TEMPORARY THRESHOLD SHIFTS PRODUCED
BY EXPOSURE TO LOW-FREQUENCY NOISES
(Reprint)

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20. **ABSTRACT:**

Groups of human subjects were exposed for 8 or 24 hours to an octave-band noise centered at 63, 125, or 250 Hz. For a 24-hour exposure at 84 dBA, Temporary Threshold Shifts (TTS) increased for 8-12 hours and then either decreased or remained constant. Although TTS was less than 20 dB, complete recovery for many of the subjects required as long as 48 hours. Accordingly, the higher level exposure which was planned at 94 dBA for 24 hours was reduced to 90 dBA for 8 hours. For this condition, TTS increased throughout the 8-hour exposure. TTS from the 90 dBA noise for 8 hours exceeded the TTS produced by the 84 dBA; however, recovery from the 24-hour exposure required as long as 48 hours, whereas recovery from the 8-hour exposure required only 12-24 hours. Thus, the time required for recovery is determined in part by the duration of exposure. TTS was not always maximal 1/2-1 octave above the band of noise, but was maximal in the frequency regions of better auditory sensitivity (350 to 750 Hz). For the 250 Hz condition, TTS increased about 1.5 dB per dB increase in noise level, whereas for the 63- and 125-Hz conditions TTS increased less than 1 dB per dB increase in noise level. More data are needed to specify the relation between TTS and the level of low-frequency noises.
Temporary threshold shifts produced by exposure to low-frequency noises

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Groups of human subjects were exposed for 8 or 24 h to an octave-band noise centered at 63, 125, or 250 Hz. For a 24-h exposure at 84 dBA, temporary threshold shifts (TTS) increased for 8–12 h and then either decreased or remained constant. Although TTS was less than 20 dB, complete recovery for many of the subjects required as long as 48 h. Accordingly, the higher level exposure which was planned at 94 dBA for 24 h was reduced to 90 dBA for 8 h. For this condition TTS increased throughout the 8-h exposure. TTS from the 90-dBA noise for 8 h exceeded the TTS produced by the 84 dBA; however, recovery from the 24-h exposure required as long as 48 h, whereas recovery from the 8-h exposure required only 12–24 h. Thus the time required for recovery is determined in part by the duration of exposure. TTS was not always maximal 1/2–1 oct above the band of noise, but was maximal in the frequency regions of better auditory sensitivity (350 to 750 Hz). For the 250-Hz condition, TTS increased about 1.5 dB per dB increase in noise level, whereas for the 63- and 125-Hz conditions TTS increased less than 1 dB per dB increase in noise level. More data are needed to specify the relation between TTS and the level of low-frequency noises.

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INTRODUCTION

While there are very many studies of noise-induced temporary threshold shifts most of these investigations have been concerned with effects produced by sounds in the frequency range of 0.5 to 4.0 kHz or less than 30 Hz (Jerger et al., 1977; Smith et al., 1977; Patterson et al., 1977; Johnson, 1982). Previous TTS studies which have used bands of noise or pure tones between 63 Hz and 250 Hz (Smith et al., 1970; Ward, 1976; Burdick et al., 1977; Patterson et al., 1977) suggest that the rules for TTS's produced by mid- and high-frequency sounds apply to TTS's produced by low-frequency sounds with perhaps two exceptions. One is that whereas TTS is greatest 1/2–1 octave above the center frequency or upper cutoff frequency of the noise (Ward, 1962; Yamamoto et al., 1970) TTS from low-frequency sounds is greatest in frequency regions of best auditory sensitivity (0.5–4.0 kHz) which can be 3–5 octaves above the exposure frequency. In other words the 1/2–1 octave shift rule may not apply to TTS's produced by low-frequency sounds.

A second exception, although not of major concern here, is that a time-intensity trading rule(s) for exposure to noncontinuous low-frequency sounds must be significantly different from the rule(s) for noncontinuous exposures to mid- and high-frequency sounds (Ward, 1976).

While there are few TTS data on the effects of low-frequency sounds, there are provocative data on permanent effects (Burns and Robinson, 1970). In this large scale industrial study, audiograms from workers exposed to noises with energy concentrated in the low frequencies (downward sloping spectra) were compared with audiograms from workers exposed to noises with energy concentrated in the high frequencies (upward sloping spectra). Audiograms from these groups were identical. That is, noise-induced permanent threshold shift (NIPTS) was about 10 dB at 4.0 kHz and decreased as the test frequency was increased or decreased. It was concluded that NIPTS will always be greatest at 4.0 kHz regardless of the spectrum of the noise, and that A-weighted sound levels provide an accurate assessment of noise levels with respect to the production of permanent threshold shifts. Some comments about these results may be helpful. As Burns and Robinson state, the downward sloping noises had significant amounts of energy at frequencies above 1.0 kHz. Thus, it remains unclear as to whether the hearing loss at 4.0 kHz was due to the energy concentrations in the low frequencies or to the presence of high-frequency noise. Moreover, there remains the issue of the ability of measures of auditory sensitivity at low frequencies to detect injuries of the mid-to-apical region of the cochlea. Bredberg (1968) shows, for example, persons with hearing levels of 0–5 dB at 125–500 Hz but with as many as 50% of the outer hair cells missing in apical regions of the cochlea. Given the observations of Bredberg on human subjects, one should probably at least consider the possibility that the hazardous effects of the "downward sloping noises" of Burns and Robinson were underestimated.

Another reason for our interest in TTS produced by exposure to low-frequency noise comes from some of the unusual responses of the auditory system to low-frequency sounds. Loudness and masking data for signals less than about 250 Hz are notably different from loudness and masking data for signals between 500 and 4000 Hz. For example, the relation between loudness and signal intensity for a 100-
Hz tone is significantly different from the relation at 1.0 kHz (Hellman and Zwislocki, 1968), and debate persists about the shape of the equal-loudness contour at 100 Hz and below (Green, 1976). In masking, the critical ratio or the signal-to-noise ratio at masked threshold (Hawkins and Stevens, 1950) decreases systematically from 8.0 to about 0.2 kHz and then increases (see Sharf, 1970). The reasons for the unusual behavior of masking and loudness at low-frequencies include the shape of the audibility curve (Zwislocki, 1979), and standing wave patterns in the cochlea produced by wave reflections from the helicotrema. A confounding factor is technical, especially measurement difficulties at such long wavelengths. Given the uncertainty in loudness and masking data at low frequencies, it seems reasonable that TTS's produced by exposure to low-frequency noises may have unusual characteristics in addition to the absence of the |-1 octave shift.

I. METHODS AND PROCEDURES

The methods and procedures used here are straightforward and similar in many respects to those given previously (Mills et al., 1979; Mills et al., 1981). In addition to the auditory measurements described below some nonauditory measurements were made also (heart rate, blood pressures, catecholamines, and cortisol). These are described elsewhere (Osghorpe and Mills, 1982).

A. Subjects

Subjects were 52 male students between the ages of 18-22 who were recruited within the community. They were compensated at a rate of $3.50/hour. Individual subjects were required to have hearing threshold levels within ± 10 dB of audiometric zero (ANSI-S3.6, 1969) at frequencies from 125 to 4.0 kHz. To obtain 52 subjects, over 100 were screened. Most rejections were due to hearing threshold levels in excess of 10 dB usually at frequencies above 3 kHz. A few subjects were rejected for failure to keep appointments and poor reliability in audiometric measurement. Four subjects were withdrawn during the noise exposure. Two were withdrawn because of parental concern and two because of bizarre audiograms possibly related to a noise-induced tinnitus.

B. Exposure to noise

Subjects were exposed in groups of two in one room on the second floor of a two-story structure. The noise exposure room was equipped with 2 cots, 1 desk, a refrigerator, and toilet facilities. Subjects read, slept, played cards, etc. In this room loudspeakers had been placed strategically so as to achieve a constant sound field in the space occupied by the subjects. Noise generating equipment and test facilities were located on the ground floor. A-weighted levels and octave-band levels were measured at several locations. Range of levels in the space occupied by the subjects did not exceed 2 dB. White noise was filtered to obtain octave bands with measured center frequencies of 63, 125, and 250 Hz (± 5 Hz), and a rejection rate of 24 dB/octave. Subjects were exposed for 24 h at 84 dBA or 8 h at 90 dBA to each of the octave bands (cf. = 63, 125, 250 Hz). There were 7-8 subjects/condition. Originally it was planned to expose subjects at 80 dBA and 90 dBA for 24 h; however, a pilot study (N = 3) for a 63-Hz exposure at 80 dBA for 24 hrs revealed no measurable TTS's. Accordingly, the level was raised to 84 dBA in the experiments reported here. Also, in the present experiment recovery of TTS from the 84-dBA exposure for 24 h required greater than 16-24 h. To insure recovery within 16-24 h, the exposure planned for 90 dBA for 24 h was reduced to 8 h. The 63-Hz exposure at 90 dBA interfered with threshold measurements, and it was necessary to attenuate the noise during threshold determinations which are described below. One additional group of subjects (N = 6) was exposed without interruption to the 63-Hz noise at 90 dBA for 8 h.

C. Auditory measurements

Pre-exposure measurements of auditory sensitivity were made daily over at least a 2-day period which preceded the noise exposure. Earphone placement was also varied so as to achieve at least five pre-exposure measurements of auditory sensitivity. The mean of these measures was used as the pre-exposure measurement of auditory sensitivity. A final pre-exposure audiogram was taken immediately before the exposure and used as a check on reliability. Discrepancies greater than ± 3 dB resulted in rejection of the subject and/or additional testing. Auditory sensitivity was measured by means of sweep-frequency (Bekesy) audiometry (Demlar, model 120). Below 250 Hz, auditory sensitivity was measured at 90, 125, and 180 Hz by means of fixed frequency Bekesy audiometry (Grason-Stadler, model E800). The tone was gated with an on time of 250 ms and a duty cycle of 50%. For the last 24 hours prior to the noise exposure, subjects were required to wear an earplug (EARS) in the test ear (ear with the better auditory sensitivity) so as to insure that the test ear was rested. The earplug was worn for at least 20-40-dB attenuation at frequencies above 500 Hz and less than 10 dB at 63 Hz.

During the noise exposure auditory thresholds were measured during periods of quiet interspersed within an exposure. At a prescribed time, a subject was removed from the noise for about 10 min during which thresholds were measured. Thus threshold shifts reported in this paper were recorded at post-exposure times between about 2 and 10 min and hereafter are called 4 min (ITS.). The time spent away from the noise was always recorded and the total duration of the exposure was corrected (a 7-min increase in duration for every 3 min of recovery).

II. RESULTS

Figure 1 (panel B) shows TTS at the test frequency of maximum shift for the 90-dBA condition as a function of the duration of the exposure. The center frequency of the noise is the parameter. With the exception of one irregularity (63-Hz condition at 4–7 h) TTS increases throughout the exposure. The 3- to 4-dB differences observed between conditions here and elsewhere in the paper are not considered meaningful
FIG. 1. TTS at the test frequency of maximal shift as a function of the duration of exposure. The A-weighted sound pressure level of the noise is 84 dB in panel A (top half) and 90 dB in panel B (bottom half). The parameter is the center frequency of the octave-band noise. The noise had a rejection rate of 24 dB/oct. N = 8 males datum point except at 63 Hz, 8 h where N = 6. Medians are reported at 8 h, std. deviations are 5.8 to 6.2 dB.

Inasmuch as the range of TTS values is 12 dB, the semi-interquartile range varies between 3 and 6 dB, and standard error of the mean varies from 2.00 to 2.75 dB. Variability of this magnitude is common in TTS experiments. Accordingly, differences between conditions of less than 5 dB (about two standard errors) are not viewed as meaningful. A rigorous statistical treatment of the data has not been attempted inasmuch as the sample size is only 6-8 subjects/condition.

Figure 1 (panel A) shows TTS for the 84-dBA condition. These results are not straightforward. For the 250-Hz condition, TTS is 8 dB after the first 2 to 8 h of the 24-h exposure, and then increases to 14 dB between 12 and 24 h. At the 125-Hz condition, TTS is only barely measurable after 4 h of exposure, increases from 4 to 12 h, and then decreases. TTS for the 63-Hz condition increases between 2 and 12 h, and then decreases. It may be worthwhile to rank-order the three bands of noise with respect to TTS. For an exposure of 4 h, the 250-Hz band produces the most TTS, then the 63-Hz band, and finally the 125-Hz band. At a duration of 12 h, the 63-Hz band produces the most TTS followed by the 250-Hz band, and finally the 125-Hz band. In different words, for the 84-dBA exposure the rank-ordering changes as the duration changes. It is not clear whether the differences between the conditions of Fig. 1 (B) are indicative of sampling variability or "real" frequency effects.

Figure 2 (panels A, B, C) shows recovery from TTS. These recovery curves show at least one consistent result, namely that recovery after the 24-h exposure at 84 dBA requires more time than recovery after the 8-h exposure at 90 dBA. This result is most obvious for the 250- and 125-Hz exposures where the 24-h exposure at 84 dBA produces significantly less TTS than the 8-h exposure at 90 dBA. Data of Fig. 2 show also that for all conditions recovery to within 2 dB of pre-exposure values occurred within 48 h for the 24-h exposure at 84 dBA and within 12 h for the 8-h exposure at 90 dBA. Another possibly remarkable feature of the recovery data is shown on panel B of Fig. 2. Note that for the 125-Hz condition TTS actually increased by 4 dB between post-exposure times of 4 and 12 h. It is not clear whether this increase represents measurement error or is an indication of a further deterioration of the ear after termination of the exposure.

Whereas a rank-ordering of the exposures in terms of the growth of TTS produced unreliable results especially for the 84-dBA exposures, a rank-ordering in terms of recovery produces a straightforward result. At post-exposure times of 2-12 h TTS was equivalent. Similarly, for the 84-dBA exposure the differences in TTS between exposure conditions are within ± 2 dB between 1-12 h of recovery.

Figure 3 shows the "TTS audiogram" produced by the 84-(panel A) and 90-(panel B) dBA exposures. The parameter is the center frequency of the octave-band noise. The data in panel A for the 84-dBA exposure are averaged across measurements made after 8, 12, and 24 h of exposure whereas the data in panel B are for an 8-h exposure. For both the 84- and 90-dBA exposures TTS is largest between about 350
and 750 Hz, and not necessarily at the test frequency 1 to 1
octave above the center frequency of the noise. One possible
exception is the 125-Hz exposure at 84 dBA where TTS is 9
dB at 125 and 250 Hz, and 7.5 dB between 250 and 500
Hz. Another possible exception is at 500 Hz for the 250-Hz
exposure. TTS is not measurable (5 dB) at test frequencies
above 2.0 kHz except for the 63-Hz exposure at 90 dBA. In
this case, TTS is equal or nearly so between 130 and 750 Hz
and then decreases with an irregularity or discontinuity at a
test frequency of 2.0 kHz. This irregularity, although small
in magnitude, occurred for five of the six subjects. For the
90-dBA exposures (panel B) differences between conditions
are most obvious at test frequencies below about 250 Hz.
These differences reflect the spectrum of the noise. At test
frequencies of 750 Hz and 1.0 kHz, however, the values of
TTS are nearly identical. In other words, the TTS between
about 750 and 1000 Hz is independent of the spectrum of the
noise.

A crude estimate of the relation between TTS at the test
frequency of maximum shift and noise level can be obtained
by a comparison of TTS after 8-h exposure at 84 and 90 dBA.
As shown on Table I, TTS increased when the noise level was
increased from 84 to 90 dBA. The magnitude of the increase
appears to be related to the center frequency of the noise.
The slope increases from 0.67 at 63 Hz, to 0.83 at 125 Hz,
and to 1.5 at 250 Hz. A more detailed treatment of the rela-
tion between noise level and TTS is hampered by the absence
of data for a 24-h exposure at 90 dBA, by our inability to
produce more intense low-frequency noises and therefore
larger TTS's, and by the absence of data for TTS's less than
10 dB.

III. DISCUSSION

Previous TTS data from human subjects exposed to
noise for 4–24 h (see Mills et al., 1979; Patterson et al., 1977)
would suggest that TTS would increase for about 8–12 h and
then reach a plateau or asymptote. Discontinuities in the
growth curves would also be expected, particularly a 3 dB or
so "overshoot" of the plateau or asymptote. Thus the data
reported on Fig. 1 are consistent with the results of previous
experiments. Some of the results of the 84-dBA exposures
are difficult to discuss, particularly the shapes of the growth
curves during the first 4 h of exposure and when one com-
pares the data points at 4 h for 125 and 250 Hz. Moreover, it
is difficult to assign the differences in the shapes of the
growth curves for the 84-dBA exposures to procedural arti-
facts. Perhaps a sampling error is operating and a much larg-
er N is needed.

The recovery data were consistent in many respects
with previous data in that the time required for recovery was
related to the duration of exposure (Mills et al., 1970; Ward,
1970; Melnick, 1976, 1977; Nixon et al., 1977). That is, recov-
ery from the 84-dBA exposure for 24 h required 24–48 h
whereas the recovery from the 90-dBA exposure for 8 h was
complete by 12–24 h. It remains unclear whether recovery
from long-duration exposures to low-frequency noise re-
quires more time than recovery from high-frequency expo-
sures. When the present data are compared to data from high
exposures obtained using nearly identical experimental pro-
cedures (Mills et al., 1979), then one can support the hypo-
thesis that recovery from low-frequency exposures requires
more time. When the present data are compared to data
from high-frequency exposures obtained under different ex-
perimental procedures (Melnick, 1976, 1977) then the hy-
pothesis is not supported.

An issue in human TTS experiments centers around the
risks presented to the subjects. Can human subjects be used
without creating a significant risk of permanent hearing loss
and permanent injury to the inner ear? The present results
suggest that the risk to the subjects is minimal. For example,
all subjects recovered to within 2 dB of pre-exposure thresh-
olds within 12–48 h after termination of the exposure. In
other words, 0-PTS was produced. Moreover, not only was
there an absence of PTS but the rates of recovery of TTS
were faster than the rates observed in animals who had 0-
PTS and small losses of outer hair cells (see Eldredge et al.,
1973). If the subjects of the present experiments had taken 3–
7 days to recover completely (PTS = 0 dB) rather than 2 days, the possibility of permanent injury to the inner ear still could not be eliminated.

In most experiments where the exposure has a spectral-ly dominant peak, TTS is maximal 1 to 1 octave band above that peak or above the upper cutoff frequency of the noise band (Davis et al., 1950; Ward, 1962; Yamamoto et al., 1970). Sometimes a second maximum is observed at frequencies nearly 3 octaves above the peak (see Mills et al., 1979). In the present data the most striking features of the TTS audiograms were that the greatest TTS was observed between about 300 and 750 Hz regardless of the center frequency of the exposure, and with one exception TTS was not measured at test frequencies above about 2 kHz. The absence of the dominant peak in the TTS audiogram may be due to a number of factors. One of the more likely possibilities for maximal TTS in the 300–750 Hz region is the difference in auditory sensitivity between, for example, 90 and 750 Hz. This difference may be as large as 50–55 dB and is indicative of the acoustic properties of the external and middle ear (Zwislocki, 1979). Thus, while the noise had spectral peaks at 63, 125, and 250 Hz when measured in the sound field, the spectral peaks when measured at the input to the cochlea would be much less prominent. The absence of TTS at frequencies above 2.0 kHz for the 125 and 250 Hz exposures is inconsistent with expectations based on previous data (Burdick et al., 1978; Patterson et al., 1977; Mills et al., 1979); however, the notch (for 5 of 6 subjects) in the TTS audiogram at 2.0 kHz for the 63-Hz exposure corresponds exactly to earlier predictions (Mills et al., 1979) as well as to much earlier data (Smith et al., 1970) showing a 5-dB notch in the TTS audiogram at 2.0 kHz produced by exposure to a 70-Hz tone. There are no obvious explanations for this equivocal support of earlier data and our expectations.

Thus uncertainties remain not only about the spread of TTS along the frequency dimension but also about permanent effects in the frequency dimension (see Liberman, 1982). The uncertainties involve empirical observations and a theoretical basis for the presence or absence of these observations, especially the 1/2–1 octave shift. Also, the inconsistent observation of a second maximum in the TTS audiogram is an enigma particularly because recent anatomical studies consistently show injured or missing sensory cells in the base and apex of the cochlea but not in mid-cochlear regions. In addition to sensory cells, Salvi et al. (1982) reports damaged cilia of sensory cells only in the apex and in the base after exposures to a low-frequency noise.

On the one hand, the impression is that 90-dBA exposures at 63, 125, or 250 Hz are equivalent or nearly so when comparisons of TTS are made at the test frequency of maximum shift. Similarly, an 84-dBA exposure at 250 Hz and an 83-dBA exposure at 4.0 kHz (Mills et al., 1979) are nearly equivalent in terms of TTS at the test frequency of maximum change. On the other hand, if exposures are judged not on the basis of the TTS at the frequency of the maximal shift but on the “TTS audiogram” then an entirely different ranking (most to least TTS) occurs as follows: 63, 125, and 250 Hz, and 2.0 kHz and 4.0 kHz. Stated differently, a much greater region of the cochlea is affected by 63 Hz than by 4.0 kHz, and therefore, the number of sensory cells and other elements at “potential risk” is significantly greater with low-frequency exposures. Thus a low-frequency noise may present greater risk when risk is defined not by overall noise levels but in terms of the spread of TTS and perhaps the time required for recovery as well.

A. TTS and level of the noise

Previous results for humans (0.5–4 kHz) and animals (0.063–4 kHz) (Burdick et al., 1977; Patterson et al., 1977; Mills et al., 1979, 1981) indicate that after 8–24 h of exposure, TTS increases at 1.5–2.0 dB for every 1 dB increase in noise level above a “safe” or “critical” level. Linear and curvilinear extrapolations are used to specify safe or critical levels. These are defined as those levels of noise which produce a TTS of 5 dB or less when the exposure duration is 8 h or longer. Only the data for the 250 Hz conditions were consistent with previous results and our expectations. Application of the linear and curvilinear procedures (see Mills et al., 1981) to the 250-Hz data gives an estimated critical level of 78–80 dBA. In other words, to produce a median TTS (5 dB), an octave-band noise centered at 250 Hz should have a level of 78–80 dBA.

For noises centered at 63 and 125 Hz the relation between noise level and TTS is unclear. In TTS experiments where the median TTS exceeds 10 dB, an observed slope of less than one is a novel event and is difficult to explain. While the possibility of sampling error can not be eliminated, we are now inclined to believe that the relation between noise level and TTS’s of 0–30 dB produced by low-frequency noise (125 Hz) may be different than that for TTS’s produced by noises in the 250–4000 Hz range. This unusual behavior of TTS may or may not be related to the unusual behavior of other auditory phenomena at low frequencies, for example, the growth of loudness (Helmholtz and Zwislocki, 1968; Green, 1976) and critical ratios in masking (Sharf, 1970).

B. Miscellaneous comments

An unsolicited response from many of the subjects involved the sensation of a “tremendous pressure build-up” in the ear, particularly for the 63-Hz exposure. These informal reports confirmed the impressions of the experimenters. Interestingly, while the nonacoustic sensation was similar to the “pressure build-up” in the middle ear associated with altitude changes. the sensation could not be eliminated by opening of the eustachian tube by swallowing, yawning, or by the Valsalva technique. A more vigorous evaluation of the “sensation” is planned in future experiments.

An additional point of some interest involves a number of basic questions concerning the relation between anatomical integrity of the cochlea and the detection of auditory signals. For example, we can not state that the “unaffected” basal region of the cochlea was not used to detect tones less than 500 Hz. A masking paradigm is needed to eliminate the possibility of “basal region detection.” Also, PTS’s can be as small as 10 dB at 250 or 125 Hz and as many as 50–65% of the outer hair can be missing (Bredberg, 1968). Thus it is possible that our estimates of the effects of the low-frequency
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