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A Comparison of Baseline Hearing Thresholds Between Pilots and Non-Pilots and the Effects of Engine Noise

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16. Abstract

Observations in simulator studies suggested that the older segments of the general aviation pilot population were having difficulty hearing specific auditory warnings in the cockpit. These observations, in combination with data from Tobias (1968a; 1968b; 1972), prompted a reexamination of the hearing capabilities of pilots and non-pilots. In Phase 1, threshold data were collected for 150 non-pilots and 150 pilots using stratified age sampling. The usual higher-frequency decrements attributable to aging and general environmental exposure were found in both samples. Significant differences were found between the non-pilot and pilot samples, with greater threshold shifts between 2 and 6 kHz in evidence among the pilots. In Phase 2, participants' thresholds were measured during both a quiet condition and during exposure to simulated aircraft engine noise. Results of both phases are discussed in terms of implications for the design of auditory warnings for general aviation aircraft.

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A Comparison of Baseline Hearing Thresholds Between Pilots and Non-Pilots and the Effects of Engine Noise

BACKGROUND

Several events of recent years have motivated a reexamination of noise levels in general aviation (GA) aircraft cockpits. First, the failure of the noise-canceling system onboard *Voyager* early during its record-setting non-stop, around-the-world flight, which resulted in significant hearing impairment to both pilots, suggested that noise was still very much an issue in piston-powered aircraft. Second, the continuing development and use of noise-canceling systems, both as contained in headsets and as installed in aircraft cockpits, indicated that noise was indeed of interest to the GA community. Third, we observed, in simulator studies, that some of the older pilots in our samples had difficulty hearing certain auditory warnings during our autopilot failure research (Beringer & Harris, 1997). Thus, a program was initiated to examine both the current hearing capabilities of pilots and non-pilots, and developments in auditory warning design that might serve to provide more distinct and detectable alerts for the pilot.

Tobias (1968a, 1968b) examined noise levels in 15 single-engine GA aircraft, which were representative of the models then being manufactured, and 11 light twin-engine aircraft. Findings were similar in both cases, with the two major sources of cockpit noise — engine sounds and exhaust resonance — producing the majority of the noise in the range of 50 to 250 Hz. There was no evidence of hazardous single-frequency components. However, there were places in the frequency distribution that exceeded the OSHA-specified two- and eight-hour exposure limits. In particular, two-hour limits were exceeded at various points between 100 and 1.6 kHz, with a 112 dB peak around 80 to 100 Hz. Eight-hour exposure limits were exceeded at various points from 100 Hz to 2 kHz. The upper end of this distribution is well into the area of speech sounds and thus could be problematic.

Tobias (1972) further examined the effects of noise on aircrew personnel to determine what effects, if any, this exposure was having on their hearing thresholds. Of all the groups measured (aerial applications pilots, flight instructors, older private pilots - 40 to 58 years of age - FAA flight inspectors, and flight attendants) only the private pilots failed to evidence significantly elevated thresholds or localized "dips" of 15 dB or more in their threshold curves. For most of the samples, then, the predicted effects of exposure to ambient cockpit noise levels were confirmed in elevated thresholds at various points along the frequency continuum.

A two-phase study was designed (1) to obtain current threshold data and determine the relationship between the pilot and non-pilot populations and (2) to examine the effects of cockpit (engine) noise on the hearing thresholds of pilots.

PHASE 1

Method

Phase 1 research was designed to assess the present state of hearing capabilities in samples of both pilots and non-pilots. Toward this end, 150 pilots and 150 non-pilots, stratified by 10 age groups with 15 participants per group, were tested to determine their hearing abilities by measuring their detection thresholds at a series of selected frequencies (0.5, 1, 2, 3, 4, 6, and 8 kHz). A standard, computer-based testing paradigm for audiometric assessment was used to obtain the data. Participants were initially tested in a sound-attenuating booth, and the test tones were presented through headphones. This process produced left- and right-ear threshold curves for each participant.

Results

Prior to analysis, all threshold measures were examined to validate accuracy of data entry, check for outliers, check for missing values, and assess the fit between distributions and the assumptions of analysis of variance (ANOVA). There were no missing values or outliers, nor were there any violations of the homogeneity of variance assumption.

Separate ANOVAs, which were executed using the SPSS General Linear Models procedure, were used to analyze the data for left and right ears. Each ANOVA consisted of a three-way, mixed-factor design. Age and Pilot Status were treated as between-subjects variables, and Test Frequency was treated as a within-subjects variable. The levels of these independent variables were as follows:

- **Age.** 10 levels: (22 and younger, 23-27, 28-32, 33-37, 38-42, 43-47, 48-52, 53-57, 58-62, and 63 and older)
- **Pilot Status.** 2 levels: (pilot, non-pilot)
- **Test Frequency.** 7 levels: (0.5, 1, 2, 3, 4, 6, and 8 kHz)

Figure 1 presents data, adapted from the results of research by Peterson and Gross (1972), that were collected at approximately the same time as the data on air crew personnel referenced earlier (Tobias, 1972). The Peterson, et al., data appear to resemble that from the present non-pilot sample, whose data are presented in Figures 2 and 3. Both figures illustrate the expected threshold shifts in the higher frequencies associated with age and, of course, longer periods of environmental exposure.

The first set of statistical evaluations centered on the mean detection threshold curves and a comparison of non-pilots and pilots. Mean threshold values for the pilots are shown in Figures 4 and 5. The ANOVA for the left ear yielded a statistically significant three-way interaction of pilot status by test frequency by age, $F(54, 1680)=1.35$, $p < .05$. The two-way interactions of pilot status (pilot/non-pilot) by test frequency, $F(6, 1680)=4.48$, $p<.001$, and age by test frequency, $F(54, 1680)=11.8$, $p<.001$, also were statistically significant, as was the main effect of test frequency, $F(6, 1680)=265.17$, $p<.001$. The ANOVA for the right ear produced statistically significant two-way interactions for both pilot status by test frequency, $F(6, 1680)=2.85$, $p<.01$, and age by test frequency, $F(54, 1680)=9.52$, $p<.001$. There was also a main effect for test frequency, $F(6, 1680) =176.65$, $p<.001$. The higher detection thresholds for the left ear were not surprising as the exposure to noise of this ear is greater by reason of seating arrangement and other cockpit variables, particularly in twin-engine aircraft.

One can compare equivalent age groups of pilots and non-pilots by specific frequencies through examination of the paired figures (2, 4) and (3,5). Closer examination of these average threshold curves indicated that differences between the pilots and non-pilots were not revealed until age group 43-47, where the thresholds were slightly though not significantly elevated for the pilots. Much larger differences in mean thresholds were seen at 3, 4, 6, and 8 kHz test frequencies for the 48-52 age groups. The differences at the 4, 6, and 8 kHz test frequencies were even greater for the 58-62 age groups. Interestingly, pilots in the 48-52 age group have an average threshold curve that looks remarkably similar to that of the 43-47 age group of non-pilots. The two oldest non-pilot age groups are clearly differentiable in Figure 2, whereas in Figure 4 the average threshold curves for the two oldest pilot age groups are not that different.

Pearson correlation coefficients (r) were calculated to determine the relationship between total hours of flight time for pilots and detection thresholds at the various test frequencies. Total hours of flight time correlated significantly with detection thresholds for the 3 (r=.27, r=.21), 4 (r=.32, r=.23), 6 (r=.34, r=.24), and 8 (r=.34, r=.29) kHz test frequencies in both the left and right ears, respectively. Additionally, a significant correlation was revealed for the left ear at 2 kHz (r=.25). Correlation coefficients were also calculated to determine the relationship between detection thresholds for the different age groups and total hours of flight time. The highest correlation between detection thresholds and total hours of flight time was obtained for the 48-52 age group (r=.34).

The second form of evaluation involved an examination of individual pilot threshold curves. Of particular interest was a comparison of our data with Tobias' (1972) data, which estimated the percentage of the pilot population that could be categorized as exhibiting a significant shift, or "dip," in their threshold curve. Tobias (1972) found that 20% of his sample, or 3 of 15 private pilots from the ages of 40-58, demonstrated a significant threshold shift, which he defined as a localized 15-dB shift from the smoothed/extended threshold curve. In our sample, 89% of the private pilots (25 of 28) in the same age range demonstrated a significant threshold shift by Tobias' definition.

Discussion

That the present sample showed a much larger proportion of private pilots with significant localized shifts in their hearing thresholds than was found by Tobias (1972) is of some concern. The explanation of this difference is complicated by history variables, including individual exposure and its moderators. The statistically significant effects underscore the reliability of the detected trends, and none are counter to what one would normally expect as a function of aging and exposure. Interestingly, there is little direct evidence of impairment in the lower frequencies given that the primary components of aircraft cockpit noise are between 50 and 250 Hz. However, generalization of the present results to lower frequencies (i.e., 50-250 Hz) may be limited because the lowest test frequency measured thresholds at 500 Hz. Losses of approximately 45 dB at 3 kHz for the oldest pilot group reinforce the subjective and verbal-report data from previous simulator studies where warning tones between 2.5 and 3 kHz could not be heard.

It should also be noted that the 58-62 age group in the nonpilot sample exhibited an average shift of about 40 dB at 8 kHz, whereas Peterson's data indicated a shift of about 30 dB for those aged 60. One should also consider, then, the possibility of an increase in general noise exposure over the intervening 26 years as a contributor to these additional threshold shifts. Whatever the contributing factors to the underlying thresholds, the use of pure-tone warnings must take into account the high-frequency loss that appears to be exacerbated by exposure to the GA cockpit environment. A second assessment was conducted with a limited sample to determine to what extent the introduction of engine noise further elevated hearing thresholds.

PHASE 2

Method

Phase 2 experimentation was designed to evaluate threshold shifts present during engine noise and when wearing headphones. Data collection was conducted in the medical clinic's sound booth where the Phase 1 measurement of hearing thresholds was performed. The procedure was the same with the exception that engine noise (digitized Piper Malibu engine sound from cruise flight) was presented at a level comparable to that present in GA cockpits (Tobias, 1968a,b). Specifications of the headphones worn by the participants indicated an attenuation effect of 21 decibels. The participants were 15 pilots from Phase 1.

Results

Pilots who returned for the noise-environment assessment fell into three age groups; 19-22 (n=4), 28-32 (n=5), and 38-42 (n=6). Figure 6 shows the average threshold shift as measured in the left ear, by frequency, for each of these three groups. The values that are shown are the means of the differences between each participant's baseline thresholds and the thresholds as measured in the noise environment. Averaged across groups, the highest positive shifts in the left ear appear from 2KHz down, which is consistent with Tobias' data showing that the preponderance of engine sounds falls into the range of 50 to 250 Hz with some components as high as 2 kHz. The shifts at 500 Hz, the value closest to the majority of engine sounds, can be seen to range from 10 dB for the 38 to 42 age group to as high as almost 19 dB for the 22 and younger group. It is consistent with expectations that the two older groups show a more-or-less steady decline in threshold shift as the test points move farther away from the noise range.

Figure 7 presents the data for the right ear, and the data are not dissimilar to those in Figure 6. The one feature of particular interest may be that the smallest threshold shifts in the youngest age group occur at 2 and 3 kHz, with elevated shifts to *either* side of those frequencies. This is unlike the data seen in the other two age groups, but should be approached with some caution due to the small sample size.

If we think of engine noise acting somewhat like a filter through masking, then we need to look at the range of frequencies key to the interpretation of speech (1 to 3 KHz). It is worth noting that the threshold for the lower end of what is considered the "voice" spectrum, around 500 Hz, exhibits a considerable shift, with a comparable shift seen at 1 KHz. The effect is somewhat diminished by the time we look at 2 KHz, and the threshold shift is minimal at 3 KHz. These data suggest that there is considerable opportunity for interference with speech comprehension.

SUMMARY

Auditory warning design is influenced not only by the ambient noise environment but also by the signal-detection capabilities of the system operator. The data obtained in this research suggest that we should proceed in several areas to improve the utility of auditory warnings and to conserve hearing ability in GA pilots. The data clearly suggest that continued promotion and proper use of hearing protection devices are in order given the threshold shifts revealed in the present data, both to prevent further hearing loss in the pilot population and to promote the comprehension of speech and other aurally presented alerts and warnings. It is also clear that the selection of auditory warning signals should take into consideration the specific points along the frequency spectrum where large threshold shifts can be seen. Present recommendations include:

- Avoid the use of pure-tone warnings at or near 3 KHz
- Promote use of clearly differentiable warning signals
- Promote use of signals easily detected by older pilots without overwhelming other auditory information
- Promote use of hearing protection devices, passive and/or active

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[1]This publication and all Office of Aerospace Medicine technical reports are available in full-text from the Civil Aerospace Medical Institute's publications Web site: http://www.cami.jccbi.gov/aam-400A/index.html

FIGURES

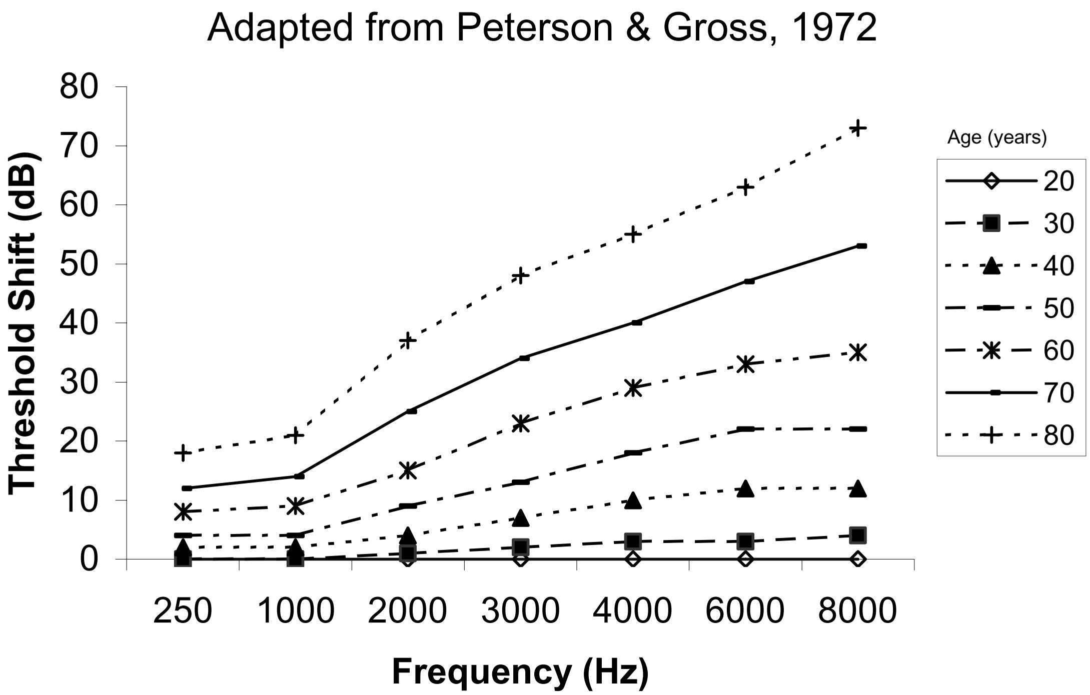

Figure 1. Non-pilot threshold shifts for male subjects from the general population by age group and frequency (adapted from data in Peterson & Gross, 1972).

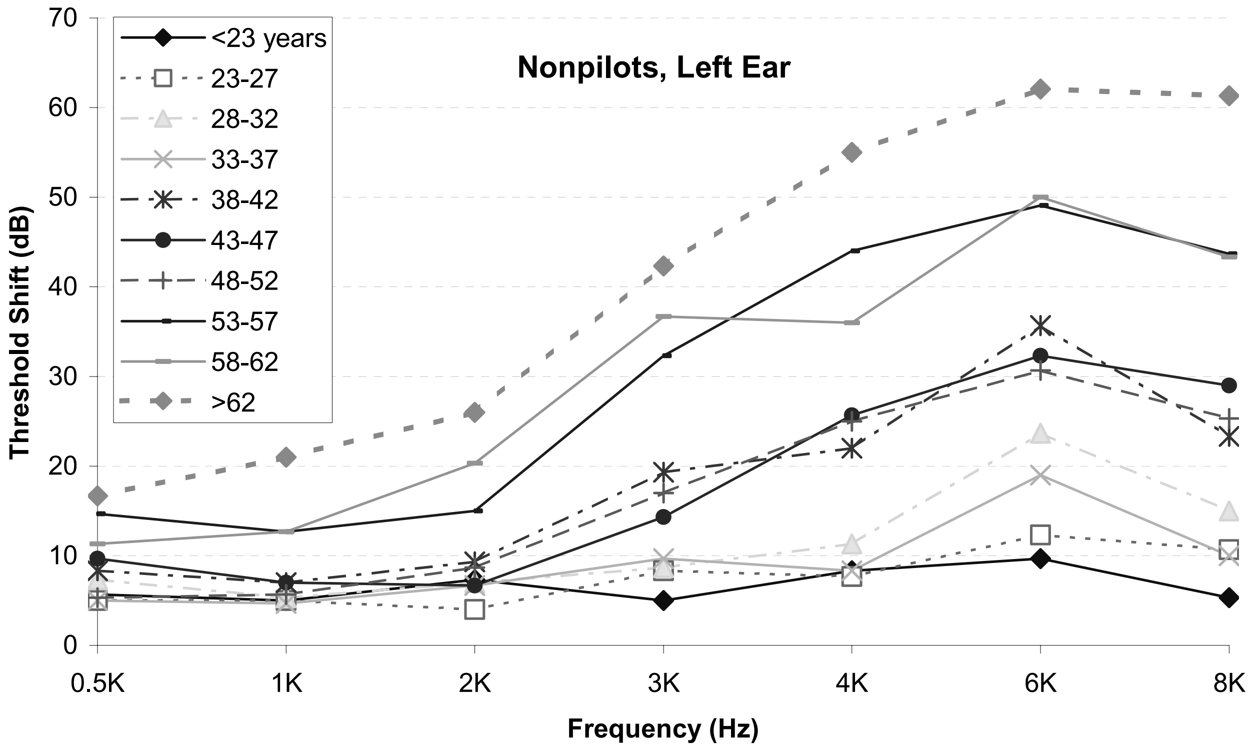

Figure 2. Mean non-pilot left-ear hearing-threshold shifts by age group and frequency.

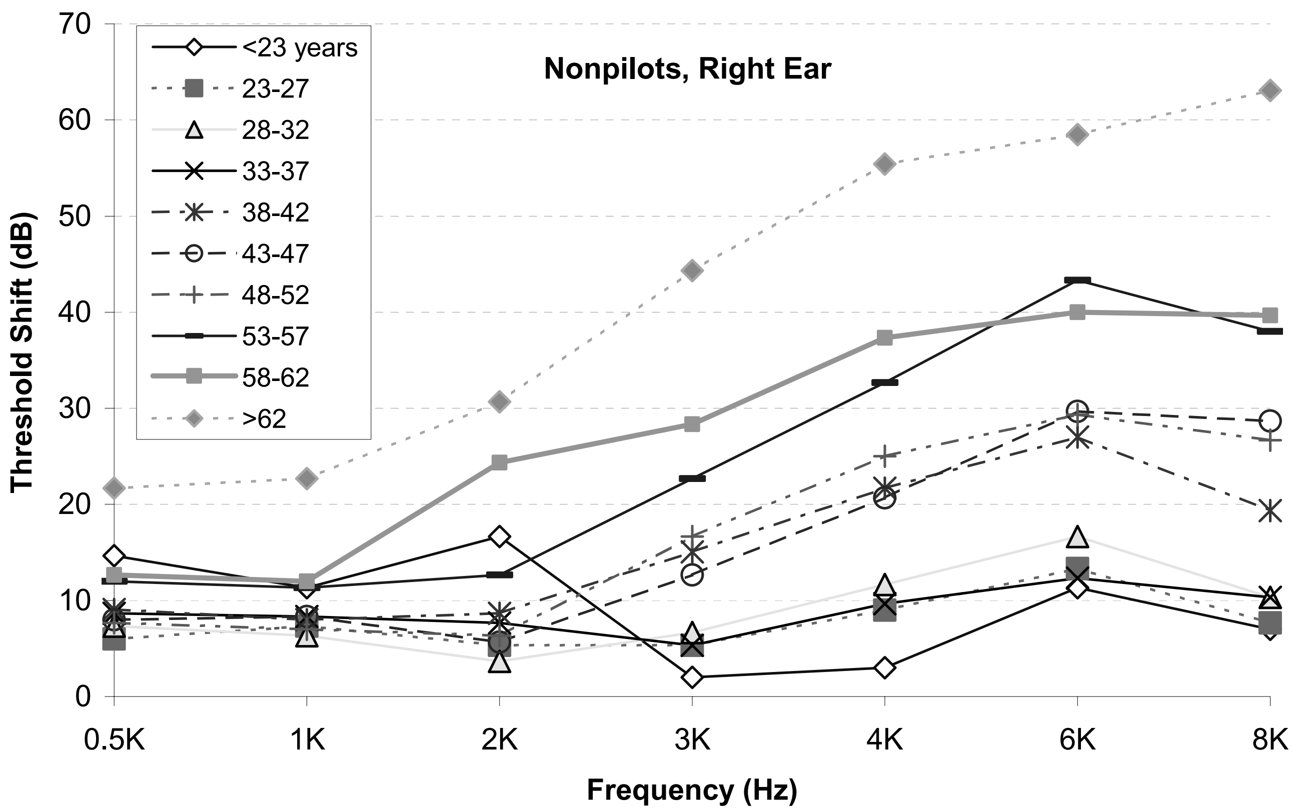

Figure 3. Mean non-pilot right-ear hearing-threshold shifts by age group and frequency.

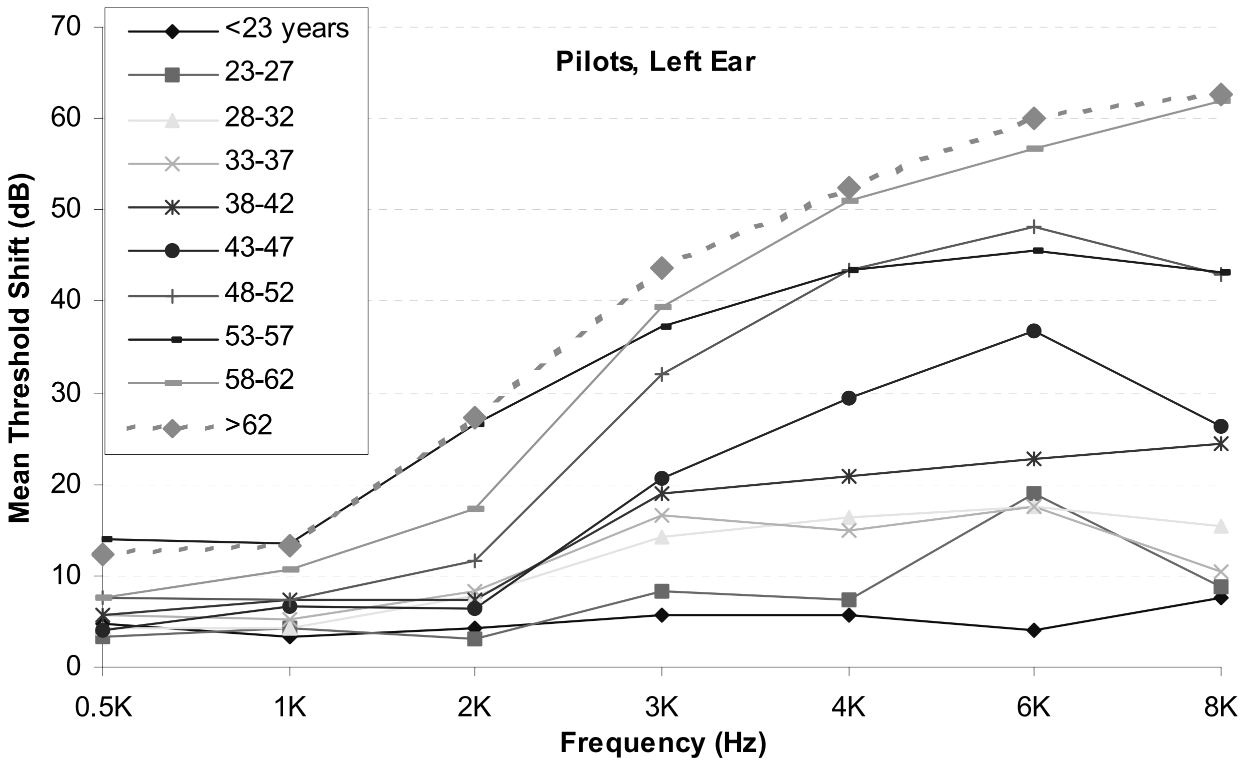

Figure 4. Mean pilot left-ear hearing-threshold shifts by age group and frequency.

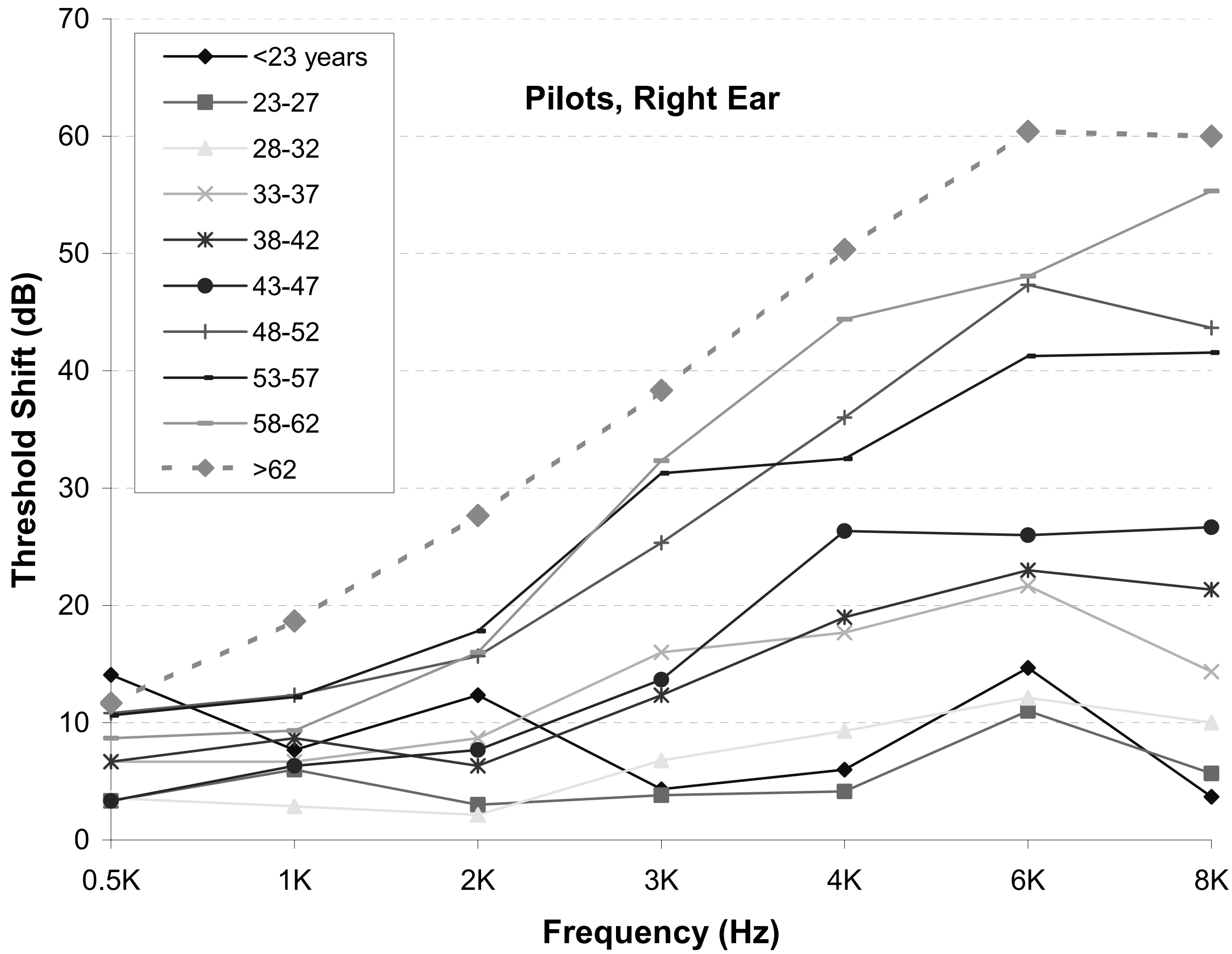

Figure 5. Mean pilot right-ear hearing-threshold shifts by age group and frequency

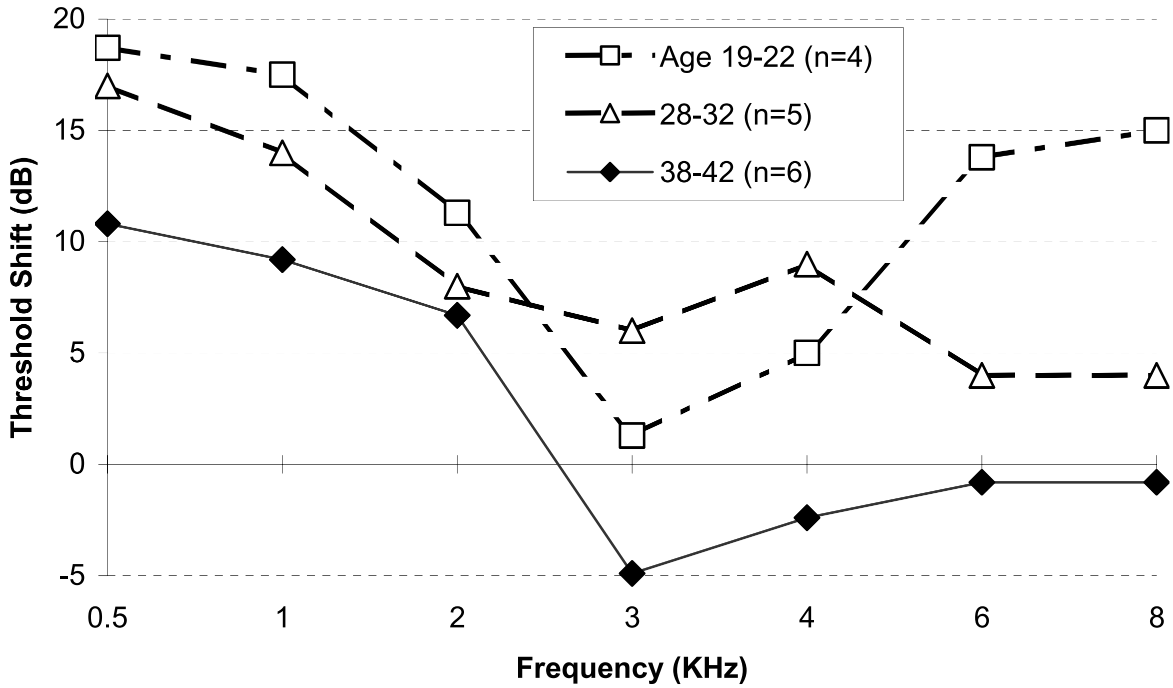

Figure 6. Mean left-ear pilot hearing threshold shifts for three age groups of pilots by frequency as measured in a simulated engine-noise environment.

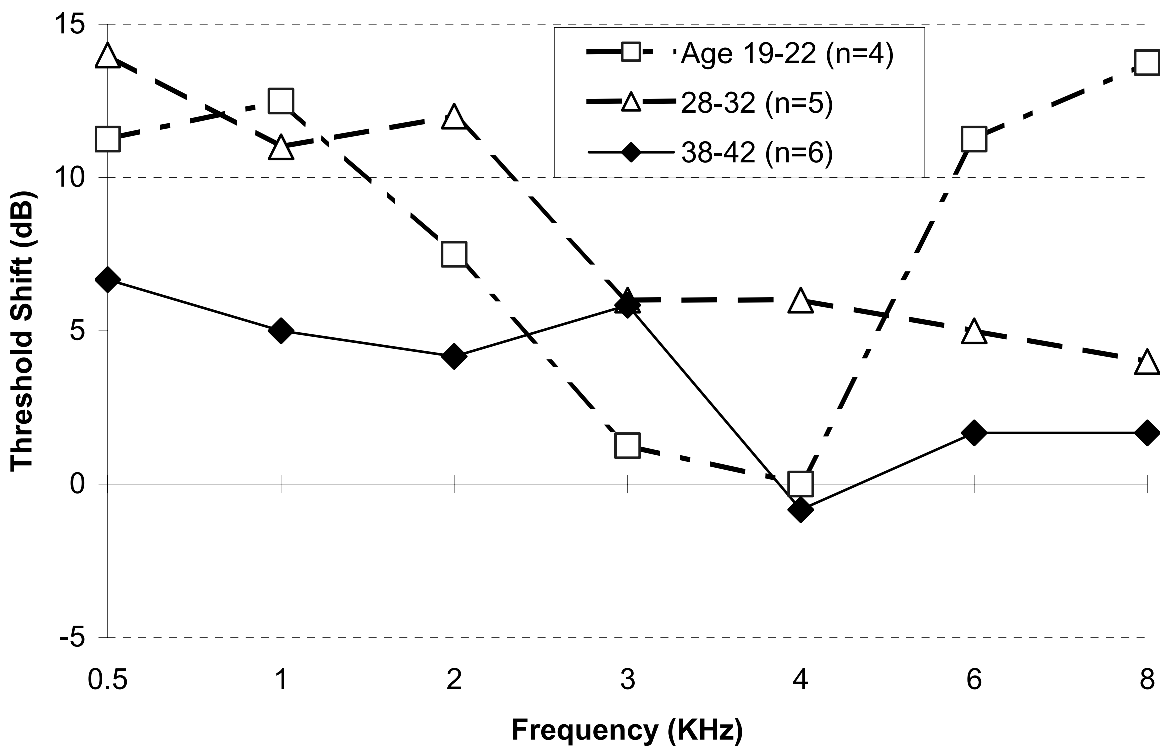

Figure 7. Mean right-ear pilot hearing threshold shifts for three age groups of pilots by frequency as measured in a simulated engine-noise environment.