria, but not the Navy criteria, did not necessarily have follow-up audiograms.) A shift was considered to be permanent if the STS was maintained at follow-up, and considered to be temporary if the STS recovered to within the STS criterion relative to the baseline level. Table 3 describes each subject with a confirmed shift.

SES criteria were defined as a decrement (worsening) in emission amplitude that was more than the group average *minus* three times the standard error of measurement. SES criteria were calculated for each emission type, level, and frequency (including the multiple-frequency bands: 2–2.8 kHz, 2.8–4 kHz, and 2–4 kHz). Results for DPOAEs (65/45 dB SPL) and non-linear TEOAEs (74 dB pSPL) are presented in Table 4. TEOAEs were consistently more reliable than DPOAEs by 1.6–2.7 dB for the equivalent frequency bands.

Emission shifts for individual PTS and TTS cases

The 12 PTS_9 ears and 13 TTS_{12} ears were examined to find (1) whether an emission shift accompanied the audiometric shift, (2) if it did, whether the shifts were at the same frequencies, (3) whether both TEOAEs and DPOAEs were equally affected or whether one type of emission was more consistent than the other, (4) if any ear had an emission shift prior to the audiometric shift, indicating subclinical changes, (5) if anyone with a TTS had a permanent emission shift (PES), and (6) if ears with no SESs had low or no emissions (that is, an emission shift could not be reliably detected because the baseline emissions were near or below the noise floor). There were not enough cases of PTS and TTS to allow strong conclusions to be drawn about the relationship between audiometric threshold shifts and EOAEs. There were, however, some interesting patterns.

Table 5 summarizes the non-linear TEOAEs (74 dB pSPL) and DPOAEs (65/45 dB SPL) for the 12 PTS_9 ears. Indicated are

Table 3. Summary of PTS_9 and TTS_{12} subjects; shown is subject number, sex, age at enrollment, which ear(s) were affected by the PTS or TTS, usage of hearing protective devices (HPD), and a general description of the subject's noise exposure; for PTS, general usage of HPDs is indicated, while for TTS, HPD usage is indicated only for the most recent noise exposure

Subject	*Sex*	*Age (years)*	*STS*	*Ear*	*HPD usage*	*Description of exposure*
3	F	30	PTS	R	Sometimes	Probably rock concerts
45	M	31	PTS	LR	Never	Submarine engine room, power tools
93	M	45	PTS	L	Sometimes	Ultra-light aircraft, power tools
120	M	22	PTS	R	Never	Drummer in rock band
169	M	19	PTS	L	Yes	Worked on deck of submarine base ship-repair facility
232	M	22	PTS	LR	Never	Amplified car stereo
245	M	31	PTS	L	Never	Primarily sonar (over headphones)
401	M	36	PTS	R	Mostly	Compressors and hand power tools
415	F	37	PTS	LR	Never	Night clubs
83	M	20	TTS	L	No	Probably clubs; possibly kitchen or ship-repair tools/machinery
164	M	35	TTS	R	Yes	Submarine base port authority (tugboats)
243	M	23	TTS	LR	No	Probably clubs
257	M	25	TTS	R	No	Mechanic at submarine base ship-repair facility
260	M	22	TTS	L	No	Carpentry
262	M	24	TTS	R	No	Mechanic at submarine base ship-repair facility
274	M	35	TTS	R	No	Mechanic at submarine base ship-repair facility
277	M	27	TTS	R	Yes	Mechanic at submarine base ship-repair facility
290	M	21	TTS	L	No	Band music at a club
399	F	33	TTS	R	Yes	Wood-chipper
451	F	20	TTS	L	No	Worked on deck of submarine base ship-repair facility
461	F	21	TTS	L	Yes	Worked on deck of submarine base ship-repair facility

Table 4. Significant emission shift (SES) criteria for half-octave DPOAEs (65/45 dB SPL) and non-linear TEOAEs (74 dB pSPL); shown, for each half-octave and multiple-frequency band, is the number of ears going into the calculation (from the $Quiet_{53}$ group), average group difference, SE_{MEAS}, and the resulting SES criteria (defined as the group average minus three times the SE_{MEAS})

Frequency (kHz)	*Number of ears*	*Average shift (dB)*	SE_{MEAS} *(dB)*	*SES (dB)*
Half-octave DPOAE 65/45 dB SPL				
1.0	93	0.61	2.56	−7.07
1.4	99	0.54	2.44	−6.79
2.0	106	0.21	2.12	−6.15
2.8	106	0.14	2.01	−5.89
4.0	103	−0.42	2.24	−7.15
2–2.8	106	0.17	1.86	−5.40
2.8–4	103	−0.19	1.80	−5.58
2–4	103	−0.07	1.66	−5.04
Half-octave non-linear TEOAE 74 dB pSPL				
0.7	83	−0.57	2.34	−7.60
1.0	98	−0.46	2.03	−6.54
1.4	103	−0.35	1.88	−5.98
2.0	100	−0.65	1.81	−6.07
2.8	94	−0.22	1.58	−4.95
4.0	86	−0.48	1.48	−4.92
2–2.8	93	−0.45	1.35	−4.50
2.8–4	84	−0.34	1.13	−3.73
2–4	83	−0.48	1.01	−3.52

emission shifts or low-level emissions concomitant with the PTS. Ears are sorted by the lowest audiometric frequency affected by the PTS. Four PTS_9 ears had associated TEOAE shifts, four had low TEOAE amplitudes or TEOAEs below the noise floor (indicated with an ↓ in Table 5) and the remaining four showed no TEOAE changes. When considering *absolute* emission levels (rather than changes), the noise-floor criterion was substituted for the missing emission, provided that the noise-floor criterion was less than or equal to the 10th percentile of the EOAE responses from the Noise group in the baseline year; thus, a high noise floor could not masquerade as a normal emission level. There were only two ears with DPOAE shifts, and both had TEOAE shifts too. Although TEOAE shifts occurred at the same frequencies as the audiometric shifts, the TEOAE shifts tended to be broader and extended into lower frequencies. The exception was subject 3R. Her PTS was at 6 kHz—higher than that measurable with TEOAEs—so only lower off-frequency changes could be evaluated.

There were no indications of subclinical changes, where an emission shift preceded a PTS and was then maintained or worsened along with the PTS. However, in two PTS_9 ears, some emission shifts were temporary (subjects 3R and 120R).

Table 6 summarizes the non-linear TEOAE (74 dB pSPL) and DPOAE (65/45 dB SPL) emission shifts for the 13 TTS_{12} ears. Six of the 13 TTS_{12} ears had an associated TEOAE shift, four had low TEOAE amplitudes or TEOAEs below the noise floor (defined as for PTS above), and the remaining three had no TEOAE changes. As with PTS, there were fewer DPOAE shifts than TEOAE shifts, and all DPOAE shifts occurred in ears with TEOAE shifts or low TEOAE amplitudes. Curiously, the TTSs occurring across multiple frequencies were more associated with TEOAE change in a single half-octave frequency band, and the higher, single-frequency TTSs were associated with multiple-band TEOAE shifts. All the DPOAE shifts occurred within a half-octave band. TTSs that extended into lower frequencies appeared to be associated with low or no TEOAEs.

There were four TTS_{12} cases with very high EOAE amplitudes (257R, 290L, 399R, and 461L), possibly due to the presence of spontaneous emissions for the last three.

In three cases (243R, 164R, and 399R) there was only partial or no recovery of the SES after a TTS (that is, the emission shift remained significant at follow-up). This lack of recovery may indicate subclinical changes in the inner ear that were yet to affect the audiogram or, possibly, high-frequency PTS that affected the lower-frequency emissions.

Table 5. EOAE summary for the PTS_9 subjects, for their PTS ears only

Ear	*PTS (kHz)*	*TEOAEs*	*DPOAEs*	*Recovery*	*Notes*
415L[a]	2–3	↓			
232R	2–4	<=M		–	
245L	2–6	↓	↓		
232L	2–8	<=M	=M	–	
120R	3	<=>M		Y	TEOAE recovers; hearing does not
415R[a]	3–4	↓			
45R[b]	3–4				
93L[a,b]	3–4				
45L[b]	4				
169L	4	↓		–	Also a TTS and DPOAE TES in previous year
401R	4				
3R[b]	6	<M	<M	Partial	Also a DPOAE TES 2 years previously

Significant emission shifts (SES) in the same year as the audiometric shift are indicated for non-linear TEOAEs (74 dB pSPL) and DPOAEs (65/45 dB SPL). SESs that are the same, lower or higher in frequency to the audiometric shifts are indicated with =, <, or >, respectively, or combinations thereof. 'S' and 'M' indicate if the SES was in only a single half-octave frequency band or spread over multiple bands, respectively. Low-level or no EOAEs in frequency bands matching the PTS frequencies are indicated by ↓. EOAE recovery is indicated with a 'Y,' 'N,' or 'Partial,' if EOAEs were recovered at only some frequencies. – , no follow-up EOAE test to measure recovery.
[a]Year 2 DPOAEs were used as a baseline.
[b]Year 2 TEOAEs were used as a baseline.

Table 6. EOAE summary for the TTS_{12} subjects, for their TTS ears only

Subject and ear	*TTS (kHz)*	*TEOAE SES*	*DPOAE SES*	*EOAE recovery*	*Notes*
243R[a]	2–4	=S		N	Also a TEOAE TES 2 years previously
260L	2–4	↓	↓		Also a DPOAE TES in previous year
262R	2–4	<S		Y	TEOAE TES at 0.7 kHz only
277R	2–4	↓	<S	Y	DPOAE TES may be due to high noise floor
164R	3–4	↓	=S	N	
243L	3–4	<S		Y	Also a TEOAE TES previous year to TTS
274R	3–4	↓	<S ↓	–	
257R	4				Also TEOAE and DPOAE SES in subsequent year
290L	4				
399R	4	<=M	=S	Partial	TEOAE does not recover; DPOAE recovers
83L[b]	6	<M	<S	–	
451L	6				
461L	6	<M		Y	

See Table 5 footnote for notation. Consistency of EOAE recovery with audiometric recovery is indicated where possible.
[a]Year 2 DPOAEs were used as baseline.
[b]Year 2 TEOAEs were used as baseline.

To illustrate how emissions may change with hearing, Figures 4–9 show each test for some of the TTS_{12} and PTS_9 subjects. Shown are the annual audiograms, the DPOAEs (65/45 dB SPL), and the non-linear TEOAEs (74 dB pSPL). Preliminary results for some of these cases have been published elsewhere (Lapsley Miller & Marshall, 2001a,b; Marshall et al, 2001).

Figures 4 and 5 illustrate PTS where EOAEs changed with hearing. Subject 232 (a 22-year-old male) was a machinist's mate in the US Navy, with a history of noise exposure and a slight high-frequency hearing loss in both ears. In Year 3 of the study, he presented with a broadband PTS at 2–8 kHz in his left ear (Figure 4a) and a broadband PTS at 2–4 kHz in his right ear (Figure 5a). DPOAE amplitudes (Figures 4c and 5c) showed broadband decreases in Year 3, but only the shift in the left ear was significant. TEOAE amplitudes (Figures 4b and 5b) also showed significant broadband decreases in Year 3 that extended to lower frequencies than the DPOAEs. The larger change in hearing in the left ear was associated with a larger TEOAE change. Although this subject was noise-exposed at work, he indicated that he consistently wore hearing protection. His hearing loss is more likely to be due to a high-powered car stereo system, which he had installed in his car the year of the PTS.

Figure 6 shows a PTS case with a *temporary* TEOAE shift. Subject 120 (a 22-year-old male) was a drummer in a rock band. He did not wear hearing protection. In Year 3, he showed a 15 dB HL shift at 3 kHz in his right ear. The subject indicated that he had been noise-exposed the previous day, but because the shift was maintained in Year 4, the shift was classified as PTS (Figure 6a). There was no change in DPOAE level (Figure 6c). TEOAEs, on the other hand, showed a significant broadband shift in Year 3, which had recovered by Year 4 (Figure 6b). A group of spontaneous emissions below 1.5 kHz in his right ear were also eliminated in Year 3, but returned in Year 4. The loss of the spontaneous emissions may also explain why the TEOAE shift was larger at lower frequencies. Why did TEOAEs and SOAEs recover? The most parsimonious explanation may be that poor audiometric reliability hid the true state of his hearing and that reliability was better for the emission measurements. If this was the case, we would conclude that in Year 3 he had a temporary noise-induced inner ear change, possibly with an associated TTS, consistent with his noise history.

Figure 7 shows a TTS case where EOAEs changed with hearing. Subject 461 (a 21-year-old female) was a seaman in the US Navy. She worked in a naval ship-repair facility where she was exposed to noise from needle guns, sanders, grinders, hydroblasters, and other noisy tools and machinery, but she indicated that she always wore hearing protection. She had normal hearing in her baseline year (Figure 7a). At her second annual test, she showed an STS at 6 kHz in her left ear. She indicated that she had been recently exposed to noise, but because the STS was outside the monitoring frequencies for the Navy, follow-up testing was not done at that time. The STS was most likely a noise-induced TTS, because in Year 3 the shift had resolved back to baseline. Her TEOAEs also shifted significantly in Year 2 and resolved in Year 3 (Figure 7b). Unlike the audiogram, however, the emission shift spread over multiple frequency bands. Her DPOAEs did not show any significant shifts (Figure 7c). Neither the TEOAE nor the DPOAE measurements extend to 6 kHz, so it is unknown whether there are EOAE changes at the same frequency as the audiometric shift.

Figure 8 shows a high-frequency TTS with accompanying TEOAE and DPOAE shifts. Subject 83 (a 20-year-old male) was a cook. He also reported being on the deck of a ship-repair facility without hearing protection for approximately 10 min per day. Outside of work hours, he attended dance clubs one to two times a week for approximately 4 h each time. He did not regularly wear hearing protection. In Year 3 of the study, he showed a 30-dB TTS at 6 kHz (Figure 8a), which had recovered by the next day (recovery not plotted here). Accompanying the TTS was a significant decrease in TEOAE level across most frequencies (Figure 8b) and a significant decrease in DPOAE level at 4 kHz (Figure 8c). Emissions were not tested at the noise-free follow-up, so it is unknown if the EOAE shifts were temporary or permanent.

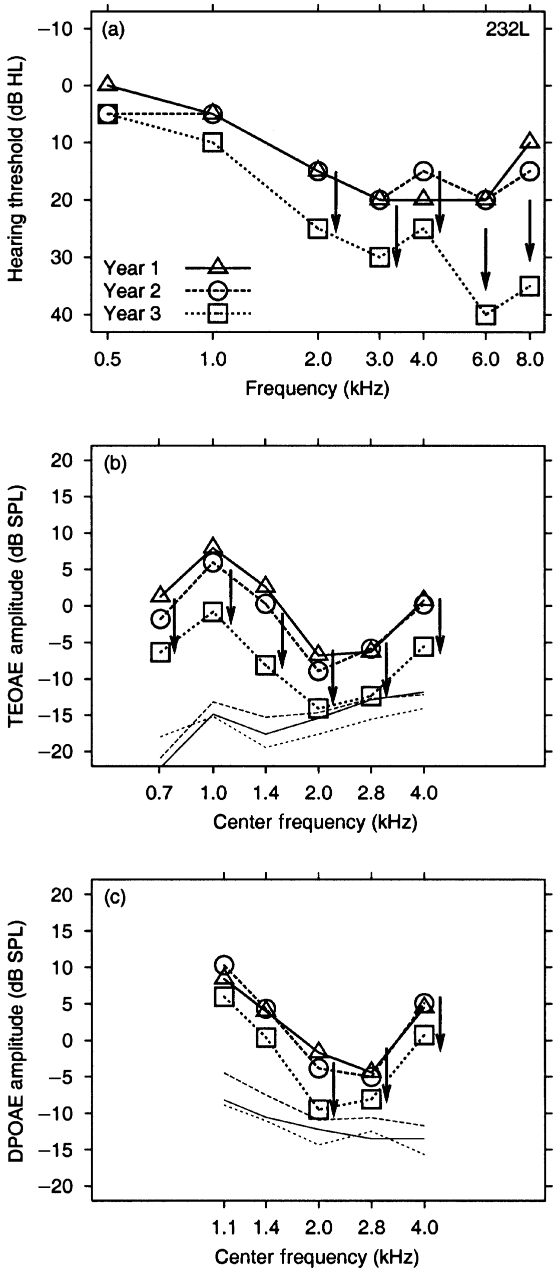

Figure 4. Subject 232, left ear. PTS where EOAEs changed with hearing. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

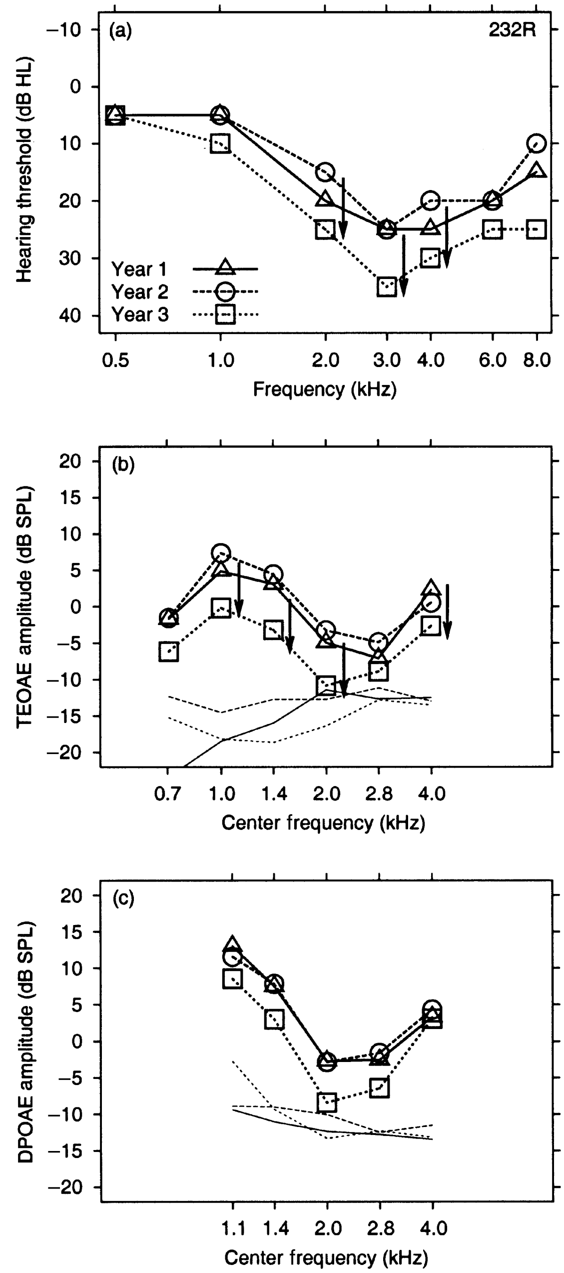

Figure 5. Subject 232, right ear. PTS where EOAEs changed with hearing. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

Figure 9 illustrates a possible subclinical case where hearing recovered but emissions remained diminished. Three weeks before her Year 3 test, subject 399 (a 33-year-old female) was exposed to noise from a wood-chipper for over 6 h. She presented with an STS of 15 dB at 4 kHz, which resolved by Year 4 (Figure 9a). Although her audiogram did not indicate any permanent damage, her TEOAEs showed a significant broadband shift, which had not recovered by Year 4 (Figure 9b). DPOAEs did not show any significant change (Figure 9c).

Discussion

The $Noise_{69}$ group showed increased hearing thresholds (1.2 dB) and decreased DPOAE amplitude (−1.3 dB), when analyzed between 2 and 4 kHz. No change over time was seen in the $Quiet_{53}$ group. These results are consistent with the effects of noise exposure.

TEOAEs analyzed between 2 and 4 kHz and hearing thresholds analyzed between 0.5 and 8 kHz, on the other hand,

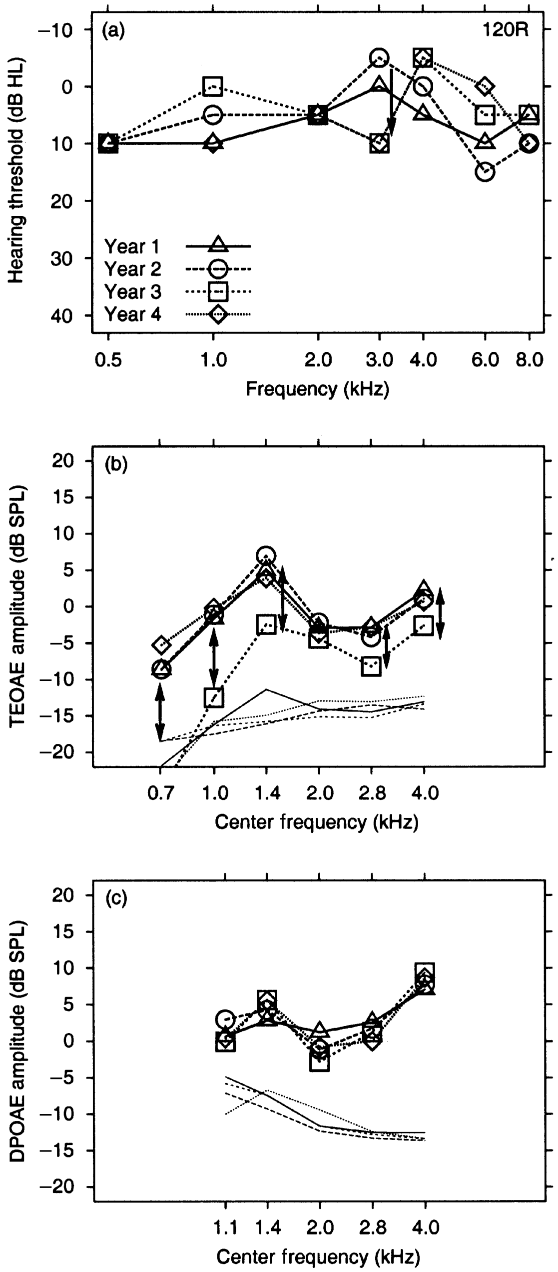

Figure 6. Subject 120, right ear. PTS where emissions recovered but hearing did not. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

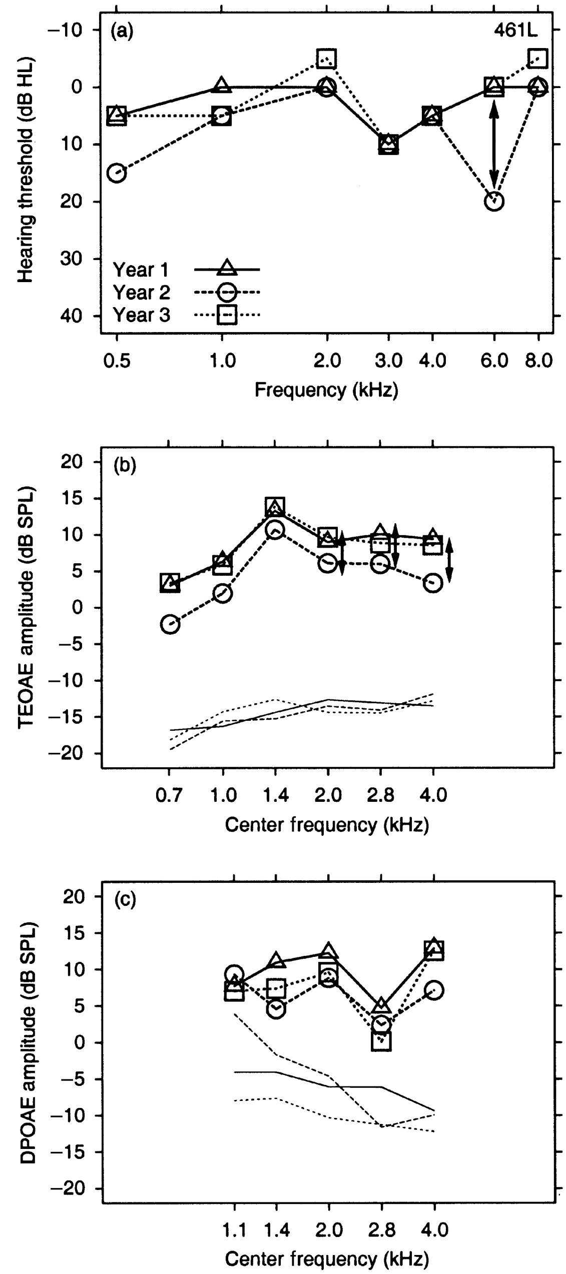

Figure 7. Subject 461, left ear. TTS where EOAEs changed with hearing. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

showed similar changes for both the $Quiet_{42}$ and $Noise_{69}$ groups. The decrease in TEOAE amplitude between 2 and 4 kHz was −0.6 to −0.7 dB, and the increase in hearing thresholds between 0.5 and 8 kHz was just over 1 dB. Because the magnitude of this change was similar for both the $Quiet_{42}$ and $Noise_{69}$ groups, it was not necessarily noise-induced, and was perhaps due to normal aging processes.

It is difficult to put an absolute number on the expected rate of change in hearing or EOAEs in 1 year, especially for a group with a wide age range and variation in noise-exposure history. However, longitudinal hearing changes reported from large population studies indicate that although a change in hearing of 1 dB in 1 year might be large, statistically it would not be unexpected (e.g. Pearson et al, 1995; Spoor, 1967, Fig. 17.4). Estimates of longitudinal changes are highly variable (Pearson et al, 1995), so generalizations must be made cautiously.

Less is known about age-related changes of DPOAEs and TEOAEs. Dorn et al (1998) considered age-related, cross-sectional changes in DPOAEs (65/55 dB SPL). They found that, even among normal-hearing ears, DPOAEs decreased with age.

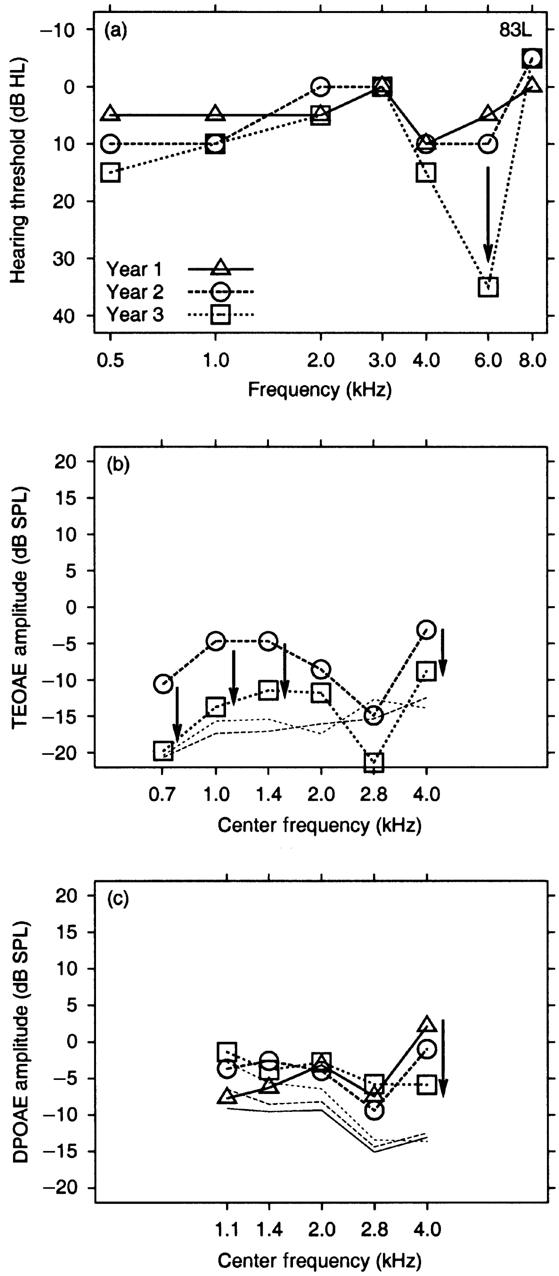

Figure 8. Subject 83, left ear. High-frequency TTS. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

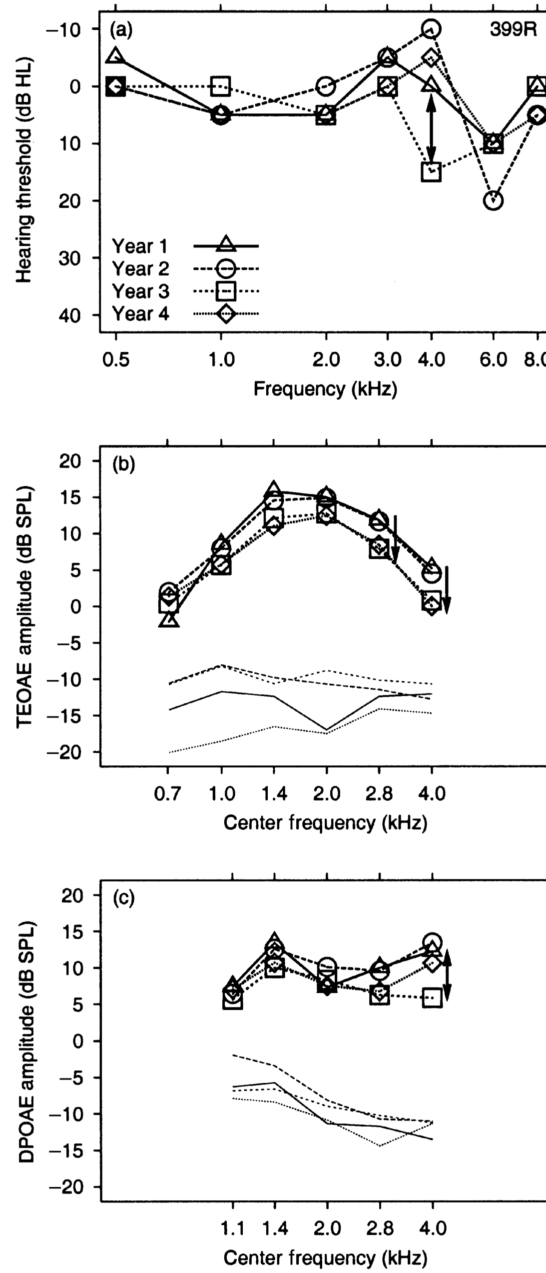

Figure 9. Subject 399, right ear. TTS and possible subclinical damage, where EOAEs did not recover with hearing. (a) Hearing thresholds. (b) TEOAEs (74 dB pSPL). (c) DPOAEs (65/45 dB SPL). Arrows indicate significant shifts. Lines without symbols indicate the noise floor.

The rate of change for 40-year-olds was about −1 to −3 dB per decade, at 3 and 4 kHz (estimated from their Figure 4). It is unlikely that this rate of change could be detected in 1 year. Engdahl (2002) also showed age and sex differences in TEOAEs and DPOAEs for a large unscreened population, but again the rates of change shown would not be easily detectable in 1 year. Murray & LePage (1993), however, considered age-related cross-sectional change in TEOAEs (using an 80 dB pSPL non-linear click) and found two periods of decline. The first decline occurred in the first 15 years, and the second decline, of about −4.2 dB per decade, occurred after 45 years of age. This is close to the amount of change seen here over 1 year. It is difficult to directly compare this estimate with the current study, because the stimulus used here was 6 dB lower, and there were too few subjects in each age bracket for a direct comparison. However, 26% of the $Quiet_{42}$ group subjects in the ANOVA were over 45 years old in Year 2 or Year 3 of the study, so age-related changes cannot be dismissed (no $Noise_{69}$ group subjects were over 45 years old).

It is not age per se that is the issue, but aging-related high-frequency hearing loss (higher than what was measured in this study), which may or may not be related to noise exposure. It is possible that an increase in high-frequency hearing thresholds may have been enough to produce a broadband TEOAE change due to non-linear interactions across frequency (see below). This could also explain why the more frequency-specific DPOAE did not show any change for the $Quiet_{42}$ group. Although there is some evidence that DPOAEs are also affected by high-frequency audiometric changes (Arnold et al, 1999; Dorn et al, 1999), the amount of change in hearing threshold may not have been enough to cause a detectable change in DPOAE amplitude (Arnold et al, 1999).

Both aging and noise exposure could result in high-frequency hearing loss. It is possible that the older, $Quiet_{42}$ group (71% women) showed age-related changes in hearing and EOAEs, and the younger, $Noise_{69}$ group (83% men) showed noise-related changes. The second TEOAE ANOVA, which used a subset of subjects with similar average age, still showed decrements in TEOAE amplitude over time for both the $Quiet_{42}$ and $Noise_{69}$ groups (however, the $Noise_{69}$ group showed a slightly larger decrement). Although some of the change may be attributable to the difference in noise exposure between the two groups, there is still some factor, aside from noise, affecting both groups.

Hotz et al (1993) and Radomskij et al (2002) also found group TEOAE decrements after noise exposure, but the magnitude of change was -1.8 to -3.2 dB, which was much larger than the -0.6 to -0.7 dB seen here. Is it possible that their changes were age-related? Hotz et al studied young males for only 17 weeks. Radomskij et al studied people before and after an MRI. Neither study followed subjects for long enough for aging to have been a factor. Sliwinska-Kowalska & Kotylo (2001), on the other hand, followed a group of quiet workers and two groups of noise-exposed workers for 2 years. The amount of TEOAE amplitude change varied with noise exposure, with the more noise-exposed group showing more TEOAE change. However, the magnitude of the change and the differences in age and sex across the groups were not reported, so the effects of age, which may vary by sex, cannot be discounted.

When considering the 25 individual ears with TTS and PTS, there were more TEOAE shifts than DPOAE shifts, and all DPOAE shifts occurred with TEOAE shifts or low-amplitude TEOAEs. This may indicate that the TEOAEs are more sensitive indicators of noise-induced inner ear changes compared with the DPOAEs. Although DPOAEs are thought to have better frequency specificity, DPOAEs measured at single frequencies were more variable than those averaged across frequency. This variability may be decreased by measuring DPOAEs at more closely spaced frequencies to enable averaging within a frequency band, but still maintaining some frequency specificity. Doing so may decrease their variability and make them more comparable to half-octave TEOAEs, but there is not usually enough time available in a hearing conservation program for this to be practical. The DPOAEs may also have been more variable than the TEOAEs because DPOAEs, as implemented on the Otodynamics equipment, sometimes give results that appear to be artefactual. These spuriously high amplitudes may have increased test–retest variability, thereby making true DPOAE shifts harder to detect. Theoretically, both non-linear TEOAEs and DPOAEs consist of linear-coherent-reflection and intermodulation-distortion components (Shera & Guinan, 1999). At the levels used in this experiment, TEOAEs may have consisted of proportionally more linear-coherent-reflection components than the DPOAEs. If the linear-coherent-reflection component is more sensitive to outer hair cell damage, this may explain why TEOAEs were more consistent with changes in hearing.

For both TTS and PTS, TEOAEs tended to show a broader shift than DPOAEs, and extended into lower frequencies than the hearing threshold shift. Several studies have shown that noise-induced changes in TEOAEs tend to affect the entire TEOAE spectrum (Avan et al, 1995, 1997; Yates & Withnell, 1999). In particular, high-frequency-damage hearing loss tends to affect lower-frequency TEOAEs. Avan et al (1995) suggested that the damage caused by high-frequency hearing loss affects the propagation of the emission because it needs to travel over the damaged region of the cochlea.

An alternative explanation is provided by Withnell et al (2000) and Yates & Withnell (1999). Although TEOAE information is recorded across a band of approximately 0.5–5 kHz, the information in each band does not necessarily map one-to-one with the evoking stimulus, due to intermodulation distortion (where the non-linear distortion interacts with other frequencies). Changes in inner ear status at higher frequencies may therefore affect lower frequencies. If a high-frequency region is damaged, then not only are the on-frequency emissions diminished, but also the intermodulation-distortion components. These components interact constructively and destructively over a wide range of frequencies, and, if removed, they could cause the TEOAE spectrum to decrease. Yates and Withnell argued that, although Avan et al (1997) were careful not to overlap the high-frequency loss with the TEOAE spectrum, there were still significant TEOAE stimulus components at high frequencies. (Measurements made by Yates & Withnell (1999) with the ILO system showed that the clicks actually roll off at around 8–10 kHz, although the display only goes up to 6 kHz. Measurements made by Mimosa Acoustics (personal communication), however, show that the ILO TEOAE click-stimulus spectrum rolls off at around 5 kHz, so it is unclear what Yates and Withnell consider to be 'significant components'.) Therefore, the findings of Avan et al may not necessarily imply a problem with EOAE propagation. The current study supports the observation that TEOAE changes tend to be broadband, but the results do not provide evidence supporting one explanation over another.

It is difficult to establish that changes in EOAEs are precursors to changes in hearing, because it takes multiple measurements over a number of years in many subjects to see enough cases. Here, there were no cases of permanent changes in EOAEs preceding a permanent change in hearing. However, there were two cases where there was a temporary change in hearing but a permanent change in EOAEs. Many more cases of PTS development are needed, where hearing and EOAEs are tracked over time, to establish what information EOAEs can give us about the status of the inner ear prior to permanent hearing loss. Because it can take many years to develop NIHL, large-scale, long-term longitudinal studies will ultimately be required to obtain a full understanding of the relationship between EOAEs and NIHL.

EOAEs may be better for detecting inner ear changes due to noise than the audiogram, because they represent a more direct measurement of inner ear processes. The audiogram, on the other hand, assesses the entire auditory system and is dependent on a behavioral response from the subject. The 5-dB step size used in clinical audiometry, along with test–retest variability, means that small changes in hearing thresholds, which would be measurable in a laboratory setting (e.g. using a smaller step size and forced-choice psychophysical procedures), are missed. Furthermore, changes in EOAEs may reflect changes in the inner ear long before they affect hearing. For instance, LePage (1998) has put forward a theory that there is outer hair cell redundancy such that only a few cells are needed for hearing at threshold. Thus, smaller amounts of outer hair cell damage do not show up on an audiogram. The TEOAE stimulus, on the other hand, is thought to stimulate all the outer hair cells. If there is damage to some of these cells, this will show up as diminished TEOAE amplitude. Large-scale studies have shown a wide range of emission levels for a small band of hearing thresholds, which LePage interpreted as evidence supporting the redundancy theory. This theory can only be borne out, however, if the same ears are followed over time to see if low emissions are predictive of subsequent hearing loss. If EOAEs are more sensitive to the early stages of NIHL, they may be useful as a clinical indicator of NIHL susceptibility.

The current study did not show a strong relationship between changes in the audiogram and changes in EOAEs. This may be because hearing thresholds obtained through clinical audiometry are inherently unreliable—a big change in hearing threshold is needed before it can be distinguished from test–retest variability. On the other hand, changes in EOAEs may not directly relate to changes in hearing threshold. LePage et al (1993) suggested that the audiogram measures to what extent the cochlea can maintain normal performance *despite* damage to the outer hair cells. Using the audiogram as the gold standard with regard to whether EOAEs are sensitive to noise-induced changes may be inappropriate.

The lower-level non-linear TEOAEs appeared to give the most useful information about inner ear status. They had the highest test–retest reliability and least artefact of the EOAE types considered here. The proportion of measurable emissions was slightly lower than for DPOAEs, but this could perhaps be partially ameliorated by taking more averages to lower the noise floor. In individuals with TTS and PTS, non-linear TEOAEs were more likely than DPOAEs to show a change consistent with the hearing change, but they had less frequency specificity. TEOAEs were possibly more sensitive to high-frequency hearing changes (either from aging or noise exposure), and this should be investigated further.

NIHL is usually a slow, insidious process. Although our noise-exposed population did show some NIHL, there were not enough individual cases of TTS or PTS to clearly establish how changes in EOAEs relate to noise-induced hearing threshold changes. To remedy this, research needs to (1) focus on groups who are exposed to noise that is more uniform in quantity, duration, level, and spectrum, and sufficient to cause hearing loss in a shorter time, or (2) study many more people over a much longer time. Furthermore, sex, age and high-frequency hearing status should be taken into account when possible.

For EOAEs to be useful in hearing conservation programs, they need to have good validity, reliability, and measurability. Furthermore, they need to be demonstrated to correlate with NIHL and/or be predictive of subsequent NIHL in individuals. Of the EOAE types examined here, no one type stood out as possessing all of these characteristics. Therefore, we must conclude that these EOAEs are not yet suitable for use in hearing conservation programs for monitoring individuals. The use of EOAEs in hearing conservation programs shows promise, but much more needs to be established about the relationship between EOAEs and hearing before EOAEs can be used to differentially diagnose and monitor noise-induced changes in *individuals*.

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