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AMRL-TDR-62-99(I)

CUMULATIVE AUDITORY EFFECTS RESULTING FROM MULTIPLE EXPOSURE TO INTENSE ACOUSTIC STIMULATION

PART I. DEAFENING EFFECTS OF NOISE ON THE CAT

TECHNICAL DOCUMENTARY REPORT NO. AMRL-TDR-62-99(I)

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[Prepared under Contract No. AF 33(616)-3844
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FOREWORD

This is Part I of a two-part report on the effect of noise, of moderately high intensity and several hours duration, on the auditory mechanism of cats. This portion deals with measurements of temporary and permanent hearing threshold shifts produced in the experimental animals by well defined exposures to noise, and correlates threshold changes with histologic findings in the same ears. Detailed description of the histopathology of the ears comprises Part II.

This research was supported by the Bioacoustics Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, under Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723102, "Response of the Nervous System to External Dynamic Forces." Major Ronald G. Hansen, Major W. J. Gannon, and Dr. J. R. Mundie served as contract monitors for the Biomedical Laboratory.

Testing of the cats was done under Contract AF 33(616)-3844 with the Hearing and Communication Laboratory, Research Division, Indiana University Foundation, Bloomington, Indiana. Dr. James P. Egan was principal investigator. The investigations were conducted by Dr. James D. Miller and Mr. Charles S. Watson.* Cling D. Anderson, Gordon Z. Greenberg, and Richard F. Gundy assisted in several phases of the program.

Histopathology of the cat ears was accomplished under Contract AF 33(616) 3637 with Washington University, Saint Louis, Missouri. Dr. Walter P. Covell was principal investigator.

Supplementary support was provided to the Hearing and Communication Laboratory by the Deafness Research Foundation, Indiana University, and by Allison Division of General Motors, Indianapolis, Indiana. Instruction in the surgical techniques for the destruction of cochlea and many helpful suggestions concerning threshold testing as well as the care of the laboratory cat were provided by Dr. W. D. Neff of Bolt Beranek and Newman Inc., Cambridge, Massachusetts.

Final stages of data analysis and preparation of the manuscript were completed after Dr. Miller was appointed to the staff of the Central Institute for the Deaf, Saint Louis, Missouri. The support of the Institute through grants from the National Institute of Neurological Diseases and Blindness is gratefully acknowledged. Dr. Donald H. Eldredge of the Central Institute for the Deaf helped in planning of the exposures and in interpreting the audiometric and histological findings.

The experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

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* Mr. Watson is now at the Department of Psychology and the Defense Research Laboratory of the University of Texas.

ABSTRACT

Aural effects of exposure to intense noise were investigated by measurements of the auditory sensitivity of cats, as determined by their behavior, before and after exposures and by histological examination of their cochleas. The results of extensive determinations of the cat's audibility threshold curve for sound fields are reported and a standard audibility curve is constructed. Threshold shifts that are measured post-exposure and decline in time to zero are denoted as temporary threshold shifts (TTS). Threshold shifts that persist over a period of several weeks are called persistent threshold shifts (PTS) and permanent injury to the auditory mechanism is inferred. Threshold shifts that have both temporary and persistent components are defined as compound threshold shifts (CTS). Broad-band noise was used as an exposure to produce the threshold shifts. Exposures of the cat to 115 db for 1/8 hour or 105 db for 1/4 hour result in TTS with the same general features and course of recovery as for man. However, 1/4-hour exposures require 18 db less sound to produce the same magnitude of shift in the cat. Noise of 115 db for 1/4, 1/2, 2, or 8 hours without interruption produced PTS in which magnitude depended on the duration of the exposure, the test-tone frequency, and the susceptibility of the individual cat. When the 2-hour exposure was divided into 16 doses of 1/8 hour each and four different inter-exposure intervals of 0, 1, 6, and 24 hours were used, PTS declined as inter-exposure interval increased. PTS audiograms produced by either continuous or spaced exposures to broad-band noise had characteristic shapes. The size of the temporary component of the CTS increased with the severity of the exposure. Its rate of recovery is most rapid the first few days after exposure. The period of recovery increases with the severity of exposure. Recovery processes seem to have stopped in all cases after the first two post-exposure months. An octave-band of noise with a band pressure level to match that of the broad-band noise was also used as an exposure. The masking pattern of the octave band was determined and was as expected except for unexplained masking at 124 cps. Exposure to the octave band produced small but definite TTS throughout the entire frequency range tested. A scale for the histological evaluation of injuries is presented and, using this scale, injuries were rated at seven locations in each cochlea. An ordering of injuries from slight changes in Deiter's cells to marked changes in both Deiter's cells and hair cells appears to have emerged. The pattern of injury ratings along the basilar membrane is highly similar to the pattern of the behavioral audiograms, if both are placed on an anatomical-frequency scale.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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I. INTRODUCTION

The relations between deafness and exposure to noise have been studied in clinical cases and by field survey methods (see, for example, refs. 26, 27). In the laboratory, histological and electro-physiological methods have been used most often (see, for example, ref. 8). In addition, inferences about acoustic trauma and noise-induced deafness have been drawn from laboratory investigations of temporary threshold shifts (see, for example, refs. 37, 39). Another laboratory method, a method of behavioral audiometry with experimental animals, was used in the experiments to be reported in this monograph.

This method has been previously used to advantage by Lindquist, Neff, and Schuknecht (ref. 20), and it utilizes the following kinds of procedures. Laboratory cats were trained to respond to tones, and measures of their auditory sensitivity are made before and at intervals after an exposure to noise. These measures of auditory sensitivity and their time course over the post-exposure interval are used to define the following variables. A threshold shift is defined as the post-exposure threshold, expressed in decibels, minus the pre-exposure threshold. If a threshold shift is measured at a time that exceeds a few seconds after the cessation of the exposure and if this threshold shift declines to zero over time, the animal is said to have suffered a temporary threshold shift (TTS). If threshold shifts are measured that are stable and persist over a period of several weeks, then these threshold shifts are said to be persistent threshold shifts (PTS's) and permanent injury to the auditory mechanism is inferred. Threshold shifts that have both temporary and fresh persistent components are defined as compound threshold shifts (CTS's). (The compound threshold shift is a new term and it is discussed in Chapter VI.)

Although each of the methods mentioned above provides a particular kind of valuable information, the method of behavioral audiometry with laboratory animals has certain advantages for the investigation of noise-induced deafness and acoustic trauma. Precise control and specification of the conditions of the exposure are possible. Audiometric measures can be made on each cat before, during, and after exposures to noise. In contrast to most electrophysiological and all histological methods, the methods of making audiometric measurements do not disturb or interfere with the later performance of the auditory mechanism. A compelling advantage of a method of behavioral audiometry is the fact that changes in the audiogram clearly define one of the most important aspects of what is meant by damage or injury to hearing.

Of course, a particular method can only answer a limited range of questions. Certain functional and structural changes produced by noise can only be determined by physiological and anatomical methods. Inferences to the human species based on data from another species must be made with care. Practical disadvantages of behavioral audiometry with animals are the time-consuming tasks of training the animals and testing their auditory sensitivity.

Utilizing a method of behavioral audiometry, we collected data which are relevant to the following issues: the audibility curve of the cat, growth of PTS with increasing durations of exposure to noise, the effect of breaking up an injurious exposure into a series of short, spaced exposures to noise, the relation between TTS audiograms and PTS audiograms, the relation between PTS audiograms and the spectrum of the noise, amount and period of recovery after exposure to the noise, and the relation between traumatic effects of noise in the human and the cat ear. In addition, a histological evaluation was made of each cat's cochlea; it is therefore possible to present an evaluation of the structural changes produced by the exposure as well as data on the relation between the behavioral and the histological findings.

II. SUBJECTS AND AUDIOMETRIC PROCEDURES

Introduction

Cats were used as subjects and they are described below. The cats were trained to respond to a tonal stimulus by the method of instrumental avoidance conditioning. The learned response, after extended training and with special precautions, was used to determine behavioral thresholds in a psychophysical procedure. All training and testing were carried out in a proper acoustical environment. Although the essentials of the training and testing procedures have been previously described by Culler and Associates (ref. 5) and by Neff (ref. 24), the apparatus and methods used in the present experiments are described in detail in this chapter.

The Cats

Forty-seven cats were used in these experiments. All were mongrels, and all were estimated to be between one and four years of age. Forty-two were trained in order that their auditory thresholds could be measured behaviorally. Five were not trained; these were used only for histological preparations. Nine of the trained cats (Cats No. 3, 4, 5, 13, 19, 20, 23, 24, and 29) were used in preliminary experiments whose procedures differed slightly from those described in the present paper. The details of the preliminary experiments are given in a previous report by Miller and Associates.*

All of the cats were in excellent general health during the course of these experiments. This was largely due to a high quality diet and to a one- to two-month period of isolation of new cats. During this isolation period, sickly cats were eliminated, while the remainder showed the beneficial effects of the laboratory diet. Two specific selection procedures tended to eliminate cats with hearing disorders: (1) those cats that were difficult to train were discarded, and post-mortem examination of these cats often revealed a middle ear infection; and (2) if an infected ear was encountered during surgery, see below, the cat was eliminated from the colony.

Aside from the exceptions noted in the text, only monaural cats were used in the behavioral experiments. These cats were prepared by surgical destruction of the left cochleas, and each operation was performed under sterile conditions while the cat was deeply anesthetized with sodium pentobarbital. Most often this operation was performed on a cat before his training was initiated, and since the operation was followed by a severe vestibular upset, it was necessary to wait several weeks after the operation before beginning training or testing procedures. Histological examination of the operated ears showed that the cochlea had been completely obliterated in all but two cases. The upper turns of Cat 20's left cochlea could be identified, but none of the sensory cells appeared to be in functional condition. In the case of Cat 71, a few inner hair cells in the upper turns appeared to be healthy and possibly functional.

All but the nine cats used in the preliminary experiments were treated as a prophylactic measure for four to seven days after surgery with penicillin. Similar prophylactic treatment with a dihydrostreptomycin-penicillin mixture (Combiotic, C.

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* Interim Report, Contract No. AF 33(616)-3844, 26 March 1958.

Pfizer and Company) was given to the nine cats used in the preliminary experiments. Even though dihydrostreptomycin may produce oto-toxic effects, none were detected in the present experiments; that is, the threshold and threshold-shift data of the preliminary experiments are in close agreement with the remainder of the data.

Apparatus

A double-grill cage (figure 1) was used for the training and testing of the cats. In its interior dimensions this cage was 33 inches long, 18 inches wide, and 18 inches high. A hurdle, 5 inches high, divided the cage into two compartments; each was 16.5 inches long. The floor of the cage was a grid formed of lengths of rectangular brass stock (1/2 inch by 1/4 inch) which were spaced, center to center, at 1-inch intervals. The top and two sides of the cage were grids formed by brass rods (1/4-inch diameter) which were welded to the grid bars of the floor. Wooden frames covered with hardware cloth were used as doors at the ends of the cage. The unit was mounted on an iron base but was insulated from it by Lucite runners. Lucite stringers along the top of the cage added strength to the construction. The double-grill cage could be electrified to act as an aversive stimulus. The shock was controlled manually by means of a pushbutton and by means of a rheostat available for intensity adjustment. The two compartments of the double-grill cage were electrically independent, the compartment to be shocked being selected from the experimenter's console.

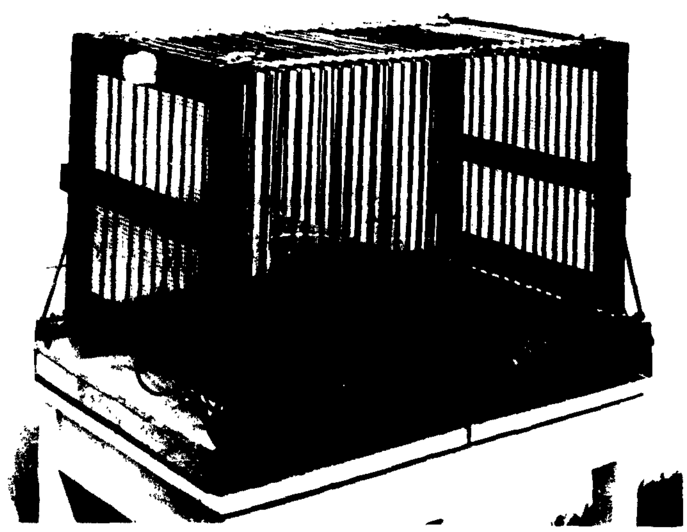

FIGURE 1. The Double-Grill Cage Used for the Training and Testing of the Cats

A buzzer was mounted on each of the doors of the double-grill cage. These buzzers generated an overall SPL* of about 70 db in the cage. Also, they provided, via the grid bars, a vibratory stimulus to the cat's feet. The sound of the buzzer served as a secondary aversive stimulus in the training procedure to be described.

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* Throughout this report the reference level of 2×10^{-4} microbar is used.

For the hearing tests an audiometer, assembled from high quality electronic components, was used. An audio-oscillator, an electronic switch, an amplifier, attenuators, and matching transformers were wired into switch panels so that circuits could be selected which were appropriate to the hearing level of the cat and the desired test frequency. The loudspeakers, the acoustic environment, and the calibration of the sound-field are described in the next section of this chapter.

The auditory stimulus for a training or testing trail consisted of either a continuous or a pulsed tone which was followed by the sound of the buzzers. The durations of these events were controlled by a reliable, multi-cam timer. A trial could be initiated by a momentary contact and it could be terminated at any time after its onset. The exact durations of the auditory stimuli are given in the descriptions of the training and testing procedures.

Acoustic Environment and Calibration of Audiometer

For the threshold tests the double-grill cage was placed on a table in a sound-insulated chamber of room-within-a-room construction. The outer room had a concrete floor, concrete-block walls of 8-inch thickness, and a ceiling of pre-formed concrete slabs. This room's interior walls and ceiling were covered with 4-inch thick blankets of Fiberglas, and its floor was carpeted. The inner room was an audiometric booth (Industrial Acoustics Company Inc., Model 402) whose interior dimensions were approximately 64 by 72 by 78 inches. The walls of this booth were 4 inches thick. Between the control room and the interior of the audiometric booth the attenuation was estimated to be about 80 db for the mid-frequency range. One-way observation windows allowed the experimenter in the control room to view the interior of the audiometric booth.

Test tones were generated in the booth (figure 2) by a pair of 10-inch loud-speakers (Altec-Lansing Company, Model 756A). For tests at 32 kc an Ionovac (Electro-Voice, Inc., Model T-3500) was used. These speakers were mounted in a cabinet; the center of the cabinet was on a line with the center of the double-grill cage at a horizontal distance of 42.5 inches and 25.5 inches above it. Thus, the speakers were about 49.5 inches from the double-grill cage.

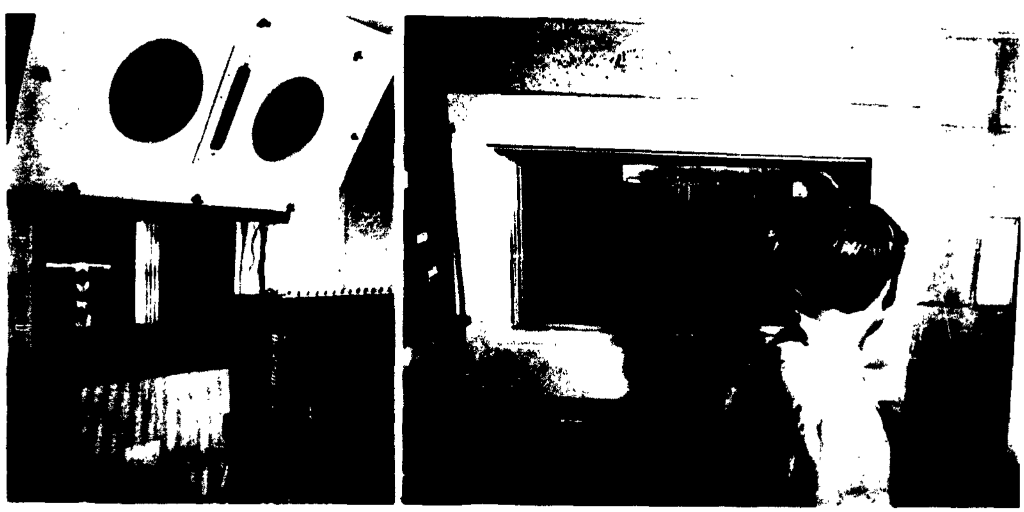


FIGURE 2. The Experimental Arrangement for the Audiometric Tests

The picture on the right shows a tester observing a cat. The picture on the left shows the interior of the audiometric booth.

The audiometer's sound field was calibrated by the following procedure. For a specified voltage across the loudspeakers, the SPL of each of the test frequencies was measured at 54 positions within the double-grill cage. These positions were uniformly distributed throughout the interior of the cage. The sound-level meter consisted of a condenser microphone (Bruel and Kjaer, Type 4111), an amplifier (Bruel and Kjaer, Type 2610), a variable filter set (Spencer-Kennedy Laboratories, Inc., Model 302), and a vacuum-tube voltmeter (Ballantine Laboratories, Inc., Model 300). The calibration of the microphone supplied by Bruel and Kjaer was used for all frequencies except 32 kc. At 32 kc the microphone was calibrated by the substitution method against a microphone whose sensitivity at 32 kc had been determined at the Biomedical Laboratory, 6570 Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio.

The variability of sound levels across the 54 positions of the microphone is shown in table I. The top row shows the frequencies of the test tone. The entries in the next three rows are deviations in decibels of the indicated percentiles from the median. The last row of table I shows the semi-interquartile ranges of these measurements. Examination of table I shows that, while the range of levels was large, for most frequencies 50 percent of the positions fell within $\pm$ 3 db of the median position.

TABLE I

SPATIAL VARIABILITY OF THE AUDIOMETER'S SOUND FIELD AT FIFTY-FOUR POSITIONS WITHIN THE DOUBLE-GRILL CAGE

Top row shows frequencies of test tone. Entries in next three rows are deviations in db of indicated percentiles from median. Last row shows semi-interquartile range.

	Frequency in Kilocycles/Second								
Percentiles	0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0
100th	4.7	6.5	6.0	5.0	9.5	8.0	5.5	7.7	6.0
75th	1.7	1.5	2.5	1.5	5.5	4.0	2.0	1.7	1.0
25th	-1.8	-1.5	-3.5	-3.5	-5.0	-5.5	-2.5	-4.3	-3.0
0th	-4.3	-5.5	-12.0	-12.5	-25.5	-23.5	-17.0	-18.3	-8.0
$\frac{75th-25th}{2}$	1.75	1.5	3.0	2.5	5.25	4.75	2.25	3.0	2.0

The contribution of variability of the sound field to variability of the threshold shift measures was attenuated by two facts: (1) each cat developed a fairly stereotyped behavior pattern within the double-grill cage, and, thus, limited the spatial variability of the sound field to a smaller range; and (2) each measurement included several determinations of the threshold. We believe that averaging procedures inherent in these measurements reduced the error due to spatial fluctuations in the sound field.

For calculation of the absolute values of the thresholds, it was decided to use the median SPL for each test frequency. While it is true that the median may not have been the best measure of the sound field for a particular cat, it was assumed that the typical cat would be sampling the typical value of the sound field.

During the normal use of the audiometer the intensity of the signal was attenuated after an amplifier in the circuit and in this way the signal-to-noise ratio at the loudspeaker was maintained. For a "high-power" arrangement of the audiometer, the signal was attenuated prior to amplification, and the output of the amplifier was placed directly across the loudspeakers. Table II shows the median level of the sound field at the maximum output of the audiometer for both the normal and the high-power (High-P) arrangements of the circuit. Also shown in Table II are the maximum threshold shifts that could be measured for an average, normal cat with either the normal or high-power circuits.

TABLE II

MEDIAN SPL AT MAXIMUM OUTPUT FOR TWO ARRANGEMENTS OF THE AUDIOMETER CIRCUIT

Also shown are the maximum threshold shifts that are measurable for an average normal cat with the two circuit arrangements. See text for explanation.

	Frequency in Kilocycles/Second								
	0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0
Normal SPL	77.1	73.9	76.9	78.4	71.9	66.7	62.9	52.5	79.5
TS	48.6	58.9	72.9	88.4	88.4	79.7	80.4	63.0	73.0
High-P SPL	101.6	100.9	102.4	103.9	97.9	91.9	86.9	76.0	—
	73.1	85.9	98.4	113.9	114.4	104.7	104.4	86.5	—

Training Procedure

A standard training procedure which evolved in the course of these experiments is described below.

Stage 1. Escape-from-shock training. Five to twenty trials of escape-from-shock training were given before the avoidance procedure was initiated. Only five trials were given in a session, and a three-minute inter-trial interval was used. On each trial the shock was gradually increased from an initial low level until the cat crossed the hurdle. (Mean time for stage 1, 15 minutes; mean number of trials, 5.)

Stage 2. Avoidance training. The avoidance stimulus was a 2-kc tone presented at an SPL of about 60 db for 1.5 to 2 seconds. If the cat did not made the desired response during this period, then contiguous with the cessation of the tone was the onset of a buzzer whose duration was 1 second. Also, if the cat failed to cross the hurdle before the onset of the buzzer, electric shocks were applied intermittently until the escape response had occurred. On the other hand, if after the onset of the tone the cat crossed the hurdle before the onset of the buzzer, the tone was immediately terminated and both shock and buzzer were avoided. Thus, each training trial terminated with the response of crossing the hurdle. For this training the inter-trial interval was 2 minutes, and no more than ten trials were given in a session. (Mean time for stage 2, 2-1/2 hours; mean number of trails, 75.)

Stage 3. Generalization training. After a cat reached a level of approximately 85 percent avoidance responding in stage 2, stage 3 was initiated. In this stage, by gradually shifting to frequencies above and below 2 kc, the cat was trained to respond at all frequencies that were to be used in the threshold tests. Also, the inter-trial interval was changed to a random schedule. These intervals ranged from 15 to 90 seconds, and the mean interval was 45 seconds. (Mean time for stage 3 is 1 hour; mean number of trials is 80.)

Stage 4a. Training in threshold procedure. A threshold procedure was introduced and used nearly as described below. Often it was necessary to give extra trials at some intensities to train the desired behavior of responding to weak tones. (Mean time for stage 4a is 6 hours.)

Stage 4b. Stabilization of performance. Even after the cat had learned to respond to weak tones, additional practice in the threshold procedure was required in order to stabilize the performance. (Mean time for stage 4b is 9 hours.) The total time to train an average cat was 19 hours.

Threshold Procedures

For the threshold tests the avoidance procedure was continued. The parameters, however, were varied as described below.

The auditory stimulus consisted of a sequence of five tonal pulses. Each pulse was 1 second in duration; the silent interval between successive pulses was 0.5 second. The rise-fall time of a pulse was 0.1 second. The buzzer was sounded for 1 second at the termination of the fifth tonal pulse.

In the determination of a threshold, a trial could terminate in three ways: (1) the cat crossed the hurdle before the buzzer sounded; (2) the cat failed to respond before the buzzer, but did cross the hurdle after the onset of the buzzer (sometimes with the additional goad of shocks); or (3) the cat failed to cross the hurdle. Throughout the text only crossings of the hurdle during the interval between the onset of the tone and the onset of the buzzer were considered successful avoidance responses; all other possibilities were referred to as failures to respond (to the tone).

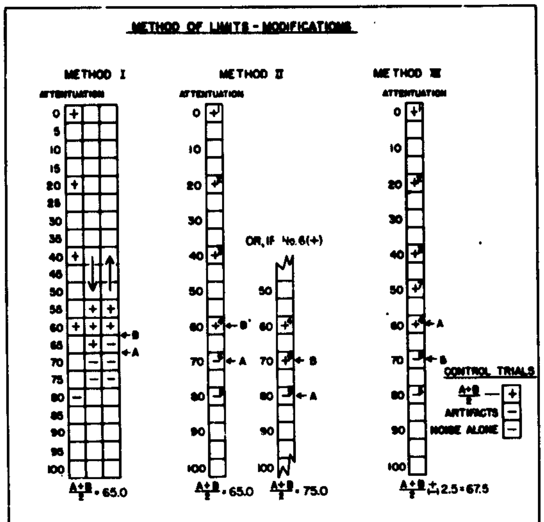
The decision to shock an animal for failure to respond was based on the animal's previous behavior. A cat was almost always shocked for failures to respond when the intensity of the tone was well above the previous value of his threshold. At lower levels of the tone, the experimenter shocked the animal for failures only when it appeared that the cat's performance was faltering in the direction of no responding. When shock was given for failure to respond to the tone at a level near threshold, the shock was usually mild. It is important to remember that the buzzer sounded after every failure to respond.

The three psychophysical methods that were used are illustrated by the sample records (figure 3). Decibels of attenuation re an arbitrary level are shown on the left-hand side of each sample record. The entry in the record of a plus indicates a successful avoidance response; a minus indicates a failure to respond.

The schedules of inter-trial intervals (ITI) that were tried with these methods are indicated at the bottom of the figure. In each case the ITI was varied randomly within the indicated limits. The lowest line shows the mean time required for a single determination of a threshold. The several conditions for the inter-trial intervals shown for each method reflect our discovery that satisfactory results could be obtained with shorter intervals than we originally believed.

First consider Method I. Initially, an approximate threshold was determined using a descending series with a step interval of 20 db. This series is shown by the pluses and the minus in the left-hand column of the example under Method I. About 20 db above the estimated threshold, a second descending series was begun. This descending series had a step interval of 5 db and it was continued until two successive failures were recorded. An ascending series was begun at the level of the last failure and continued until two successive pluses were recorded.

The descending threshold was defined as the level one-half way between the level at which the last avoidance response had occurred and the level at which the first of the two successive failures had occurred. The ascending threshold was defined in an analogous manner. The threshold recorded for the measurement was the average of the ascending and descending thresholds. This scoring procedure is indicated in figure 3.



METHOD	I	I'	I"	II	III	III
I.T.I. MEAN	60 SEC.	48 SEC.	46.5 SEC.	46.5	46.5	28.5 SEC.
I.T.I. RANGE	30-90 SEC.	30-90 SEC.	30-75 SEC.	30-75 SEC.	30-75 SEC.	15 - 50 SEC.
MEAN TIME/ THRESHOLD	15 MIN.	12 MIN.	11.6 MIN.	5.4 MIN.	*6.2 MIN.	*3.8 OR 5.2 MIN.

* NOT INCLUDING CONTROL TRIALS

FIGURE 3. Sample Record Sheets Which Illustrate Three Psychophysical Methods Used for the Determination of the Cat's Auditory Sensitivity

Decibels of attenuation re an arbitrary level are shown on the left-hand side of each sample record. The entry of a plus on the record indicates a successful avoidance response; a minus indicates a failure to respond to the tone. The superscripts associated with the pluses and minuses indicate the ordinal position of the trial within the sequence. The method used to calculate thr threshold is illustrated for each method. The several schedules of inter-trial intervals that were tried with these methods are indicated along the bottom of the figure.

It was noticed that the approximate threshold determined as the first step in Method I was usually very close to the threshold arrived at by the full procedure. This fact suggested Method II which is also illustrated in figure 3. Method II is a simple descending series with a step interval of 20 db. In addition, after a failure to respond had occurred, the intensity of the tone was raised 10 db and another trial was run. The threshold was taken as the level one-half way between the lowest plus and the highest minus.

Methods IIIa and III were complications of Method II. They started as a descending series with a step interval of 20 db. However, after the first failure was encountered, a bracketing procedure was introduced.

A sample record sheet for Methods IIIa and III is shown in figure 3 and a detailed description of these methods is as follows:

(1) On the first trial the tone was presented 40 to 60 db above threshold.

(2) After a plus-trial, the intensity of the tone was decreased 20 db.

(3) After a minus-trial that was immediately preceded by a plus-trial, the intensity of the tone was increased 10 db.

(4) After a minus-trial that was immediately preceded by a minus-trial, the intensity of the tone was increased by 20 db.

(5) An approximate threshold was calculated when the following three conditions were met: (a) pluses were recorded at two intensities separated by 10 db, (b) minuses were recorded at two intensities separated by 10 db, and (c) trials had been run at all 10-db steps between the pair of adjacent pluses and the pair of adjacent minuses.

These five steps constituted Method IIIa. For Method III, the following additional steps were included:

(6) Three additional trials were used to complete the measurement as follows: (a) Tone-plus-artifacts-and-noise. This was a trial given with the level of tone at the approximate threshold. If the cat responded at this level, 2.5 db of attenuation was added to the approximate threshold, and if he failed to respond 2.5 db was subtracted. (b) Artifacts-plus-noise. This trial was run exactly as trial (a); however, a resistor was substituted for the audio-oscillator. (c) Noise alone. With the equipment set as described for (a), an interval equal to the duration of the tone was timed with a stop-watch and the occurrence or non-occurrence of a response was noted. The order of the trials described under (a), (b), and (c) was randomized. While the trials described under (b) and (c) did not enter into the calculation of the threshold, a sufficient number of such trials provided the following additional information: (1) the false-alarm rate at threshold; and (2) the response rate in the presence of possible artifacts.

(7) Occasionally thresholds were obtained which deviated widely from the previous result on the same cat. To reduce the probability of such a measure influencing the data, any threshold which deviated by more than 20 db from the previous result was rejected. In this case the measurement was immediately repeated; this second measurement was always accepted.

Experimental Comparison of Audiometric Methods I, II, and IIIa

A series of observations was made to compare Methods I, II, and IIIa. For this comparison the mean inter-trial-interval was 46.5 seconds for all methods. All measures were accepted. Method IIIa was used as described in steps 1 to 5 above. For this procedure two test sessions were run using each method for each of 17 cats. A test session consisted of threshold measurements at each of the frequencies at the nine one-octave steps from 0.125 kc to 32 kc. The order of test frequencies was randomized within each test session.

As shown (figure 4), the mean thresholds obtained by these three methods differed by less than one decibel. Since all three methods gave the same absolute values for the thresholds, they could only be distinguished on the basis of reliability, time, and suitability for long-term testing of the cats. A comparison of the methods with respect to reliability and time is shown in figure 5. The ordinates are measures of within-subject variability, while the abscissas are the times required to obtain the data. For each method the points from left to right are the estimated standard errors of the means based on 1, 2, .., 6 observations, respectively. These standard errors were estimated using the data for all frequencies. It can be seen that for a given level of reliability Method I requires fewer threshold determinations but more time than Methods II or IIIa.

Indeed, since Method II gave the greatest reliability for the least expenditure of time it would appear to be the method of choice. Method III was finally selected, however, because it provided more opportunities than Method II for animals to respond to the very weak tones, and, thus, it was thought to be more suitable for the long-term testing of the cats.

The schedule of inter-trial intervals was shortened to a mean value of 28.5 seconds with a range of 15 to 50 seconds. In this form Method III required about 5 minutes per threshold. While the variability of thresholds collected using Method III in its complete form is given in detail in Chapter III, it may be mentioned that Method III in its final form was more reliable and faster than Methods I, II, or IIIa; the standard error of a single measurement being about 6.15 db.

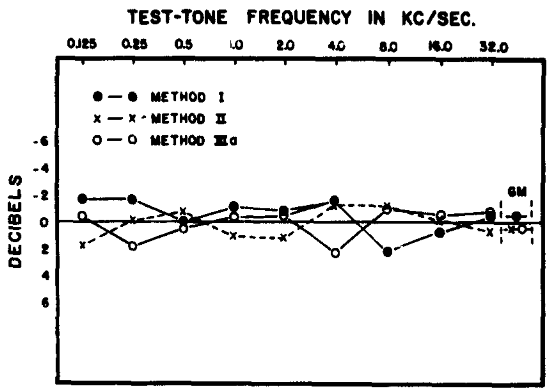


FIGURE 4. A Comparison of Mean Thresholds Obtained Using Methods I, II, and IIIa

The ordinate for each point is the deviation in decibels of the mean obtained by a particular method from the mean for all three methods. Similar results are shown for the grand means over all frequencies.

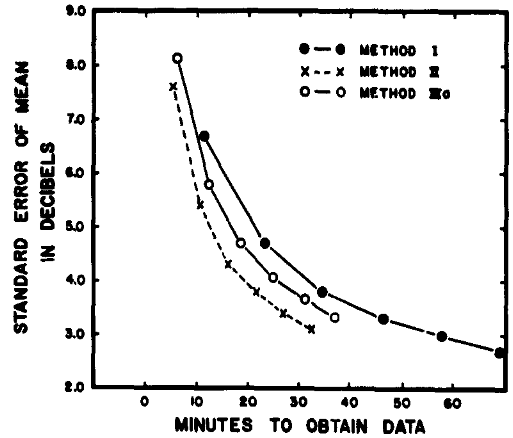


FIGURE 5. A Comparison of the Intra-Cat Reliability for Methods I, II, and IIIa

Based on the standard error of the mean threshold (σ_R) using 1 to 6 observations. The ordinates are standard errors of the means in decibels, while the abscissas are times in minutes necessary to obtain the required number of measurements. For each method the data points from left to right show the expected standard error of the mean threshold for 1, 2,......and 6 determinations, respectively. For example, the fourth open circle from the left shows that four measurements using Method IIIa would require about 24.8 minutes and the standard error would be about 4.05 db.

III. MINIMUM AUDIBLE FIELD OF CAT

Introduction

Behavioral measurements of the cat's audibility curve have been more extensive than those for any other sub-human species. Dworkin and Associates (ref. 9) published the first extensive set of data on the cat's audibility curve. These authors, however, did not calibrate their sound field by direct measurement. Kryter and Ades (ref. 19) published thresholds at three frequencies for which the sound field had been calibrated. Neff and Hind (ref. 25) published an audibility curvé for the cat based on direct calibration of the sound field for frequencies at and below 16 kc. These authors also showed that the cat could hear at frequencies as high as 60 kc. Recently, McGill (ref. 23), Elliott, Stein, and Harrison (ref. 15), and Miller and Associates* have also measured audibility curves for the cat in calibrated sound fields.

During the course of the present experiments audibility curves were obtained under standard conditions for each of thirty-four highly trained cats. These cats were tested using Method III, which is described in the previous chapter. The test frequencies were the nine one-octave steps from 125 to 32000 cps. A cat was tested at all nine frequencies in each of five sessions, and the order of frequencies was randomized within each session. At each test frequency a cat's threshold was defined as the mean of the five measurements. These means served as the basis for the calculation of threshold shifts in the deafness experiments, and they are presented in this chapter as a contribution to our knowledge of the cat's auditory sensitivity.

Variability of Thresholds

Figure 6 shows the variability among cats. At most frequencies 50 percent of the cats fall within $\pm$ 3.5 db of the median cat; furthermore, almost all of the data are included within $\pm$ 15 of the median. Only Cat 84 consistently deviated from the median by more than 20 db. This cat was dropped from the experiments, and a post-mortem examination showed that cerumen was impacted in the ear canal in the region of the drum. The overall agreement among the cats becomes even more striking when the spatial variability of the sound field is recalled, see table I. Certainly some of the variability among cats can be accounted for by the variability in the sound field.

The within-cat variability was estimated using all data, both pre- and post-exposure, collected in these experiments. For this purpose approximately 627 threshold measurements (19 thresholds for each of 33 cats) were available for each of the nine frequencies. Figure 7 shows the relation between the estimated population standard deviation (σ_r) and frequency of test tone. This standard deviation increases about 0.33 db for every octave increase in frequency. For practical purposes, however, one estimate of the intra-cat variance was used for frequencies at and below 1.0 kc and another was used for frequencies at and above 2.0 kc. The square roots of the average values of σ_r^2 were 5.24 and 6.80 for the low and high frequencies, respectively. To estimate the reliability of a mean, that is, its standard error for the particular sample of cats (σ_R), the formula is

$$R = \frac{\sigma_r}{(Nn)^{1/2}}$$

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where N is the number of cats, and n is the number of threshold determinations per cat. The number obtained by this calculation is probably an underestimate of the true σ_R, since each estimate of this measure of reliability is based on the variability of the threshold over a period of 3 or 5 successive days. The variability for measures separated by longer periods, say several days, weeks, or months, is ubdoubtedly greater. This means that if a cat's threshold were measured at 1.0 kc on 5 successive days and these tests were repeated one month later, a test for the significance of the difference between the means of each group of 5 measures would be biased toward a significant result. This bias is noted here, since this type of statistical test is used in later chapters of this report.

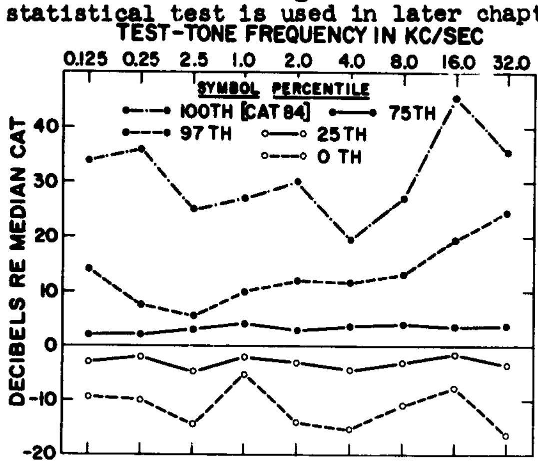

FIGURE 6. Variability Between Cats in Their Quiet Absolute Thresholds

The frequency of the test tone is shown along the top of the figure, and the deviation of the indicated percentile from the median is shown on the axis of ordinates. Cat 84 was not used in the trauma experiments.

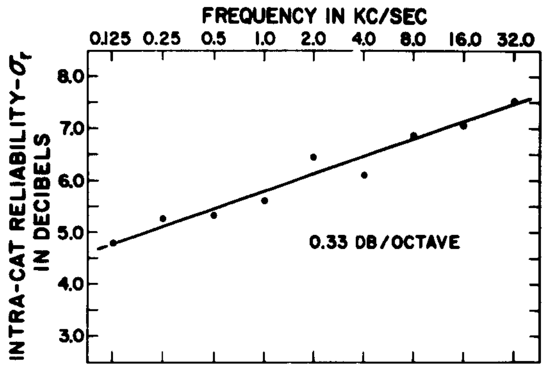

FIGURE 7. Intra-Cat Reliability for the Nine Frequencies of the Test Tone

At each frequency, each cat's variance was calculated. The measure of reliability shown on the axis of ordinates is the square root of the mean of the estimated population variances of all cats used in these experiments.

False-Alarm Rates and Artifacts

Recent investigations have demonstrated the important influence of procedural variables on detection behavior (see, for example, Swets, ref. 34). In addition, on both procedural and theoretical levels these investigations have suggested that a threshold should be thought of as equivalent to an index of sensitivity and that any additional connotation is questionable. The hit rate (response rate to tones) in a simple yes-no experiment is dependent on the false-alarm rate (rate of spontaneous responses) as described by an operating characteristic. Now, even though the procedures of the present experiment are much more complicated than the simple yes-no experiment, the cat's hit rate is undoubtedly dependent on his false-alarm rate, and thus, his threshold values will be dependent in some complex way on his false-alarm rate. Moreover, it is likely that an animal's false-alarm rate is more closely related to the immediate experimental context than is the false-alarm rate of the human listener. For, while the animal's behavior is oriented to the avoidance of shock, the human listener's behavior is usually oriented by the verbal concept of "hearing" given in the instructions. Thus, it may be more important to control and describe the hit- and false-alarm rates in the case of sub-human listeners than it is in the case of human listeners.

When the hit- and false-alarm rates are specified at threshold values of the signal, in a sense, the cat's criterion is described. The procedures of the present experiment (see Method III, step 6 in Chapter II) represent a move in the direction of better control and description of these response rates, and in this spirit the following data were collected. The proportion of responses to tones presented at the approximate threshold was 0.485. The proportion of responses to possible artifacts was 0.038. And, the proportion of responses on noise-alone trials was 0.044. Each of these proportions was based on 1530 trials.

Under the assumption that these data could be treated as describing a point on an operating characteristic, the threshold levels given in this paper can be interpreted as levels which have a detectability index, d_s, of about 1.7. A clear explanation and definition of this index is given by Egan, Greenberg, and Schulman (ref. 10). The advantage of describing the threshold value in terms of a constant detectability index is that this number may be relatively independent of procedural variations.

Since the cats in our experiments could detect a tone generated by a 10-microvolt potential across the loudspeakers' voice coils, the possibility of artifacts of similar magnitude could not be ignored. Although artifacts were not audible to human listeners, it was still possible that the cat could hear them. The control apparatus for our audiometer, in fact, did produce clicks of very small magnitude in the audio circuits, and while these clicks could be observed on an oscilloscope, we were not able to measure them. In general, it should be remembered that artifacts are always associated with a tone presentation and that their elimination is a matter of degree. In relation to this problem the closeness of the response rate to artifacts to the rate for noise alone was an important finding, since it proved that the cats did not respond to artifacts, when these artifacts were presented in isolation. Also, the audibility curves show that artifacts did not control the cat's response. Our experiments, however, do not eliminate the possibility that under some conditions artifacts could serve the function of a ready signal.

The Audibility Curves

The results of all investigations of the cat's auditory thresholds that have been done in calibrated sound fields are shown in figure 8. In each case the plotted points are the medians of the values given by the original authors. Two sets of data are new. The filled circles at the nine one-octave steps from 125 to 32000 cps are the median thresholds of the present group of thirty-four cats. The filled squares at 350, 700, and 1400 cps are median thresholds based on tests of eight of the thirty-four cats.

Examination of figure 8 shows that the results of the present study are in good agreement with the results from other laboratories. This agreement cannot be ascribed to bias introduced by the testers, for the threshold determinations were made in terms of attenuation; the associated SPL values were not known to the testers.

Differences among the several experiments do not seem to be consistently related to the type of apparatus or to the type of reinforcement. Similarly the type of animal preparation, binaural or monaural, does not appear to differentiate these functions. Indeed, when the many possible sources of error are considered, the overall agreement among the several studies is quite good.

After careful study of the several sources of data, the threshold values were weighted and averaged. Weights were assigned on the basis of the number of cats, the adequacy of the calibration, and on an estimate of the quality of the threshold tests. The values of the weighted averages are given for the octave steps in table 3, and they are shown graphically in figure 9. Note that the audibility curve is smooth and orderly except for the notch at 4 kc. Since this notch appeared in three of the investigations, it may represent a true effect. Other irregularities may be present at some of the interpolated points. At and above 32 kc the calibrations are uncertain and more data will be required before confidence can be placed in the absolute values. Except for the frequencies above 32 kc, nonetheless, it is recommended that the values given in table 3 and figure 9 be used as a standard for the laboratory cat. By comparing new values to the standard, an experimenter will be able to evaluate his methods, or after gaining confidence in his methods he will be able to evaluate the hearing level of his cats. These values should also prove useful for the comparison of the cat's audibility curve to other types of data.

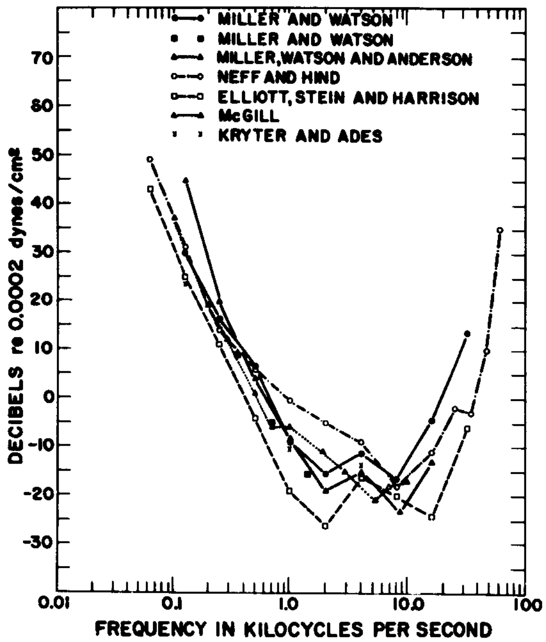

FIGURE 8. Audibility Curves of Cat

Median results are shown for five previous sets of data from calibrated sound fields and for two new sets of data (filled circles and squares). The values of the median thresholds are shown in decibels re 0.0002 dynes/cm² along the axis of ordinates, and the abscissas are frequencies of the test tones shown in kilocycles/second. The test-tone frequency is shown on a logarithmic scale.

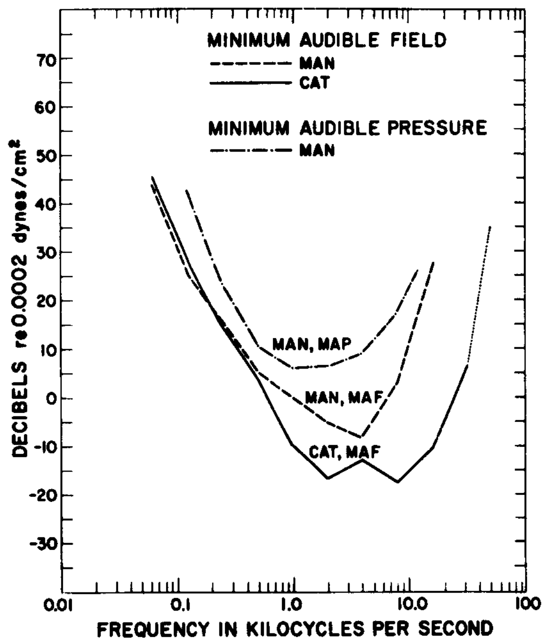

FIGURE 9. Audibility Curves for Cat and Man

The audibility curve for cat is a "best estimate" based on all of the data shown in figure 8. The minimum audible field (MAF) shown for man is a calculated curve presented by Sivian and White (ref. 33) for binaural listening with random incidence of the sound. The curve for minimum audible pressure (MAP) shown for man is based on recent data given by Corso (ref. 3).

TABLE III

MINIMUM AUDIBLE FIELD FOR CAT IN SPL

	Frequency in Kilocycles/Second									
	0.0625	0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0
SPL	45.5	28.5	15.0	4.0	-10.0	-16.5	-13.0	-17.5	-10.5	+6.5

Values given in the table are a best estimate based on all published data.

Man's audibility curve calculated by Sivian and White (ref. 33) for binaural listening with random incidence of sound is shown in figure 9 for comparison with the cat's threshold. In order that the reader can conveniently relate the field thresholds to pressure thresholds, which are perhaps more familiar, man's minimum audible pressure (MAP) is also shown in figure 9. This MAP function is based on data given by Corso (figure 1 in ref. 3). Examination of the curves for minimum audible field (MAF) shows that man and cat have nearly identical sensitivity in the frequency region from 62.5 to 500 cps. Between 500 and 4000 cps the cat is more sensitive than man by about 8 db. Above 4 kc, the cat's superiority becomes more marked, for while the upper limit of hearing for man is about 20 kc, the cat's upper limit is at least 60 kc. In evaluating the difference between cat and man, one should remember than on figure 9 the MAF curve for man is for his most sensitive listening condition. Therefore, the true difference between cat and man is probably as great or greater than the difference shown here. We believe that the cat's superior sensitivity at frequencies above 500 cps is clearly established.

It seems likely that the differences between cat and man will be partially explained by differences in the acoustical properties of the external, middle, and inner ears. Only after these biophysical differences are quantitatively understood and some of the difference between cat and man remains unexplained, will it be legitimate to consider possible differences in the physiological and anatomical properties of the hair cells and nerves.

IV. EXPOSURE TO THE NOISE

Noise Field

The noise field for the deafness experiments was generated in a small, reverberant room. The components of the noise system were as follows: a noise generator, an attenuator, a high-pass filter whose cut-off was at 250 cps, and a 50-watt, high-fidelity amplifier. Two driver units (University Loudspeakers, Inc., Type SA-HF) mounted on each of two public address horns (University Loudspeakers, Inc., Type LH) served as the transducers. Figure 10 shows the experimental arrangement for the exposure of the cats to noise. After a few experiments, hardware-cloth cages were substituted for the restraining device pictured in figure 10, because we feared that a cat would pull his head down into the collar and, thus defend his ears from the sound.

FIGURE 10. The Experimental Arrangement for the Exposure of Cats to the Noise

After a few experiments hardware-cloth cages were substituted for the restraining device shown here, because it was feared that a cat would pull his head down into the collar and, thus, defend his ears from the sound. The microphones and a recording sound-level meter were used to monitor the sound levels during all exposures to the noise.

The intensity of the noise field was carefully calibrated in the region of the restraining device. A General Radio Type 1551-A sound-level meter was used for measurements of the overall level of the noise. A spectral analysis of the noise was made with the same instruments as were used to calibrate the sound field of the audiometer. With these instruments the noise was analyzed in 1/2 octave-bands.

In the region of the restraining device, the maximum undistorted output of the noise system was 117 db, and at ten surrounding positions the levels were within $\pm$ 0.25 db of this value.

The spectrum of the noise is shown by the solid line in figure 11. The left-hand ordinates are the levels for bands of 1-cps width expressed in decibels re the overall level, and the right-hand ordinates are the spectrum levels in SPL when the overall SPL of the broad-band noise is 115 db. These measures were calculated from several analyses of the noise made with 1/2-octave bands. Figure 12 shows the same data as the solid curve of figure 11 plotted as octave-band levels. These figures show that the spectrum level has a maximum at about 750 cps and that it drops off slowly on either side of this value. Notice that the octave-band levels are about equal in the three bands centered at 850, 1700, and 3400 cps.

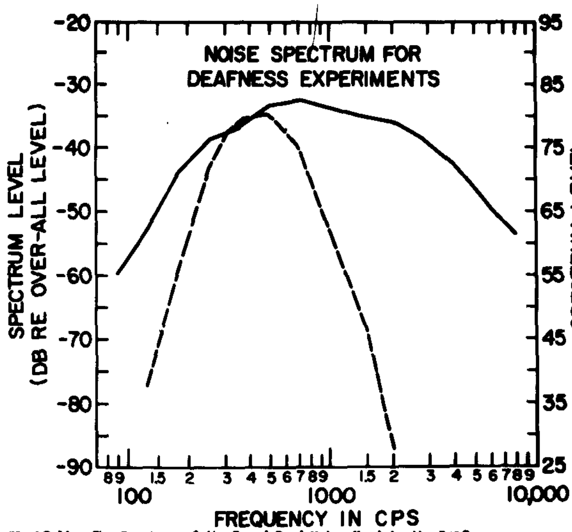

FIGURE 11. The Spectrum of the Broad-Band Noise Used in the Deafness Experiments

Spectrum is shown by the solid line. The dashed line shows an estimate of the spectrum of a one-octave band of low-frequency noise used in the experiments of Chapter VIII. The left-hand ordinates are the levels in banks of 1-cps width expressed in decibels re the overall level, and the right-hand ordinates are the spectrum levels when the overall SPL of the broad-band noise is 115 db.

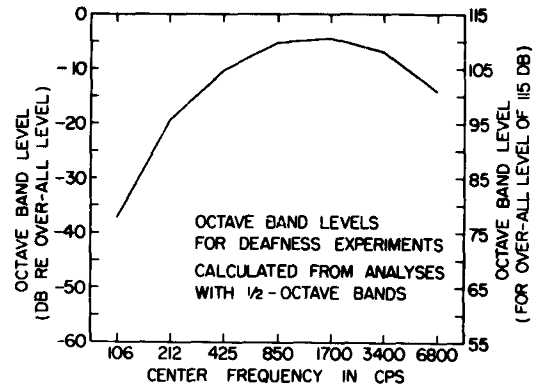

FIGURE 12. Octave-Band Levels of the Broad-Band Noise Used in the Deafness Experiments

The broad-band noise was used as the deafening stimulus in all experiments but one. This exception is clearly noted in the text. An estimate of the spectrum of the low-frequency noise used in the exceptional experiment is shown by the dashed line of figure 11. This dashed line is discussed in Chapter VIII.

Procedure

All exposures to the broad-band noise were administered as described here. (A slightly different procedure was used for exposure of the cats to a low-frequency band of noise, and this procedure is described in Chapter VIII.) The cats were placed in the reverberant room, and they were restrained either in the device shown in figure 10 or in individual hardware-cloth cages. In this manner one to six cats could be exposed simultaneously. It should be noted that the cats were not anesthetized and that no other special procedures were used to prepare them for the exposure. When the cats were settled in the room, the noise was turned on slowly over a period of 7 seconds; at the completion of the exposure, it was turned off over the same period of time. Throughout an exposure the noise level was monitored by a microphone and it was registered on a sound-level recorder.

Cat's Behavior

During an exposure the behavior of the cats was observed through a one-way glass. There were no dramatic responses to the noise. At the onset of the noise there was a mild increase in activity. Behaviors such as circling in the cage or loud yowling were noticed. After a few minutes they became quieted, either sitting or lying down. During the longer exposures of 2 hours or more, many of the cats appeared to go to sleep. Of those that appeared to be asleep, some were aroused when the experimenter turned off the noise and entered the room. Others were not aroused until the experimenter gently shook their cages, and a few were not aroused until they were touched. It may be that these cases of apparent deep sleep were in part a result of the severe deafness present at the time. Anthony, Ackerman, and Lloyd (ref. 1) have described the behavior of mice, rats, and guinea pigs during exposure to noise at about the 140-db level. These authors found a decrease in activity during this intense exposure.

V. TEMPORARY THRESHOLD SHIFTS

Experiments on temporary threshold shifts (TTS's) were conducted on cats for the following reasons: (a) since in the case of man the general characteristics of noise-induced TTS are well established, similar information for the cat could provide one basis for comparison of the deafening effects of noise on these two species; and (b) it was hoped that some of the relations between temporary and persistent threshold shifts could be clarified by a comparison of these two effects in the case of the cat.

Temporary threshold shifts are available for three groups of cats that were exposed to similar conditions. Group A, composed of seven cats, and Group B, composed of four cats, were exposed to the noise at an overall SPL of 105 db. Group C, composed of five of the cats used in the preliminary experiments (see Chapter II), was exposed at 103 db. For these three groups the duration of the exposure was 1/4 hour. Unlike all other cats used in these experiments, the cats of Group A were binaural.

In another experiment (see Chapter VII) three groups of four cats were exposed to the noise at an overall SPL of 115 db for 1/8 hour. One of these groups was tested extensively, and their results are reported below.

In all of these TTS experiments, the order of test frequencies was counterbalanced for the post-exposure tests, while prior to exposure it was randomized.

TTS Audiograms

As representative of the effects of the 1/4-hour exposure at 105 db, TTS audiograms at several times after exposure are shown for Group B in figure 13. The TTS audiograms of Groups A and C, not shown, were in close agreement with those of Group B. Figure 14 shows the TTS audiograms resulting from the 1/8-hour exposure to the 115-db level. While the shapes of the audiograms shown in figure 14 are typical, we believe that the absolute values of the shifts are atypically large. Taking into account all of the data for this condition, we believe that a typical cat would have TTS's similar to those induced by the 105-db exposure. In other words, it is our opinion that the 1/8-hour exposure at 115 db and the 1/4-hour exposure at 105 db are nearly equivalent exposures for the typical cat.

The findings shown in figures 13 and 14 can be summarized as follows: (1) sizable TTS's are limited to the frequency region between 2 and 16 kc; (2) the maximum TTS was measured at 4 kc; (3) because of its importance for the comparison of temporary and persistent threshold shifts, the relation between TTS at 2 and 8 kc should be noted; TTS was greater at 8 kc than at 2 kc for 14 of the 16 cats for which this comparison could be made; (4) since no TTS was measured at some frequencies, it can be inferred that the measured threshold shifts were not due to a general disruption of the cats' behavior in the threshold task; and (5) recovery from TTS is orderly and complete, and it is discussed in more detail below.

The above results confirm and extend the earlier findings of Lindquist, Neff, and Schuknecht (ref. 20). Using a noise like that of the present experiments, these authors exposed cats at an overall level of 107 db for durations of 1/4, 1/2, or 1 hour. As in the present experiments, large values of TTS were found, and the maximum shift was at 4 kc.

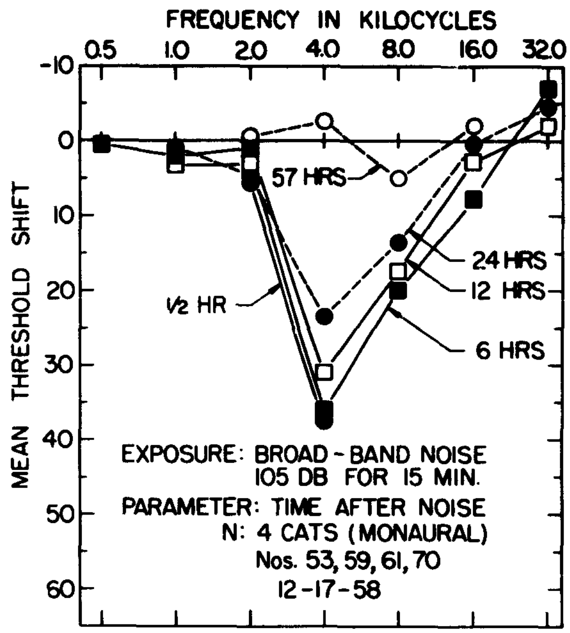

FIGURE 13. Temporary Threshold Shifts After Exposure to the Noise at an Overall SPL of 105 db for 1/4-hour

The parameter is the time after noise in hours.

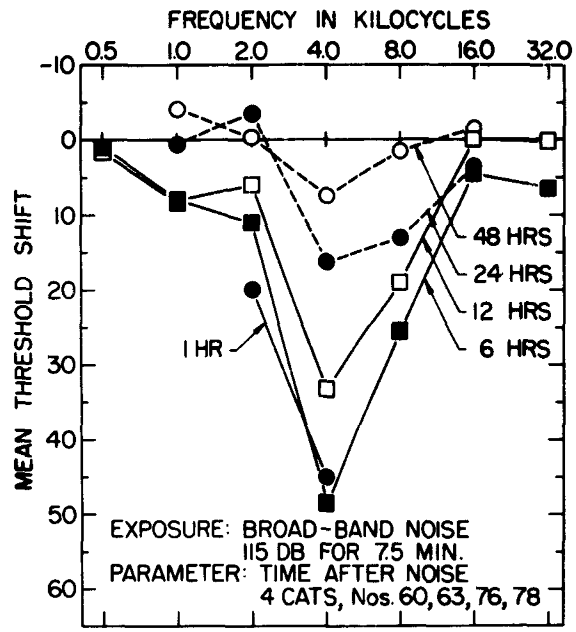

FIGURE 14. Temporary Threshold Shifts After Exposure to the Noise at an Overall SPL of 115 db for 1/8-hour

The parameter is the time after noise in hours.

Recovery from TTS

Ward and Associates (refs. 37-39) have shown for man that recovery from TTS at 4 kc follows a logarithmic course for a wide range of conditions. Specifically, this logarithmic course is expected when (a) the time after exposure exceeds 2 minutes, and (b) the TTS at 2 minutes after exposure (TTS_2) is less than about 40 db. When TTS_2 is greater than about 40 db the recovery follows a quite different course. Ward (ref. 36) and Miller and Associates* have described the recovery from these high values of TTS for man and cat, respectively, and their results are shown in figure 15. The dashed curve shows the course of recovery for two of the human subjects (ref. 36, figure 1, Subjects HH and MB). To produce TTS_2 of 40 to 50 db, one of these human subjects was exposed for about 36 minutes, while the other required about 132 minutes; for both listeners the noise was the octave band from 1200-2400 cps. The symbols are means for the several groups of cats that were described earlier in this chapter. It is apparent that the course of recovery from these high values of TTS is nearly identical for cat and man. Note that, in terms of log time, the recovery is initially very slow and that it gradually increases in rate. As Ward (ref. 36) points out, the recovery from high values of TTS can be described as a linear function of time when the time after exposure exceeds 1 to 2 hours. During this latter period the rate of decline of TTS is about -0.8 db/hour.

Comparison of TTS for Cat and Man

When man is exposed to a broad-band of thermal noise, it is generally true that TTS is greater for high than for low frequencies and that TTS often has a maximum of about 4 kc. The data reported here show that similar features are found

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* Interim Report

for the cat. It has been demonstrated, in addition, that the course of recovery from high values of TTS is the same for both cat and man. Therefore, it is probably true that the qualitative characteristics of TTS and its underlying processes are the same for these two species. A quantitative comparison is given below.

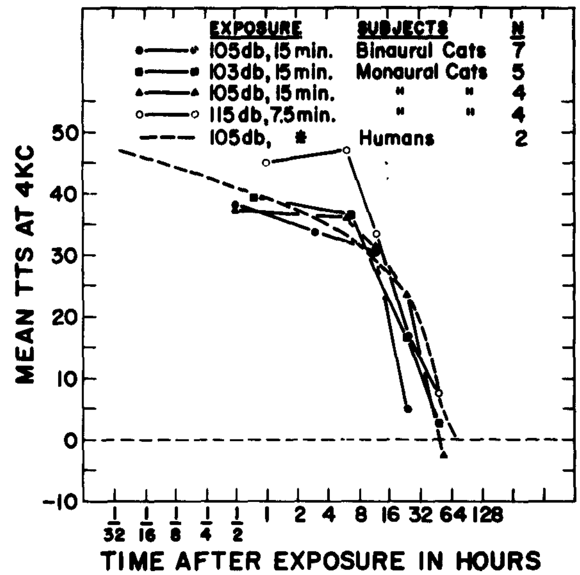

FIGURE 15. Recovery from High Values of Temporary Threshold Shifts at 4 kc

The ordinates are TTS's in decibels, while the abscissas are times after exposure in hours on a logarithmic scale. Data for cat are shown by the symbols, and similar data for man are represented by the dashed line. See text for explanation.

Although an experimental comparison of cat and man was not made in our laboratories, it was possible to make an estimate of the quantitative differences between cat and man. For this comparison, only TTS at 4 kc was considered and the 15-minute exposure at the overall SPL of 105 db was taken as a reference exposure. The equations and constants given by Ward, Glorig, and Sklar (ref. 39) were used to calculate the expected results for man and the required changes in the reference exposure, if man were to have temporary threshold shifts equal to those for the cat. The calculated values obtained for man can be regarded as close approximations to empirical values for exposures at SPL's of 106 db or less and for durations from several minutes to several hours, since the equations are based on data provided by such exposures. The exact values obtained by extrapolations to SPL's above 106 db are tentative.

After the reference exposure, the temporary threshold shifts at 2 minutes after exposure (TTS_2) and at 60 minutes after exposure (TTS_{60}) were calculated for man. These values were TTS_2 = 22.5 db and TTS_{60} = 9.9 db. Sixty minutes after the reference exposure, the cat's temporary threshold shift (TTS_{60}) is 38 db. The cat's TTS_2 was estimated by extrapolation to be 44 db. Therefore, TTS_2 and TTS_{60} for the cat are greater than those for man by 21.5 and 28.1 db, respectively.

If man's TTS_2 were to equal the cat's estimated TTS_2 of 44 db, it was calculated that the reference exposure would have to be increased for man by either 18 db in SPL or by 11 db in time. The results of these calculations at the test frequency of 4 kc are summarized in table IV.

TABLE IV

COMPARISON OF TTS FOR CAT AND MAN

	TTS_2	TTS_{60}	Required SPL if duration is 15 min and TTS_2 = 44 db	Required duration if SPL = 105 db and TTS_2 = 44 db
Man	22.5 (cal.)	9.9 (cal.)	123 db (cal.)	180 min. (cal.)
Cat	44.0 (est.)	38.0 (obs.)	105 db	15 min.
Diff. in db	21.5	28.1	18 db	11 db

On the basis of the comparisons given above it is hypothesized that (a) the qualitative characteristics and the underlying processes of noise-induced TTS are the same for cat and man, and (b) a given exposure will produce more TTS in cat than in man. As a first approximation, it appears that in order to produce equivalent TTS in cat and man, the noise level for man must be 18 db higher than that for cat.

VI. PERSISTENT THRESHOLD SHIFTS AFTER CONTINUOUS EXPOSURE TO NOISE

In the experiments to be described below, all cats were exposed to the same spectrum (figures 11 and 12 of Chapter IV); the duration of the exposure was the variable. The overall SPL of the broad-band noise was 115 db, while the duration of the exposure was 1/4, 1/2, 2, or 8 hours.

Procedure

Preliminary experiments. Cats were exposed to the noise for durations of 1/4, 1/2, and 2 hours. Each cat was tested frequently and regularly throughout its post-exposure life, but no one schedule was used for all cats. All of these cats were killed in order that their cochleas could be studied by histological methods. The length of their post-exposure lives varied from 85 days to 181 days. The details of these preliminary experiments are given in another report by Miller and Associates*.

Later experiments. Since the results of the preliminary experiments could be questioned on the grounds that the cats had been treated with dihydrostreptomycin, see Chapter II, these experiments were repeated and extended using cats that had no treatment with an oto-toxic drug. In these later experiments three cats were exposed for 1/2 hour, eight cats** were exposed for 2 hours, and six cats were exposed for 8 hours. As in the case of the preliminary experiments the overall SPL of the noise was 115 db.

A standardized schedule of test sessions was used for all cats in the confirming experiments. A test session consisted of measurement of a cat's threshold for the frequencies at each of the nine octave steps from 125 to 32,000 cps. In each test session, thresholds were determined at all nine frequencies and the order of test frequencies was randomized.

In order to stabilize the data, results from several test sessions were averaged. Five test-sessions were completed before a cat was exposed to the noise, and the cat's pre-exposure threshold was defined at each frequency as the mean of the five determinations. The schedule of test sessions during a cat's post-exposure life is shown in table V. Note that test sessions were conducted daily during the first two post-exposure days and that, thereafter tests were conducted at about 1/4, 1/2, 1, 2, and 3 lunar months after the exposure. Note that the number of determinations per defined threshold varies with time after the exposure. A threshold shift at a particular frequency is defined as the difference between the pre-exposure and the appropriate post-exposure threshold described in table V.

All of the cats in these later experiments were perfused for histological preparation within 1 to 7 days after the last test session; thus, their post-exposure lives were about 90 days.

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* Interim Report

** Four of these cats, Numbers 60, 63, 76, and 78, had previously been exposed to noise as described in Chapter VII on spaced exposure to noise. These previous exposures had no persistent effects on their audiograms.

TABLE V

SCHEDULE OF POST-EXPOSURE TESTS AND DEFINITIONS OF THRESHOLD

Defined Threshold	N	Time after exposure of test sessions*
0 day	1	2-6 hours**
1 day	1	24 hours
2 day	1	48 hours
7.5 day	2	7 and 8 days
14 day	3	13, 14, and 15 days
28 day	3	27, 28, and 29 days
56 day	3	55, 56, and 57 days
84 day	5	82, 83, 84, 85, and 86 days

* The results in a given row were averaged for the calculation of thresholds and threshold shifts.

** Not run in all cases.

Definition of PTS and $\overline{\text{PTS}}$

The threshold shifts at 84 days after exposure are referred to in the text as persistent threshold shifts (PTS's). It is claimed that recovery is completed by 84 days and that the thresholds obtained at 84 days represent the new persisting state of the cat's auditory sensitivity. This claim is strongly supported by the data on recovery and by the histological findings. In the case of a cat used in the preliminary experiments, each cat's final thresholds were used to define his PTS's, and the time at which these final thresholds were measured ranged from 75 to 171 days after the exposure.

It is convenient to use a single statistic in order to summarize the PTS audiogram. For the purpose of this report a statistic, $\overline{\text{PTS}}$, was defined as the mean PTS for the frequencies at the eight octave steps from 125 to 16,000 cps. Shifts at 32 kc were not included in this measure, since not all of the cats were tested at this frequency. It will be shown that $\overline{\text{PTS}}$ behaves in an orderly fashion and that for the conditions of these experiments the audiogram and the histological findings can be predicted when $\overline{\text{PTS}}$ is known.

Growth of Persistent Threshold Shifts

The relation between $\overline{\text{PTS}}$ and the duration of the exposure to noise is shown in figure 16. On this graph the abscissas are the durations of the exposures in hours, while the ordinates are the $\overline{\text{PTS}}$'s in decibels. Values of $\overline{\text{PTS}}$ are shown for individual cats by the symbols; the open circles represent cats from preliminary experiments, while the solid points represent cats from later experiments. The line connects the mean $\overline{\text{PTS}}$'s.

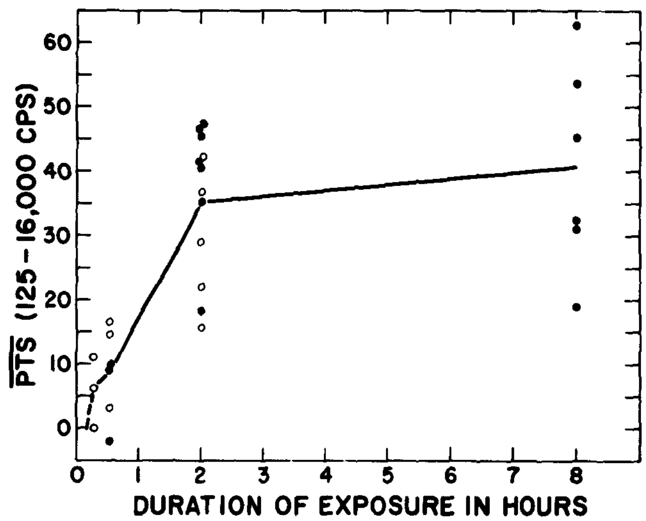

FIGURE 16. Growth of PTS, the Persistent Threshold Shift Averaged Across Eight Octave Steps from 125 to 16,000 cps

The abscissas are the durations of the exposure in hours, while the ordinates are the $\overline{\text{PTS}}$'s in decibels. The symbols show the values of PTS for the individual cats; the open circles represent cats from the preliminary experiments, while the solid points represent cats from the later experiments. The line connects the mean values of $\overline{\text{PTS}}$. The dashed segment of the curve reflects the fact that other experiments (see Chapters V and VII) have shown that exposure to the noise for 1/8 hour will produce little or no $\overline{\text{PTS}}$.

First, it should be noted that the individual differences are large. This spread among the cats is almost entirely due to the noise exposure; that is, the inter-cat variance after exposure to noise is approximately 16 times greater than the inter-cat variance prior to exposure. The intra-cat variance, on the other hand, was not greatly affected by the exposure.

Another feature of these data which is illustrated in figure 16 is the compatability of the results from the preliminary experiments with those from the later experiments. For the exposure durations of 1/2 and 2 hours it can be seen that preliminary cats overlap with the cats from the later experiments. Thus, since only procedural differences exist between the preliminary and the later experiments, these two sets of data are treated alike during most of the remainder of this report.

Other experiments in our laboratory (Chapters V and VII) have shown that exposure to this noise for 1/8 hour produces little or no PTS in the cat. The dashed portion of the curve reflects this fact. Thus, the mean $\overline{\text{PTS}}$ leaves zero after an exposure of about 9 to 15 minutes. As the duration of the exposure is extended up 2 hours, $\overline{\text{PTS}}$ grows rapidly. When the exposure is increased beyond 2 hours, the rate of growth then declines; two hours of exposure result in a mean $\overline{\text{PTS}}$ of 35 db, while an additional six hours of exposure increases this value by only 5.6 db.

The growth of $\overline{\text{PTS}}$ was approximated by a logarithmic function of time. The dashed line on figure 17 shows the line obtained by fitting the equation

$$\overline{\text{PTS}} = A(10 \log_{10} T) + B$$

to the $\overline{PTS}$ data by the method of least squares. The symbols show the mean $\overline{PTS}$ for each duration of the exposure, and the bars show the distance plus and minus one standard error of the mean. It can be seen that for every doubling of the exposure duration, the mean $\overline{PTS}$ increases by about 8 db. It is obvious that these data cannot be used to reject the notion that the growth of $\overline{PTS}$ can be accurately described by a logarithmic function. On the other hand, the best estimate that could be made from the present data is that the growth function would be S-shaped when plotted against log time.

The growth of PTS for individual frequencies is shown in figure 18. On this graph the abscissas are the durations of the exposures in hours, while the ordinates are the mean PTS's in decibels. The parameter is the frequency of the test tone. The growth curves for individual frequencies are similar in form to that shown for $\overline{PTS}$, that is, once the growth of PTS begins, it is initially rapid, and then, the rate of growth declines. These data suggest that the rate of growth may be higher for frequencies at and above 1 kc than it is for frequencies below 1 kc.

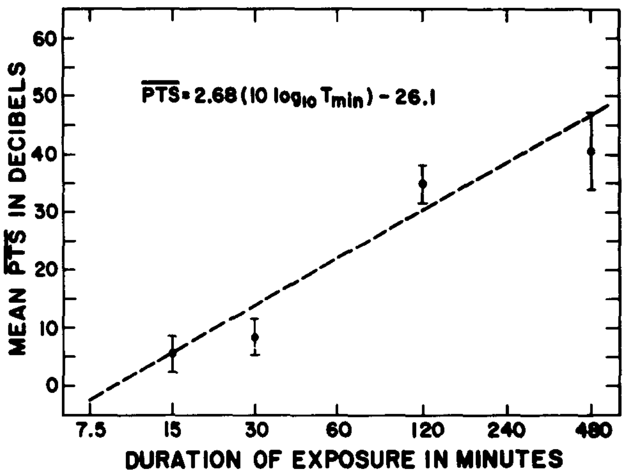

FIGURE 17. Growth of $\overline{PTS}$ as Described by the Best Fitting Logarithmic Function of Time

The symbols show the mean $\overline{PTS}$ for each duration of the exposure to the noise at an overall SPL of 115 db. The vertical bars show the region of $\pm$ 1.0 standard error of the mean; this standard error is based on the inter-ear variance.

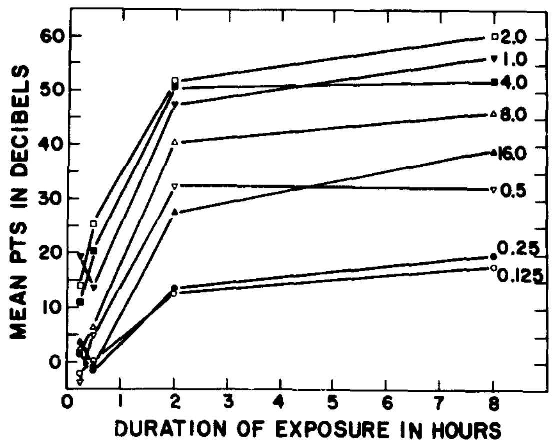

FIGURE 18. Growth of PTS for Individual Frequencies

The abscissas are the durations of the exposures in hours, while the ordinates are the mean PTS's in decibels. The parameter is the frequency of the test tone.

Audiograms

The PTS data resulting from these continuous exposures are shown in the conventional form of audiograms in figure 19. Inspection of this figure shows that the largest shifts are found between 1.0 and 4.0 kc. It should be noted that unlike the case of TTS, the loss at 2.0 kc is consistently greater than the loss at 8.0 kc. This display of the data clearly shows again that the major effect of increasing the duration of the exposure was between the 1/2-hour and the 2-hour durations. The properties of the audiogram will be discussed in more detail in Chapter X.

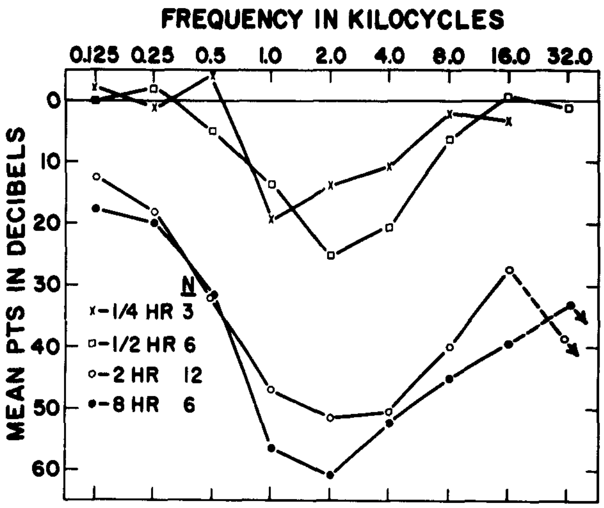

FIGURE 19. PTS Audiograms After Exposure to the Noise for the Indicated Durations

All data points are means and these are the same data as shown in figure 18. The arrows indicate that at least one cat in these conditions did not respond at the audiometer's maximum output. For this calculation the cat's score was entered as the maximum PTS that could be measured. Thus, the indicated point is a lower bound on the sample mean.

Table VI summarizes the PTS data that have been presented above (figures 16, 17, 18, and 19). This table shows the composition of the groups, the mean PTS for each frequency, as well as $\overline{\mathrm{PTS}}$. Below each mean two measures of variability are given. The first, labeled σ_m, is the standard error of the mean based on the estimated inter-cat variance. The second, labeled σ_R, is an estimation of the reliability of the mean for the particular cats of these samples; in other words, it is an estimate of the standard error of the PTS based on the intra-cat variability. Examination of these measures of variability shows that while these means are precisely determined for the particular cats of these experiments, the enormous inter-cat variability precludes precise estimates of the population means from these small numbers of cases. As previously mentioned, the inter-cat variability is due largely to the noise exposure, since prior to exposure the inter-cat variance in thresholds is smaller than after exposure by a factor of about 16. The intra-cat variance on the other hand is relatively unaffected by the noise. For an individual cat, the largest increase in intra-cat variability was a factor of 10; the increase of the mean intra-cat variance from before exposure to 84 days after it was 1.26 db.

Ratings of Cochlear Injuries

The methods for the preparation of the cochleas for histological examination and the rating scale used as a measure of the degree of injury are given in Chapter IX. The analysis of the relations between the behavioral findings and the histological findings is given for all exposures to the broad-band noise in Chapter X. Nevertheless, the mean injury ratings will be presented here for the continuous exposures to the broad-band noise.

Table VII shows the mean of the injury ratings, which can vary from 1.0 for a normal end organ to 5.0 for complete destruction of the external hair cells, at each of several positions along the basilar membrane. It should be understood that these positions are only approximate and that the rating was based on an examination of the indicated region, not a particular distance from the round window. In table VII the positions along the basilar membrane are indicated. Below the name of each location the approximate distance from the round window is given in millimeters, and the corresponding test-tone frequency, as determined by Schuknecht (ref. 28), is also shown.

TABLE VI

PERSISTENT THRESHOLD SHIFTS AFTER CONTINUOUS EXPOSURE TO NOISE, SHOWN FOR EACH DURATION OF THE EXPOSURE ARE THE MEAN PTS's

The standard errors of the mean based on both inter-cat variance, σ_m, and intra-cat variance, σ_R, are also shown.

Duration	Number of Cats: Prelim.	Later on	Total		Frequency in Kilocycles/Second: 0.125	0.25	0.5	1.0	2.0	4.0	8.0*	16.0	32.0**	$\overline{PTS}$+
				PTS	-2.1	1.2	-4.0	19.2	13.8	10.8	2.3	3.5	-	5.6
1/4	3	-	3	σ_m	2.0	3.1	4.8	5.4	9.8	9.0	3.9	3.1	-	3.2
				σ_R	1.9	1.9	1.9	1.9	2.5	2.5	2.5	2.5	-	0.8
				PTS	-0.2	-1.9	4.9	13.5	25.3	20.4	6.3	-0.6	1.3	8.5
1/2	3	3	6	σ_m	2.5	2.5	2.3	3.5	6.9	9.5	4.8	3.6	5.2	2.6
				σ_R	1.4	1.4	1.4	1.4	1.8	1.8	1.8	1.8	1.8	0.6
				PTS	12.5	18.1	32.3	47.1	51.5	50.6	40.0	27.6	38.8	35.0
2	4	8	12	σ_m	2.5	3.3	5.6	4.3	2.6	3.1	5.3	7.1	11.9	3.2
				σ_R	1.0	1.0	1.0	1.0	1.2	1.2	1.2	1.2	1.2	0.4
				PTS	17.7	19.8	32.2	56.6	60.9	52.3	46.3	39.1	33.2	40.6
8	-	6	6	σ_m	3.7	1.2	7.4	8.9	4.8	6.2	12.8	12.0	13.6	6.7
				σ_R	1.4	1.4	1.4	1.4	1.8	1.8	1.8	1.8	1.8	0.6

* The cats in the preliminary experiments were tested at 8.8 kc rather than 8.0 kc.

** The test frequency of 32.0 kc was not used in the preliminary experiments.

\+ Mean is the mean of the frequencies from 0.125 to 16.0 kc.

TABLE VII

MEAN INJURY RATINGS FOR COCHLEAS OF CATS EXPOSED TO THE BROAD-BAND NOISE

Duration of Noise Hours	Number of Cats: Prelim.	Later		(Mean)	Location of Injury: III A	U	II M	L	U	I M	L
				mm from R. W.	20.5	17.0	15.3	13.5	10.8	7.5	4.5
				Equivalent Frequency in Kilocycles/Second	0.15	0.7	1.09	1.7	3.4	7.6	17.0
1/4	2	-	I	1.87	1.50	2.00	2.75	2.25	2.00	2.00	1.5
			σ_m	0.18	0.0	0.50	0.25	0.25	0.50	0.0	0.0
1/2	3	3	I	2.04	1.50	1.83	2.17	2.42	2.06	2.33	1.75
			σ_m	0.16	0.13	0.11	0.17	0.21	0.34	0.40	0.28
2	4	8	I	2.88	1.79	2.13	2.88	3.67	3.83	3.04	2.88
			σ_m	0.16	0.11	0.14	0.19	0.24	0.28	0.28	0.33
2*	-10-		I	2.41	1.70	2.00	2.50	3.25	2.85	2.80	1.75
			σ_m	0.31	0.11	0.13	0.17	0.08	0.24	0.38	0.15
8	-	6	I	3.36	2.17	2.75	3.33	4.08	4.00	3.67	3.5
			σ_m	0.21	0.20	0.17	0.21	0.20	0.26	0.36	0.71

* Binaural and untrained with short post-exposure life.

Examination of table VII reveals that the greatest injury is found in the lower and middle portions of Turn II and the upper and middle portions of Turn I. It can be seen that as the duration of the exposure increases, the severity of the injury increases. Also, the longer the exposure the greater the spread of the injury along the basilar membrane.

Note that a group of binaural, untrained cats is included in table VII. This group was used to control against the possibility that some aspect of our laboratory procedures increased the cats' susceptibility to noise. For example, it was feared that perhaps the destruction of one ear, or the laboratory diet, or the training procedure in some unknown way made the cats susceptible to the noise exposure. In order to control against these possibilities seven cats were exposed to the noise in the very same morning that each was received from the dealer. These cats were perfused between 2 and 4 hours after the cessation of the noise. Two of the cats were discarded because evidence of middle-ear infection was observed during post-mortem examination. Ten ears from five cats were examined and rated for cochlear injury. The results in table VII show that injury was present in these cochleas, although the ratings are not quite so high as those for the trained cats with long post-exposure lives.

Overall, the histological findings are consistent with the behavioral findings. Permanent injuries inferred from the behavioral findings were, in fact, observed. Untrained cats that had never lived in the laboratory showed injury patterns that were similar to those observed for trained cats. Differences that do exist in the histological findings for trained and untrained cats can probably be attributed to differences in the lengths of their post-exposure lives. See Chapters IX and X for more detailed accounts of the histological findings and their relations to the audiograms.

Recovery

Temporary threshold shifts (TTS's) that are induced by exposure to sound are defined as those threshold shifts which recover to zero. Persistent or permanent threshold shifts (PTS's) that are induced by sound are those stable threshold shifts that remain after the completion of recovery.

In a case where noise exposure produces PTS, we believe that threshold shifts measured before recovery is complete should be distinguished from TTS. This distinction is proposed on the general grounds that recovery from an exposure to noise which has produced a new and permanent injury may involve complex interactions among fatigue processes, temporary injuries, and permanent injuries which differ from those factors controlling recovery from "pure" TTS. This distinction also is proposed on the specific grounds that, for the conditions that we have studied, "pure" TTS has different frequency characteristics than "pure" PTS. For these reasons we shall use the term compound threshold shift (CTS) to describe threshold shifts that have both temporary and new permanent components.

While recovery from TTS has been extensively studied by Ward, Glorig, and Sklar (refs. 37-39), and others, only few data on the recovery from the temporary components of CTS's have been available. Knowledge of the course and duration of the recovery from CTS to the final PTS level is required for the design of experiments, the practical decisions of hearing conservation, and for theories of the recovery process. Moreover, it is obvious that before a threshold shift can be asserted to be permanent, the recovery from the temporary components of the CTS must be shown to be complete.

Initial data on the recovery from the temporary components of the CTS were obtained during the preliminary experiments. After a single exposure to noise, the cats in these experiments were tested periodically throughout their post-exposure lives, which ranged from three to six months. Recovery followed a regular and decelerating course, the major portion of the recovery occurred within 1 to 5 weeks after the exposure to noise, and, generally, recovery was completed in the first two post-exposure months. While in most cases the post-exposure thresholds were remarkably stable, this was not true in all cases. At some frequencies some of the cats did recover an additional 8 to 13 db during the third and fourth post-exposure months. Because of several difficulties encountered in these preliminary experiments, we doubt that these cases of additional recovery were due to auditory processes.

Our most reliable and extensive set of data on the recovery from the temporary components of CTS were obtained during the later experiments. Recovery curves for the test frequencies of 0.25, 2.0, and 8.0 kc are shown in figure 20 as examples of these results. On each panel of this figure, the abscissas are the times after exposure in days, while the ordinates are the mean threshold shifts in decibels. The parameter is the duration of the exposure to the noise. A hat over a symbol means that at least one cat in the group had a threshold shift so large that he did not respond at the audiometer's maximum output. The dotted lines, which connect the symbols with hats, represent lower bounds on these mean recovery curves. The broken lines and open symbols represent data from the preliminary experiments, while the solid lines and solid symbols represent data from the later experiments.

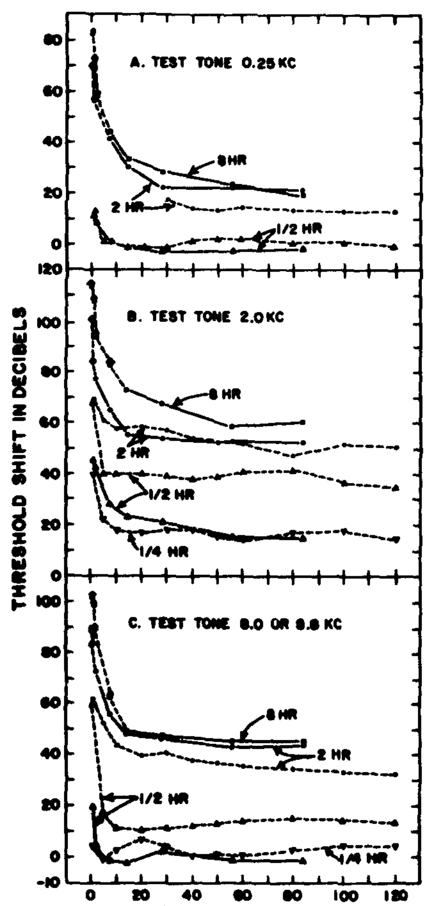

FIGURE 20. Recovery of the Threshold Shift After Exposure to the Broad-Band Noise at an Overall SPL of 115 db

The parameter is the duration of the exposure to noise. The abscissas are the times after exposure in days, while the ordinates on each panel are the mean threshold shifts in decibels. Dashed curves and open circles are based on data obtained during the preliminary experiments. The solid points are mean values of threshold shifts measured at the indicated times after exposure during the later experiments. A hat over a symbol means that at least one cat in the group had a threshold shift so large that he could not respond at the audiometer's maximum output. In such cases the maximum output was used to calculate the lower bound on the threshold shift.

The recovery curves for other test frequencies are not shown since they were highly similar to those shown in figure 20. For all frequencies recovery is extremely rapid during the first few post-exposure days, and, thereafter, the rate gradually slows. Also, the duration of the period during which recovery can be observed seems to increase with the duration of the exposure. In almost all cases the curves have become horizontal by 84 days after the exposure.

Since during the later experiments test sessions were run at regularly scheduled times after the exposure, the recovery from threshold shifts will be examined in more detail for these experiments.

The data of these later experiments were examined to determine whether or not recovery had stopped by 56 days after the exposure. For each cat and test-tone frequency, the difference between the 56 and 84 day threshold shifts was examined, using the standard t-test, for statistical significance at the 5 percent level of confidence. Since of 288 tests only 13 proved significant, it seems unlikely that recovery was continuing beyond 56 days after the exposure. The change in the threshold shift during the period from 56 to 84 days after exposure was calculated for all frequencies and cats. Mean values of this statistic were 0.54 db for the 1/2-hour exposure, 0.46 db for the 2-hour exposure, and -0.17 db for the 8-hour exposure. Thus, on the basis of all the recovery data that we have obtained, we believe that recovery from CTS is complete by two to three months after exposure and that for these exposure conditions cases of recovery during the fourth post-exposure month are rare, if not artifactual.

The relation between the time to recover and the duration of the exposure was also examined. Since it is difficult to determine the time at which a recovery curve has reached its asymptote, the following statistic is defined as the period of recovery. This statistic is the number of days required to recover within 6 db of the threshold shift at 84 days, that is, the number of days for threshold shift to fall within 6 db of the PTS. For the cats used in the later experiments, this measure was obtained for each of the test-tone frequencies.

A related variable is a measure of the amount of recovery. It is defined as the difference in decibels between the threshold shift at 1 and 84 days after the exposure; this difference, of course, is the magnitude of the temporary component of the compound threshold shift at the indicated time. In most cases, it was impossible to measure thresholds one day after exposure, since the cat would not respond at the highest intensity of the audiometer. Nonetheless, a lower bound could be obtained on the amount of recovery.

Table VIII shows both the period of recovery and the amount of recovery as they were defined above. The duration of the recovery period increases with the duration of the exposure. The periods of recovery for the average threshold shift are 11.1 days for the 1/2-hour exposure, 18.7 days for the 2-hour exposure, and 32.9 days for the 8-hour exposure. Examination of the data for individual frequencies also supports the notion that the time to recover increases with the duration of the exposure.

The total amount of recovery as represented by the difference between the threshold shifts at 1 and 84 days after the noise shows a regular increase with the duration of the exposure. The last column of table VIII shows that the magnitudes of the temporary component of the threshold shifts at one day after exposure are, on the average, 23.1 db, more than 39.2 db, and more than 49.7 db, for the 1/2, 2-, and 8-hour exposures, respectively. In the case of the 1/2-hour exposure, only the data for test tones of 0.5, 1.0, 2.0, and 4.0 kc are relevant to the recovery of the CTS to the PTS, for no PTS's were measured at other frequencies.

Another feature of these data on recovery is the lack of a strong dependence on frequency. There is some indication in the case of the 2-hour exposure that the recovery continues over a longer period at low frequencies than high frequencies.

When the data from all experiments are considered, nonetheless, strong frequency effects become apparent. As will be shown in Chapter X, the longest recovery periods usually are observed for frequencies having the greatest PTS. Changes in the shape of the audiogram as recovery proceeds also are discussed in Chapter X.

TABLE VIII

AMOUNT OF RECOVERY AND THE DURATION OF THE RECOVERY PERIOD

For each exposure condition the mean difference between the CTS measured 1 day after exposure and the PTS measured 84 days after exposure is shown. Also shown are the mean number of days to recover with 6 db of PTS. Only the data of the later experiments are used.

Exposure Duration		Frequency in Kilocycles 0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	Mean (125-16,000 cps)
1/2 hr	1d-84d	8.0	17.1	22.2	33.7	30.9	33.3	20.4	17.2	24.8	23.1
	Days of Recovery	12.3	7.5	9.9	19.2	26.1	10.8	4.0	1.8	2.0	11.1
	N = 3 cats										
2 hr	1d-84d (lower bound)	41.1	47.8	50.8	43.1	32.4	40.8	34.9	30.3	35.6	39.2
	Days of Recovery	23.3	20.1	27.7	17.5	18.9	16.6	17.9	18.5	22.7	18.7
	N = 4 cats										
8 hr	1d-84d (lower bound)	48.6	52.5	61.1	51.6	47.2	48.1	52.5	36.2	47.6	49.7
	Days of Recovery	31.3	40.4	34.8	40.1	28.0	31.8	21.8	34.1	36.8	32.9
	N = 6 cats										

Comparison with Other Data for Cat and Man

These experiments show that sizeable persistent threshold shifts are induced when an awake cat is exposed to the broad-band noise for 1/4 to 8 hours at an overall SPL of 115 db. Lindquist, Neff, and Schuknecht (ref. 20) did not encounter persistent losses for the cat after exposure to noise at 107 db for durations as long as one hour. Since their noise was similar to the noise of our experiments, we conclude for exposure durations of this range that injury to cat's inner ear begins at an intensity between 107 and 115 db. Although recent results by von Schulthess (ref. 31) support this conclusion, other results for the cat are surprising in light of our findings. Hawkins, Lurie, and Davis (ref. 18) exposed a few unanesthetized cats to pure tones of 500 cps at about 150 db for durations from 1/2 to 8 minutes. In this case neither the cochlear microphonic or the histological findings indicated permanent damage to the cat's ear. On the other hand, guinea pigs or anesthetized cats exposed to the same condition show serious auditory injury. The authors suggested that the resistance of the unanesthetized cat to very intense tones may have been due to protective actions of the ear. It may be then that the difference between our findings and those of Hawkins, Lurie, and Davis is that the cat's protective mechanisms are strongly dependent on frequency as shown by Simmons (ref. 32) and, perhaps, also dependent on intensity as suggested by Loeb and Riopelle (ref. 21).

The data available for man lead to the conclusion that the exposure conditions of our experiments which produced PTS's for cat would not produce PTS for man. In particular, Davis and Associates (ref. 7) report data for men exposed to noise similar to the one we used to deafen cats. Overall SPL's of 110, 120, and 130 db and durations from 1 to 32 minutes were used; also, one exposure at an overall SPL of 120 db had a duration of 64 minutes. While large TTS's were found, no persistent threshold shifts resulted from these exposures.

It will be recalled that on the basis of a comparison of TTS for cat and man, it was estimated that man would require, for the same TTS as cat, an exposure about 18 db greater than that for the cat. If this difference be correct for susceptibility to permanent injury, then 133 db would produce results for man similar to those for cat. This prediction does not seem at variance with the known data for man.

The difference between cat and man in susceptibility to PTS can be estimated from known properties of their ears and hearing. Above 500 cps, the cat's auditory sensitivity to tonal sound fields is at least 8 db better than the comparable sensitivity of man. If this difference is due to properties of the external and middle ears of these animals, then, in a given sound field, at least 8 db more energy is reaching the inner ear of cat than that of man. But once in the cochlea, a greater bandwidth is mapped onto a millimeter of the cat's basilar membrane than onto a millimeter of man's basilar membrane, as inferred by Elliot, Stein, and Harrison (ref. 15), Greenwood (ref. 17), and Watson (ref. 41). In the case of a broad-band noise, this factor could increase the exposure of cat over that for man by a factor equivalent to an SPL change of about 3.0 to 7.0 db. Thus, 11 or more db of the tentative 18 db difference between cat and man can be accounted for by the acoustic properties of the external, middle, and inner ears.

Hypothetical Growth of PTS and Related Variables

Several important variables have been related to the duration of the exposure to noise. These are the amount of PTS, the size of the temporary component of CTS at any particular time after exposure, and the time required for recovery from the temporary component of CTS. Unfortunately, the relations between these variables and the exposure duration are complex and not completely determined by our experiments. Our best estimates of these relations are given in the text below and illustrated in figure 21. The discussion below is limited to exposures to the broad-band noise at the 115-db level, and only test-tones in the mid-frequency range from 1 to 4 kc are considered.

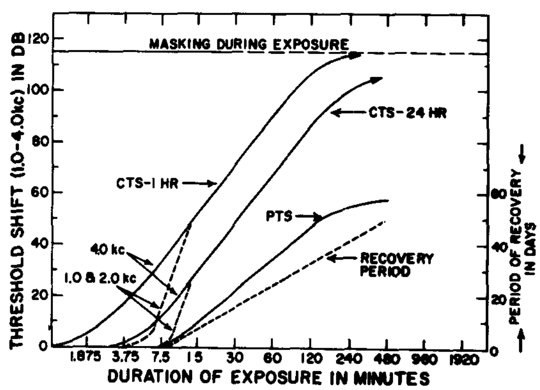

FIGURE 21. Hypothetical Growth of CTS, PTS, and the Period of Recovery for a Typical Cat Exposed to the Broad-Band Noise at an Overall SPL of 115 db

Although the lines of this graph are hypothetical, they are drawn in a fashion consistent with the available data. The abscissas are the durations of the exposure in minutes placed along a logarithmic scale. The left-hand ordinates are the threshold shifts in decibels, while the right-hand ordinates are the periods of recovery in days.

We believe that post-exposure threshold shifts cannot exceed those measured in the presence of the noise; that is, the masking produced by the noise. It is possible to estimate the amount of masking produced by the broad-band noise using measurements made by Watson (ref. 41). The horizontal line at about 117 db in figure 21 indicates the amount of masking for the conditions under consideration and it reflects our assumption that the amount of masking places an upper bound on post-exposure threshold shifts. Compound threshold shifts, measured 1 or 24 hours after cessation of the noise, are shown approaching the assumed upper limit. Note, nonetheless, that throughout a broad range of exposure conditions both CTS and TTS are shown as linear functions of the logarithm of exposure duration.

If the duration of the exposure is less than about 7.5 minutes, only temporary threshold shifts are observed. As the duration of the exposure increases to 15 minutes, permanent threshold shifts are induced, and the shifts become, on the average, equally severe for each of the mid-frequencies. The initial branching of the functions labelled CTS indicates that greater shifts are found at 4 kc than at 1 or 2 kc for those short durations of exposure that only produce TTS.

It was noted earlier that the exact course of the growth of PTS cannot be determined from the present data. Our best guess about this growth is shown in figure 21 by the line labelled PTS. Over its linear portion, the slope of this curve appears to be less than that for CTS. It is not known whether or not the PTS-curve reaches a maximum. One cat (No. 90) did have PTS's as large as 78 db after an exposure of 8 hours; perhaps, more typical cats would reach PTS's of that size if the duration of the exposure were made sufficiently long.

The number of days required for recovery from the temporary component of CTS is also shown in figure 21. The reader should recall that the duration of the recovery period is defined here as the number of days required for the CTS to reach a level within 6 db of the PTS. So defined, the duration of the recovery period appears to grow as a linear function of the logarithm of the duration of the exposure. We conjecture that this function must reach, and perhaps pass through, a maximum. This conjecture follows from the hypothesis that for any exposure spectrum only a given set of structural elements in the sensory system can be temporarily or permanently injured. For sufficiently long durations of exposure, it is hypothesized that all elements which can be permanently injured have been so injured; furthermore, it is suspected that only a few elements would remain that could be temporarily injured by the spectrum. Thus, for extremely long exposures, the temporary component of CTS would probably be small and recovery from it would be relatively quick.

VII. PERSISTENT THRESHOLD SHIFTS FROM SPACED EXPOSURES TO NOISE

In this set of experiments the effect of breaking up a long continuous exposure into a series of short, spaced exposures was examined. Because it was known that exposure to the broad-band noise for 1/8 hour at an overall SPL of 115 db produces little or no permanent injury, this duration was chosen for all of the short exposures in the series. Furthermore, because a continuous exposure to the noise at 115 db for 2 hours was known to produce sizeable PTS, all cats were given 16 of the short exposures to noise and, thus, were exposed a total of 2 hours.

Four groups of four cats each were exposed according to the following schedules. Group I received a 2-hour exposure to the noise which was continuous in time. Groups II, III, and IV were exposed to the noise in sixteen, 1/8-hour doses. These doses were spaced, from onset to onset, at 1-hour intervals for Group II, at 6-hour intervals for Group III, and at 24-hour intervals for Group IV. Since the level of noise was constant for all groups and since all cats were exposed for a total of two hours, all cats were exposed to the same total energy.

Temporary and Compound Threshold Shifts During a Series of Exposures

The cats in Group IVa* were first used to determine the TTS audiogram for the single, 1/8-hour exposure, and these data were presented in figure 14 of Chapter V. About one month after the first exposure to the noise, a series of 16 of these 1/8-hour exposures, which were spaced at 24-hour intervals, was begun on the cats of this group. These animals were tested at 2.0 and 4.0 kc before and after each exposure. These tests were accomplished during the 1-hour period preceding the exposure and during the 1-hour period that began 30 minutes after the exposure. For three control days prior to the beginning of the experiment the threshold tests were conducted, but there were no exposures to the noise.

The effects of this series of exposures are shown in figure 22. The threshold shifts at 4.0 and 2.0 kc are shown in the upper and lower panels, respectively. Throughout this series of exposures the reference thresholds are the normal thresholds which were established prior to beginning the series. The squares on the left-hand portion of the figure show the results of the original 1/8-hour exposure to the noise, which was given one month prior to the series of 16 exposures. The circles on the left-hand portion of the panels show the control results obtained when the noise is omitted. To the right of the vertical line on each panel the results obtained during the sequence of the 16 successive exposures are shown. The striking finding shown in figure 22 is that the size of the threshold shift decreases during the series of exposures to noise. Although this decrease is reliable, it is not understood. It may be that somehow the cats were becoming more resistant to the noise. Or, it may be that the cats suffer a post-exposure tinnitus and that the decreases in the threshold shift reflect the possibility that the cats learn to distinguish the test tone from the tinnitus.

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* The cats in Group IV had the following history of exposure to the broad-band noise at 115 db: (1) one 1/8-hour exposure (Chapter V on TTS), (2) a series of 16 spaced exposures with an inter-exposure interval of 24 hours, (3) a series of 8 spaced exposures also at an inter-exposure interval of 24 hours, and (4) a continuous 2-hour exposure. Group IV is termed Group IVa for the exposures listed under (1), (2), and (3). These same four cats are called Group IVb for the exposure listed under (4).

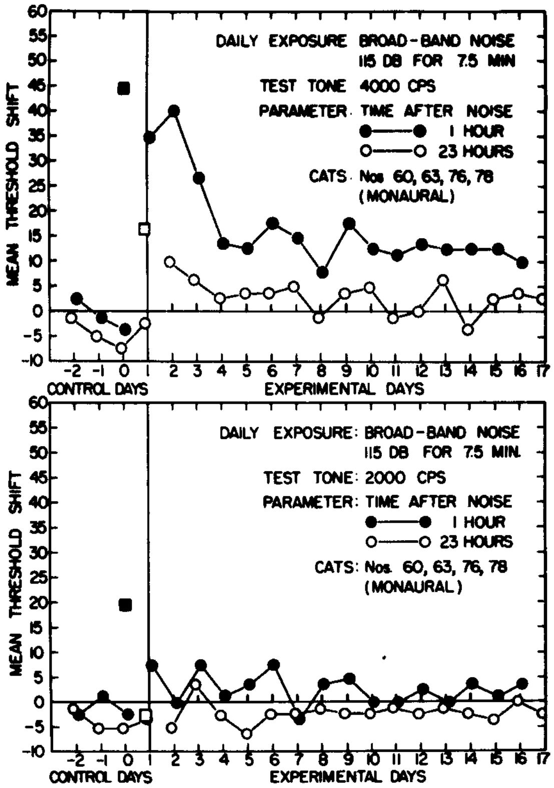

FIGURE 22. Threshold Shifts Measured Before and After Each of a Series of Exposures to the Noise

For this case the inter-exposure interval (IEI) was 24 hours; each exposure to the broad-band noise was for 7.5 minutes at an overall SPL of 115 db. The ordinates are the mean threshold shifts in decibels re the threshold before the beginning of the experiment. The filled symbols in all cases are measures taken during the period from 30 to 90 minutes after exposure. The open symbols represent threshold shifts measured approximately 23 hours after an exposure. The circles on the left-hand portions of the graphs show the results of tests on three control days when the noise was not turned on. The squares on the left-hand portion are the comparable data points for these four cats after they had been given a single exposure to the noise for 7.5 minutes approximately one month prior to the series of sixteen successive exposures. The results of this single, previous exposure are shown in more detail in figure 14 in Chapter V.

After a four-month rest from the noise these cats were given a second series of eight exposures. The schedule was the same as before, and the results, although they are not shown, matched those of the last seven days of the first series. If the decline of TTS during the first series represents a learning phenomena, then there was no forgetting after a 4-month rest. After an additional 1-month rest, these cats were exposed to the uninterrupted noise for 2 hours. For the purpose of presenting the result of the continuous exposure, this group is referred to as Group IVb. (Because Group IVb and Group I received the same continuous exposure for 2 hours, there were eight cats under this condition. The data for these eight cats are presented here and in the previous chapter.) It should be noted here that these cats in Group IVb were neither more nor less susceptible to the continuous exposure of 2 hours than those of Group I who had no previous exposure to the noise. Thus, if the cats in Group IV did learn to protect themselves from the short, 1/8-hour exposures, their learning did not help them in the case of the longer 2-hour exposure.

The growth of threshold shift during the series of exposures is shown for all of the groups of this experiment in figure 23. (The results for Group IVa previously shown in figure 22 are also shown in figure 23.) For all groups these measurements were made about 1 hour after each cessation of the noise. The solid symbols are for the threshold shifts at 4 kc, while the open symbols show the shifts at 2 kc. The squares, triangles, and circles represent inter-exposure intervals (IEI's) of 1, 6, and 24 hours, respectively. First examine the results for the inter-exposure interval of 1 hour. During the initial four or five exposures, there is only a slight increase in the threshold shift. After exposure number five, the threshold shift begins to increase. Note that as this series was continued the mean value of the threshold shift reached a lower bound of about 88 db. Because of the short time between exposures these cats were tested at 2 kc only after exposures No. 6, 7, 10, and 12. Note, however that by exposure No. 6 the shift at 2 kc is large and about the same as the shift at 4 kc. Next examine the results for the inter-exposure interval of 6 hours. Note that the shift at 4 kc initially increases and then slowly decreases. In contrast with other groups, this condition results in roughly constant threshold shift at 4 kc. The shift at 2 kc, however, follows a different course. After exposures No. 1, 2, and 3 little shift is observed at 2 kc; but after the fourth exposure, the shift at 2 kc suddenly becomes about as large as the shift at 4 kc. While the significance of this jump in the threshold shift at 2 kc is unknown, it may mark the beginning of permanent injury.

Comparisons among the conditions for this portion of the experiment show that the threshold shifts measured during such a series of exposures may increase, remain approximately constant, or decrease.

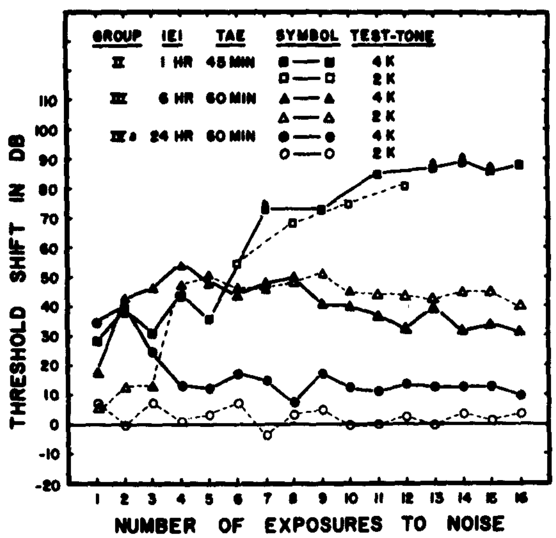

FIGURE 23. The Growth of Threshold Shift During a Series of Sixteen Exposures to the Broad-Band Noise

Each exposure is at an overall SPL of 115 db for a duration of 7.5 minutes. The parameters are the inter-exposure intervals (IEI) and the frequency of the test tone.

Recovery and PTS for Spaced Exposures

The build-up of the threshold shift during the series of exposures was shown above. Figure 24 shows the recovery from threshold shift after the final exposure in the series. The top two curves display for the continuous exposures the recovery of the mean thresholds, as shown by the reduction in the mean threshold shifts. The bottom three curves show the recovery after the series with inter-exposure intervals of 1, 6, or 24 hours. It can be seen that orderly recovery curves, which are asymptotic to values above zero, are obtained for the topmost four curves, while the 24-hour spacing resulted in little or no PTS. All of the data on recovery from the spaced exposures are consistent with those found for continuous exposures; that is, the more severe the threshold shifts, the longer the period of recovery. Recovery to an asymptotic value is complete in all cases by 56 days after exposure.

The relation between mean PTS and the inter-exposure interval is shown in figure 25. Symbols on this figure represent the results for individual cats and the mean of each group is shown by the line. Inspection of this curve shows that while an inter-exposure interval of one hour reduces the mean PTS, the inter-exposure interval must be extended beyond six hours if all cats are to be protected from persistent threshold shifts. It is apparent then, that for exposure schedules similar to those used here, a very small duty-cycle of the order of 1.0 percent or

0.5 percent is required in order to reduce PTS to nearly zero for all cats. An electrophysiological investigation by Eldredge, Covell, and Gannon (ref. 14) supports this view. For equated total exposure energy, a 28 percent duty-cycle and a 100 percent duty-cycle were equally injurious for intense exposures.

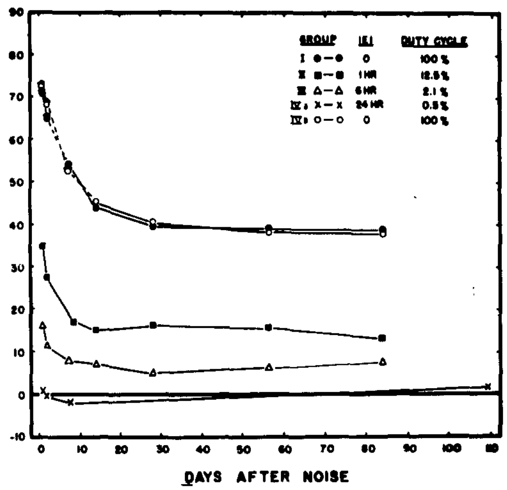

FIGURE 24. Recovery of the Threshold After a Series of Sixteen Exposures to the Broad-Band Noise

Each exposure was at an overall SPL of 115 db for a duration of 7.5 minutes. The abscissas are the days after the last exposure in the series, while the ordinates are the threshold shifts averaged over the eight octave steps from 125 to 16,000 cps (CPS). The parameter is the interval between the successive exposures. Note that for the continuous condition, the symbols with hats should be taken as lower bounds on the sample means.

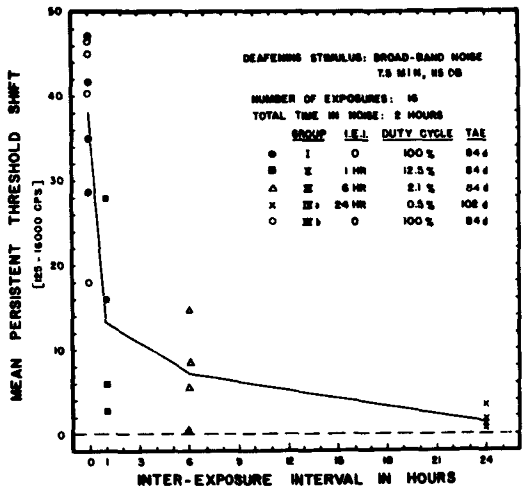

FIGURE 25. Reduction in PTS with Increasing Inter-Exposure Interval

The symbols show the results for individual cats, while the lines connect the group means. The abscissas are the inter-exposure intervals in hours; the ordinates are values of PTS in decibels. The times after exposure at which the PTS's were measured are shown on the figure.

It is interesting to note the equivalent continuous exposure for each of the inter-exposure intervals. The inter-exposure intervals and their equivalent continuous durations are respectively as follows: 0 hour, 120 minutes; 1 hour, 48 minutes; 6 hours, 24 minutes; 24 hours, 9 minutes. These values were found by interpolation on figure 16.

The wide individual differences in susceptibility to the noise exposure should be noted. As in the case of the continuous exposures, these cats differed only slightly in their auditory sensitivity before exposure to the noise. Although an analysis of variance allows us to infer that the downward trend which is present in the graph is present in the population, it is obvious that the course of this downward trend is only crudely established by these variable sample data.

Table IX shows the mean values of PTS for each of the conditions of the present experiment. Also shown are the standard errors of the mean, σ_R and σ_m, that are based on the intra- and inter-cat variances, respectively.

Table X shows the injury ratings for these animals. These findings are consistent with the audiometric data of this section.

The mean PTS audiograms for the several inter-exposure intervals are shown in figure 26. The shapes of these audiograms do not seem to differ significantly from those resulting from continuous exposure to noise. It should be noted again that the major loss falls between 1.0 and 4.0 kc.

TABLE IX

PERSISTENT THRESHOLD SHIFTS AFTER SPACED EXPOSURES TO THE BROAD-BAND NOISE FOR EACH INTER-EXPOSURE INTERVAL (IEI)

The standard errors of the means based on the inter-cat variance, σ_m, and the intra-cat variance, σ_R, are also shown.

			Frequency in Kilocycles/Second									
Group	IEI		0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	PTS
I	0	PTS	16.2	23.0	42.8	53.2	49.7	47.6	47.4	25.7	>38.2	38.2
		σ_m	6.31	6.16	6.45	6.06	7.00	8.53	7.94	16.11	-	3.97
IVb	0	PTS	14.6	19.6	30.2	48.7	54.9	36.7	40.4	35.9	>39.4	37.6
		σ_m	2.69	5.37	11.44	12.60	4.31	2.57	9.83	11.60	-	6.63
II	1	PTS	6.0	6.8	13.2	17.0	22.5	26.8	11.0	2.8	-0.8	13.2
		σ_m	4.02	5.84	9.93	9.39	8.50	11.31	6.57	3.77	3.20	5.74
III	6	PTS	0.2	4.8	9.2	16.8	16.0	14.0	-1.0	-2.25	2.25	7.2
		σ_m	1.44	1.89	4.27	9.99	9.70	7.94	0.82	2.18	1.38	3.06
IVa	24	PTS	2.2	2.0	1.1	0.8	0.0	5.9	4.2	-2.0	-2.4	2.3
		σ_m	2.83	0.96	2.75	0.60	1.74	2.59	2.71	0.65	1.01	0.61

σ_R for $f \leq 1.0$ kc = 1.7 db
for $f > 1.0$ kc = 2.2 db

σ_R for $\overline{PTS}$ = 0.7 db

TABLE X

MEAN INJURY RATINGS FOR COCHLEAS OF CATS EXPOSED TO THE BROAD-BAND NOISE FOR TWO HOURS

Data are shown for continuous and for spaced exposures with IEI's of 1 and 6 hours.

IEI*	Number of cats		(Mean)	Location of Injury: III A	U	II M	L	U	I M	L
			mm from R.W.	20.5	17.0	15.3	13.5	10.8	7.5	4.5
			Equivalent Frequency in kc/Second	0.15	0.7	1.09	1.7	3.4	7.6	17.0
0**	12	I	2.88	1.79	2.13	2.88	3.67	3.83	3.04	2.88
		m	0.16	0.11	0.14	0.19	0.24	0.28	0.28	0.33
1	4	I	2.25	1.63	2.13	2.75	3.25	2.63	2.0	1.38
		m	0.29	0.12	0.24	0.48	0.32	0.37	0.34	0.24
6	4	I	1.77	1.50	1.88	2.00	2.13	2.00	1.63	1.25
		m	0.14	0.20	0.12	0.35	0.24	0.20	0.12	0.14

* Histological data not available for animals with IEI of 24 hours, since these cats were given an additional continuous exposure.

** Same data as those shown in table VII for trained cats given a 2-hour exposure which was continuous.

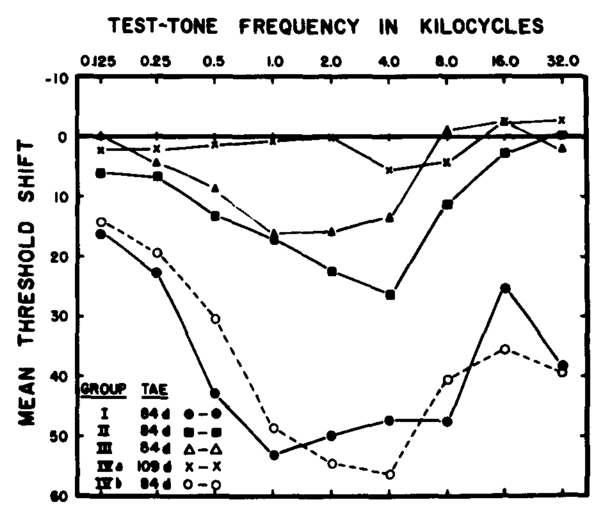

FIGURE 26. Mean PTS Audiograms for Groups Exposed to the Broad-Band Noise in 16 Doses of 7.5 Minutes in Duration

Inter-exposure intervals of 0, 1, 6, and 24 hours were used for Groups I, II, III, and IVa, respectively. Group IVb was exposed continuously; that is, the inter-exposure interval was zero.

One other interesting relation was suggested in these data. Differences in PTS's among cats were positively correlated with their CTS's measured 2 hours after the final exposure in the series. This relation was noted for both the 1-hour and the 6-hour inter-exposure intervals, but the intercept of the regression line depends on the experimental condition. For example, if the average PTS for 2.0 and 4.0 kc be 30 db, then the corresponding CTS's measured 2 hours after exposure would be about 55 db and 85 db for the 6-hour and the 1-hour inter-exposure intervals, respectively. Table XI summarizes the data relevant to this point. If these trends be true, then to predict PTS's from CTS's the exposure conditions would have to be specified.

TABLE XI

COMPOUND THRESHOLD SHIFTS AND PERSISTENT THRESHOLD SHIFTS
AFTER A SERIES OF SPACED EXPOSURES TO NOISE

CTS is the mean of the CTS's measured 2 hours after exposure at 2 kc and 4 kc. The PTS is the corresponding average of the threshold shifts 84 days after exposure, while $\overline{PTS}$ is the average across frequencies. Results are shown for inter-exposure intervals of 1 and 6 hours.

IEI	CAT	$CTS_{2\ hr.}$	PTS	$\overline{PTS}$
1 hr.	72	64.8	1.0	2.8
	50	77.8	16.5	6.0
	69	85.5	41.5	16.0
	39	98.5	39.5	28.2
6 hr.	52	-4.0	3.0	0.0
	56	39.0	3.5	5.8
	74	57.8	23.5	8.4
	62	52.0	30.0	14.8

Discussion

The experiment reported above was designed to provide information concerning the effects of interspersing silent intervals between exposures to noise. In the case of TTS it has been shown that rest intervals reduce the TTS present at the completion of a series, see for example Ward, Glorig, and Sklar (refs. 37, 40). But this finding is expected for TTS, since TTS by its nature and definition is a quantity which does, in fact, recover in the absence of sufficient stimulation. In the case of PTS, it was not at all obvious that breaking up an exposure by rest intervals would reduce the total permanent injury. For PTS by its definition is persistent and it is not clear that rest intervals should somehow allow recovery from it.

Nevertheless, the data that have just been presented show that both CTS and PTS decrease with increases in the duration of the silent interval between successive exposures to the noise. While trying to analyze this experiment, it became apparent that an understanding or conception of the processes underlying the build-up of PTS or injury during a series of spaced exposures depends on an understanding or conception of the processes underlying the results of the simpler experiment of increasing the duration of a continuous exposure to noise.

Stochastic Models - Why does increasing the duration of an exposure to noise increase the amount of injury? While the answer to this question is not known, it is clear that the role of the duration of an exposure depends upon the injurious action of the noise. Two views of this action are sketched below and their implications are discussed. One view is that during any very short period of time the probability of permanent injury to a particular sensory element of the inner ear depends on the spectral and intensive properties of the noise and that this probability is independent of the duration of the noise. According to this view, an increase in the duration of an exposure increases the opportunities for injury and, therefore, the total number of permanently injured sensory elements increases with the duration of the exposure. A mechanical conception which corresponds to this view would be that on any portion of the basilar membrane a measure of its motion controls the probability of injury.

A second view of the injurious action of the noise differs from the first in that the momentary probability of permanent injury to a sensory element depends on the element's history of exposure to noise. According to this notion an element has more than the two states of being either normal or permanently injured. A third state, a susceptible state, is conceived. One can imagine a susceptible state of a sensory element as either metabolic change with structure remaining normal, or as an injury which would heal if further insult be prevented. (It should be noted that the "susceptible state" could be represented as a series of sub-lethal injuries graded from slight to severe.) While in the susceptible state, a sensory element has an increased probability of being permanently injured. Furthermore, an element can return from the susceptible state to the normal state, that is, an element can recover. By these notions the proportion of elements permanently injured during a short interval will depend not only on the spectral and intensive properties of the noise, but also on the number of elements in the susceptible state. The number of sensory elements in the susceptible state will in turn depend on the preceding duration of a continuing exposure or on the opportunity for recovery from a previous exposure to the noise. By this conception the noise must do some work to get an element into a susceptible state, and if recovery is allowed, this work can be vitiated. Our data seem to support this second conception of the process. Nevertheless, it may be that the first conception of the process is closer to the truth in the case of very intense sounds, that is, it seems to us that extremely intense sounds should be able to permanently injure sensory elements immediately without an intermediate step of susceptible state or of sublethal injury.

Protective Mechanisms - There is another possible explanation of the results of our experiment. The cat can protect his inner ear from sound by closing his external ear and by contraction of his intra-aural muscles as has been mentioned by Hawkins, Lurie, and Davis (ref. 18). One might conjecture that these protective mechanisms adapt during a continuous 2-hour exposure, but do not adapt nearly so much during a short, 1/8-hour exposure to the noise. If the recovery of the protective mechanisms depends on the inter-exposure interval, then cats receiving widely spaced exposures would have more active protective mechanisms during a greater proportion of the on-time of the noise than those cats receiving less widely spaced exposures. Thus, the more widely the exposures are spaced, the lower the expected level of stimulation to the inner ear. It seems to us that for the long silent intervals of the present experiment, recovery of the protective mechanisms during the silent intervals would not be very different for the 1-hour, 6-hour, and 24-hour inter-exposure intervals. Therefore, we believe that the role of protective mechanisms was not significant in producing a difference among the three conditions for which the inter-exposure interval was greater than zero. It should be perfectly clear, however, that the difference between the continuous exposure and spaced exposures could be easily explained by the action of the protective mechanisms of the external and middle ear.

VIII. EFFECTS OF OCTAVE-BAND NOISE OF LOW FREQUENCY

The broad-band noise of the previous experiments produced effects in the range from 125 to 500 cps which were surprisingly large. A mean PTS of about 32.0 db was found at 500 cps after the continuous exposures of 2- and 8-hours, and an individual cat had a PTS as high as 61.0 db at this frequency. For these same exposures injury ratings for the apex and the upper part of Turn II attained mean values of 1.79 to 2.75, and individual ratings as high as 3.0 were noted for this portion of the basilar membrane. If the noise energy in the frequency region near 500 cps is largely responsible for these PTS's and injuries, then it should be possible to produce them by exposure to an octave-band of noise (300-600 cps), if the spectrum levels in the pass-band match those of the broad-band noise. The experiments of this section were designed to investigate this possibility.

As a first step in these experiments, the masking pattern of the low-frequency noise was measured. It is believed that these measurements give an estimate of the pattern of stimulation induced by the noise. After the masking data were obtained, the cats were exposed to this low-frequency band of noise and the post-exposure threshold shifts were measured.

Subjects and Apparatus

The loudspeakers used to produce the deafening noise of the previous experiments, see Chapter IV, were placed in the audiometric booth. The speakers were "aimed" at the double-grill cage. The exposures to the noise were administered in the double-grill cage and not in the reverberant room. To produce the octave-band noise the filtered output of a noise generator was amplified, and placed across the speakers. An estimate of the spectrum produced in this way is shown in figure 11 of Chapter IV. This estimate was based on the following: (a) the assumption that the response of the loudspeaker was flat in this region; (b) the fact that the frequency response of the filters was measured and known; (c) the fact that overall level of the noise was measured at 16 positions distributed throughout the double-grill cage. The median value of the overall SPL was taken as the SPL of this octave-band of noise. The test tones were produced in the usual way.

Eight cats were used in these experiments. Four of these, Numbers 53, 59, 61, and 70, had been used in an extensive study of masking of tones by noise reported by Watson (ref. 41), and they had also undergone three brief exposures to the broad-band noise. These previous exposures produced only TTS. The cats' audiograms were normal at the time of the present experiments. The other four cats, Numbers 75, 79, 98, and 99, had not been used in previous experiments.

Masking

Masked thresholds in the presence of the band of noise (300-600 cps) were determined for each of four overall SPLs of the noise, 70, 85, 95, and 105 db. When the noise was at its highest level, 105 db, the limitations of the audiometer made it impossible to measure thresholds near the center of the noise-band; thus, these thresholds had to be estimated from the masking within the pass band of the noise when the overall level of the noise was 95 db or less. For this purpose it was assumed that the signal-to-noise ratio remains constant at the masked threshold. When masked thresholds were measured at the 95-db and 105 db levels of the noise, only one measurement was made per cat per session, and for each cat the time between sessions was about 40 minutes. In this way the possibility of injury being produced during the masking experiments was held extremely low. All eight cats were used for the measurements.

The results of this experiment are shown in figure 27. On this figure the ordinates are the threshold values of the signal in SPL. Along the top of the graph the distance along the cochlear duct is shown in millimeters from the round window. On the bottom of the chart, frequencies are marked at their probable locations of maximum stimulation. (Throughout this chapter the anatomical-frequency scale that was developed by Schuknecht, ref. 28, is used.) The mean masked thresholds are shown by the symbols connected by the heavy lines. The dotted lines show the estimated spectrum plus the signal-to-noise ratio at masked threshold for a uniform noise measured by Watson (ref. 41). The audibility curve for these cats is also shown. The inset shows masking, the difference between the masked and the quiet thresholds for the noise at an SPL of 105 db.

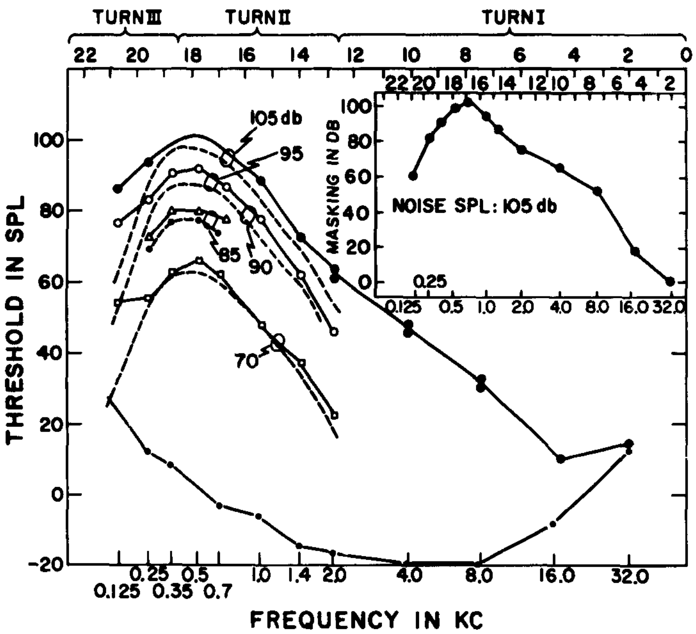

FIGURE 27. Masking Pattern of a 300-600 cps Band of Thermal Noise

The ordinates are threshold values of the signal in SPL. Along the top of the graph the distance along the cochlear duct is shown in mm from the round window. Test-tone frequencies are marked on the bottom of the chart at their probable locations of maximum stimulation. The mean values of the masked thresholds are shown by the symbols connected by heavy straight lines. The dotted lines show the estimated spectrum plus the signal-to-noise ratio at masked threshold as measured by Watson (ref. 41). The curve nearest the bottom of the graph shows the audibility curve for the cats of this experiment. The inset shows the masking, the difference between the masked and quiet thresholds, for the 105-db SPL of the noise. Each symbol on this figure represents the mean of measurements made on eight cats.

Please note that from 0.25 to 2.0 kc there is a close correspondence between the dotted lines and the solid lines. Thus, over a broad range of frequencies the relative values of the masked thresholds may be anticipated from the knowledge of the spectrum and the signal-to-noise ratios of Watson's previous experiment.

The discrepancies between the observed and predicted masked thresholds will now be discussed. First consider the results for the frequencies near-to or included in the pass-band, 0.25, 0.35, 0.5, and 0.7 kc. In this case the 70, 85, and 95 db levels produce about 2 to 4 db more masking than measured by Watson. While the reason for this discrepancy is unknown, it should be noted here that Watson measured signal-to-noise ratios in terms of voltages across the voice coils of the loudspeakers, since the same loudspeakers were used for tones and noise. The signal-to-noise ratio of the present experiments depends on the acoustic calibrations of both the tones and the noise, since separate sources were used. Certainly, in the present situation, these acoustic measurements are more subject to error than are the electrical measurements of Watson.

For the test-tone frequency of 125 cps an unexpected result was obtained. The obtained masking was greater than the predicted amount by 27 db. A listening test showed that hum or a resonance could not account for this 27-db discrepancy. Also, additional threshold tests verified the values of masked thresholds. This finding deserves further investigation. It may be that this large amount of masking is similar to the remote masking of Bilger and Hirsh (ref. 2).

The source of masking present at frequencies above 2.0 kc is unknown, because neither the noise spectrum nor the response of the filter was examined above this frequency.

The lowest curve of figure 27 shows the quiet absolute thresholds for these cats. The difference between the quiet and the masked thresholds are shown in the inset for the 105-db noise. It can be seen that masking is produced over a broad range of frequencies and that the peak in the masking curve is at about 700 cps.

Effects of Short and Prolonged Exposures to the Noise

All of the eight cats were exposed to the noise at the 105-db level for 1/8-hour. Threshold tests were made at 0.35, 0.5, 1.0, 2.0, and 4.0 kc before and during the period from 17 to 42 minutes after the exposure. The order of frequencies was randomized. The mean TTS's were -0.625, -1.25, -0.625, 0.0, -1.875 from the low to high frequencies, respectively. Thus, no TTS could be measured at about 1/2 hour after the exposure.

The cats were then divided into two groups of four cats each. One group, the 8-hour group, was exposed to the 105-db noise for 8 hours, while the other group, the 48-hour group, was exposed to the same noise for 48 hours. As in the previous experiments designed to produce PTS, post-exposure testing followed the schedule given in table V.

Neither group suffered any significant PTS, that is the threshold shifts of all cats were near zero when measured at 84 dats after exposure. Injury ratings were done for these cats' cochleas even though no PTS had been measured. These ratings suggest that permanent injuries were present in the upper part of Turn I and the middle and lower parts of Turn II. These data are shown in figure 28; also shown are the comparable results for the 2-hour exposure to the broad-band noise that was continuous in time. The symbols joined by solid lines show the PTS results, while those joined by the dashed lines show the mean injury ratings. From this figure it is obvious that even though the low-frequency noise was on continuously for periods longer than the broad-band noise by factors of 4 and 24, only negligible threshold shifts could be measured. The histological findings are, nonetheless, that slight injuries occurred in the upper part of Turn I and in the lower and middle portions of Turn II. These injuries are about the same as those noted after exposure to the broad-band noise for 1/2 hour.

The location of the injury does not seem to be coincident with the mapped location of the peak of the noise, or the masking audiogram, or, as it will be shown, with the peaks of the TTS findings.

The TTS measured after the 8- and 48-hour exposures will now be discussed. Figure 29 shows the TTS during the first few weeks after the 48-hour exposure. In panel A of this figure audiograms of individual cats are displayed. Note that three of the four cats have audiograms with two peaks; that is, a low-frequency dip between 0.25 and 1.0 kc and a high frequency dip between 4.0 and 16.0 kc are observed. One of the cats, No. 53, displays a single dip at about 1 kc. Panel B shows the mean audiograms for this group at various times after exposure. Note that both dips are retained as recovery proceeds.

These results were not obtained after the 8-hour exposure. In this case small shifts, usually less than 10 db, were measured one day after the exposure. These small but definite shifts were spread throughout the frequency range. By 7 days after the exposure these shifts were all within normal limits. One exceptional result should be noted; one day after exposure cat No. 70 had a large TTS of 42 db at 8.0 kc. This shift persisted through the second post-exposure day, but by 7 days after exposure it had disappeared.

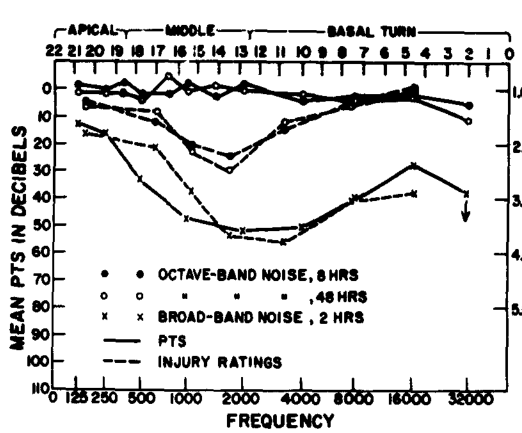

FIGURE 28. Mean Injury Ratings and PTS After Exposure to a Low-Frequency Band of Noise (300-600 cps) for 8 or 48 Hours

Data for an exposure to the broad-band noise are shown for comparison.

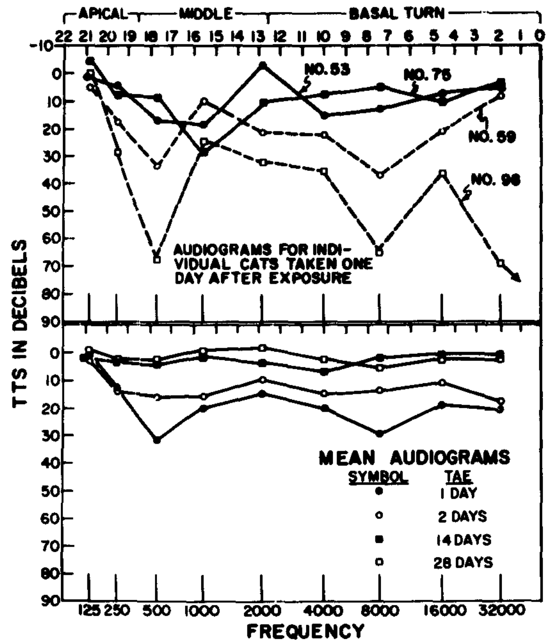

FIGURE 29. TTS After Exposure to Octave-Band Noise (300-600 cps) for 48 Hours

The upper panel shows the audiograms of individual cats measured 24 hours after the cessation of the noise. The lower panel shows the mean audiograms for these cats. These audiograms were measured at 1, 2, 14, and 28 days after the cessation of the noise.

Summary and Conclusions

In this set of experiments the masking pattern of an octave-band of thermal noise (300-600 cps) was measured for an overall SPL of 105 db. These results show that the relative values of the masked thresholds can be anticipated near and above the center frequency of the band, if the spectrum of the noise and the signal-to-noise ratio at masked threshold for tones at the center of a broad-band of noise are known. Nonetheless, unexpectedly large amounts of masking were measured at the lowest frequency of 125 cps.

Exposure of the cats to this octave-band noise for 1/8 hour produced no measurable effects on the threshold at about 1/2 hour after the exposure.

Four of the cats were exposed to this noise for 8 hours, while the remaining four were exposed for 48 hours. In most cases the 8-hour exposure produced slight threshold shifts (less than 10 db) throughout the frequency range. These threshold shifts persisted for about two days. The 48-hour exposure produced more marked threshold shifts (up to 68 db) which recovered over a period of about two weeks. Three of the four cats showed both a low-frequency dip between 0.25 and 1.0 kc as well as a high-frequency dip between 4.0 and 16.0. Neither exposure produced any PTS's which could be confidently accepted as greater than zero.

What appear to be significant injury ratings were noted for both the 8- and 48-hour exposure to this noise. These injuries were in the upper part of Turn I and in the middle and lower portions of Turn II which correspond to frequencies of about 1.0 and 2.0 kc.

Thus, masking has a peak about 700 cps, TTS is widespread with possible peak effects above and below 1.0 kc, PTS appears to be zero, and injuries were noted in a region of the basilar membrane corresponding to 1.0 and 2.0 kc. At the present time the relations among these variables are not understood. It may be that analysis like that of Tonndorf (ref. 35) of the response of the basilar membrane to noise will aid in the clarification of these puzzling relations.

The octave-band noise of these experiments and the broad-band noise of the previous experiments showed nearly identical spectrum levels in the region from 300 to 600 cps. In this frequency range, however, no PTS was produced by the octave-band noise, while large PTS's were measured after exposure to the broad-band noise. Although the locations and magnitudes of the injury ratings are puzzling, those obtained after exposure to the octave-band noise are very much less than those obtained after exposure to the broad-band noise.

The differences between the effects produced by the octave-band noise and those produced by the broad-band noise could be attributed to many factors. For example, the exposure to the broad-band noise was in a reverberant room, while the exposure to the octave-band noise was in a dead room; thus, different directivity patterns existed. Or, it could be argued that the particular frequency content of the band was the critical variable which produced the differences between the two experiments. While both of the above hypotheses have some merit, we believe that the results of this chapter suggest that, at least at low frequencies, PTS and injury are related to the bandwidth of the exposure stimulus. If future experiments confirm the importance of bandwidth, then it will be interesting to determine the relative importance of the associated variables of overall level and peak factor.

IX. HISTOLOGICAL FINDINGS

The Scale for Judging Degrees of Injuries

The injuries to the organ of Corti that were observable by our methods ranged from complete destruction to barely discernible alterations of the supporting and sensory cells. The minimum amount of change that is recognizable by light microscopy and the usual hematoxylin and eosin stains consists primarily of a swelling of cytoplasm, vacuolization, and minor displacements of cells. It is extremely difficult to judge minor changes and it may be that further study by histochemical methods and electron microscopy will explain differences that now exist between minor injuries and the functional tests of the present data. On the other hand, it seems to us that the presence or absence of moderate to severe injuries can be determined with reasonable certainty by ordinary histological methods.

The scale by which injuries were judged is described below. Given in this description are those effects of intense sound which served as the principal criteria for each grade of injury. There are other features of the inner ear which may influence the judging and these are discussed later.

Grade 1.0. No discernible changes.

Grade 1.5. Slight changes are apparent in supporting cells such as Deiters' and internal phalangeal. These are usually found to be cytoplasmic vacuoles or just distinguishable swelling.

Grade 2.0. Mild to moderate changes become apparent in the supporting cells. The nuclei may be enlarged and stain poorly or be slightly shrunken and the cytoplasmic changes more pronounced.

Grade 2.5. Moderate to severe changes in supporting cells without appreciable injury to external hair cells. The internal hair cell may be somewhat altered and the internal phalangeal markedly swollen. A partial collapse of one of the tunnel rods is sometimes present.

Grade 3.0. In addition to the changes listed above (Grade 2.5), external hair cell injury of slight degree is apparent. This consists usually of cytoplasmic changes, but a deeply stained and shrunken nucleus or an enlarged and poorly stained nucleus may be present.

Grade 3.5. Nuclear and cytoplasmic changes in Deiters' cells become marked and occasionally these cells are loosened from the basilar membrane. External hair cell changes are apparent to a moderate degree although the organ of Corti and its reticular lamina are not ruptured. The tunnel of Corti may be almost completely collapsed.

Grade 4.0. (See figure 31) Supporting cells may show moderate to marked changes. External hair cells are extremely altered in an otherwise intact organ of Corti; an occasional one may be missing. The reticular lamina may show a point of rupture.

Grade 4.5. This grade of injury is the greatest that can occur without complete rupture and loss of the organ of Corti from the basilar membrane.

Grade 5.0. The external hair cells and Deiters' cells have been lifted from the basilar membrane. Sometimes the internal hair cell and internal tunnel rod remain in a relatively unaltered state, as may also external and internal sulcus cells. This grade of injury also includes the complete loss of the organ of Corti from the basilar membrane.

The scale given above was used to rate each of seven regions of each cochlea. The histological methods for obtaining stained and mounted sections of the temporal bone were identical to those described for the guinea pigs by Covell and Eldredge (ref. 4) except that the sections of the cat material were usually 18-20 microns in thickness. The approximate locations of the regions which were rated are shown in figure 30. The lower part of the basal turn does not appear in this mid-modiolar section. It should be recognized that these regions are approximate and that neighboring sections were often used to extend and confirm the observations made on the mid-modiolar sections.

FIGURE 30. A Mid-Modiolar Section Through a Cat's Cochlea Showing the Different Turns with the Exception of the Lower or Basal Portion of the First Turn

T_{1M}, middle of first turn; T_{1U}, upper part of first turn; T_{2L}, T_{2M}, T_{2U}, lower, middle and upper parts of second turn; T_A, part of the small apical turn. X 12.

It is worthwhile to compare the present scale for the cat with the previous scale developed by Davis and Associates (ref. 8) for the guinea pig. The results for the guinea pig have been based largely on animals with severe trauma and short post-exposure lives. Discrepancies between this scale and electrophysiological tests of function have been noted by Eldredge and Associates (refs. 11-14) for certain exposure conditions, and examination of the present series of cats has suggested certain changes in the scale. These amount to differences in the emphasis placed on the various signs of injury.

Before discussion of these differences, it should be noted that the data provided by the cats' cochleas differed in two important ways from those previously obtained from the guinea pigs' cochleas.

The cytoplasm of Deiters' cells strains deeper for the cat than for the guinea pig. Some of this may be due to the increase in thickness of the section. It is, therefore, probable that minor changes in the cytoplasm of these cells are detected more readily in cat than in guinea pig.

Unlike most of the guinea pig preparations, nearly all of the cats had long post-exposure lives. It was, therefore, possible to see degeneration of spiral ganglion cells and of peripheral nerve fibers. The presence of these degenerative changes was of value in confirming the importance of the extent and degree of changes in the organ of Corti. They served as a basis for the modification and extension of the importance assigned to various injuries observed in other structures of the inner ear.

The differences in the present scale of injuries and the previous scale for guinea pigs are related primarily to the condition of Deiters' cells. A progression from mild changes in these supporting cells associated with normal hair cells to severe changes in both types of cells seems to have emerged. Accompanying changes in cell groups and membranes other than Deiters' cells, external hair cells, and nerve cells have assumed a position of somewhat less importance. Certain of these features which were previously believed to be necessary for a moderate or severe grade of injury are commented on below.

Rupture of Reissner's membrane is not always consistent with other signs of injury, and it has been observed to occur even with relatively mild changes in the organ of Corti. It should be remembered that even with careful examination of the appearance of the ruptured ends of a membrane, it is not always possible to differentiate ruptures produced by the sound from artifacts produced in the preparation of the sections. Stretching or rupture of one or both layers of Reissner's membrane does not correlate to any great degree with other signs of injury.

The loss of mesothelial cells is not always apparent even for severe grades of injury. Consistent changes in these cells have not been observed when slight and moderate degrees of injury are present to the organ of Corti.

The internal hair cell and its phalangeal cell may sometimes present few, if any, changes in regions showing marked injury to the external hair cells and Deiters' cells. They may show marked injury in regions where the external hair cells and Deiters' cells are relatively unchanged. In other words, the severity of injury to the internal hair cells cannot always be correlated with the grades of injury.

The tunnel of Corti in the presence of damaged supporting cells can undergo varying degrees of collapse, or it may remain fairly well intact as shown in figure 31. In the case of this sign of injury, as in the case of the other ancillary signs mentioned above, no precise relation between it and the scale has been established.

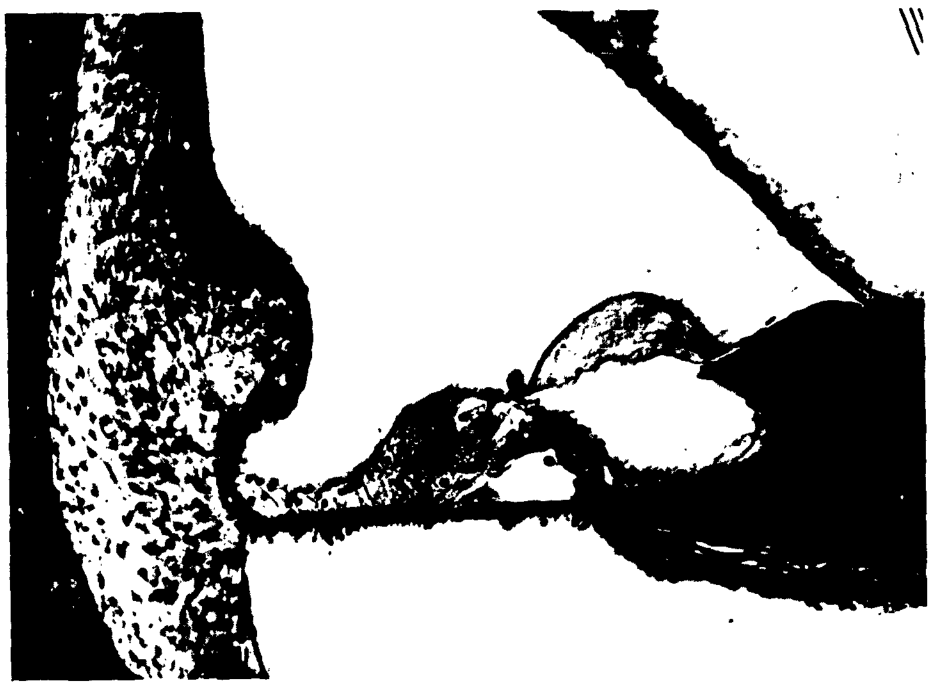

FIGURE 31. Lower Part of the Second Turn of a Mid-Modiolar Section Through the Cochlea of a Cat

The reticular lamina is ruptured, external hair cells and supporting cells are markedly altered. The internal hair and supporting cells show less marked changes. There is some loss of mesothelial cells. This is actually a severe grade of injury although the organ of Corti remains on the basilar membrane and the tunnel is intact except for fracture of the external tunnel rod. There was degeneration of some peripheral nerve fibers and spiral ganglion cells from this area. This was classified as a Grade 4 injury. X 140.

Comments on Findings

In addition to the comments on the histological findings, which are presented below, the following results are presented: The results of the judging of each cochlea are given in the table and the accompanying test of Appendix A; means and variances of the ratings for cochleas grouped by exposure conditions are given in the relevant portions of this monograph; and a comparison of behavioral and histological findings is given in Chapter X.

General - While different animals exposed to the same conditions often had widely different histological findings, the locations of the injuries along the basilar membrane appear to be nearly common to all; the upper part of Turn I and the region from the lower into the middle part of Turn II seem to be the areas of the cat's cochlea that are most susceptible to injury by these exposures. Nonetheless, it should be noted that after the longest exposures of 2 and 8 hours severe injury sometimes included the lower part of Turn I, and rarely, the injuries extended into the apical turn.

Comparison on the basis of duration of exposure - The broad-band noise for 1/4-hour produced changes in the cat's cochlea that were very slight. For the 1/2-hour exposure the injuries were mild in degree, and with the exception of one animal they were found to be greater than those found in the case of the 1/4-hour exposure. The exposures of 2-hour duration produced moderate tc severe injuries, and those for 8 hours resulted in severe injuries.

In the majority of the cochleas the lesions were more in evidence in the middle and upper portions of the first turn and in most of the second turn than in other portions of the cochlea. Approximately one-half of those exposed for 2 hours also revealed moderate to severe injuries in the lower part of the first turn. A pattern similar to that found for the 2-hour exposures was also found for the 8-hour exposures. In the latter all but one cochlea showed moderate or severe injury in the lower portion of Turn I.

In general, it can be stated that the amount of injury increased with the duration of exposure to the broad-band noise. The differences are greatest between the 1/4-hour and the 2-hour exposures, although the injuries became slightly more severe when the duration of the exposure was increased from 2 to 8 hours.

Duration of post-exposure life - A group of untrained cats was sacrificed 2 to 4 hours after exposure to the broad-band noise at 115 db for 2 hours. The severity of the lesions was only slightly less, in most instances, than for the trained cats that had post-exposure lives of 80 to 90 days. Fewer of the untrained cats showed a grade of injury in the lower part of Turn I comparable to that for the majority of the trained cats with long post-exposure lives.

Spacing of exposures - Exposure to the broad-band noise at 115 db in 16 doses of 1/8 hour each (two hours total) with an inter-exposure interval (IEI) of one hour resulted in slight to moderate changes in three and moderate to severe injuries in the fourth cat. When the experiment was repeated with a new set of four cats and the IEI increased to 6 hours, comparatively slight injuries were observed.

If the injuries for the continuous, 2-hour exposures are compared to the spaced exposures with the same total duration, it is evident that the continuous exposures are more detrimental than the spaced exposures. These differences are more marked for the 6-hour interval between exposures than for the 1-hour interval.

Prolonged exposure to an octave band - A narrow band of low-frequency noise (300-600 cps) at an overall SPL of 105 db resulted in slight injuries when the duration of the exposure was 8 hours, and it resulted in slight to moderate changes when the duration was 48 hours.

X. RELATIONS BETWEEN TTS AUDIOGRAMS, PTS AUDIOGRAMS, $\overline{\text{PTS}}$, INJURY RATINGS, AND OTHER DEPENDENT VARIABLES

Introduction

In previous chapters the dependent variables have been grouped and discussed in relation to the parameters of the exposures. In the present chapter the data are organized by the severity of the average threshold shifts, specifically $\overline{\text{PTS}}$, and the major emphasis is placed on the analyses of the relations between dependent variables. This re-examination of the data was prompted by an inspection of the results for individual cats which suggested that knowledge of $\overline{\text{PTS}}$ specified the remaining dependent variables.

For most of the analyses to be presented in this chapter, only data from cats exposed to the broad-band noise are used; thus, the spectrum of the noise is a constant and only the gross temporal characteristics of the noise are variable. That the spectrum was constant makes more plausible the necessary working assumptions that the relations between the dependent variables are largely independent of differences either in the exposures or in the susceptibility of the individual cats. In most instances the data do not seem to conflict with these assumptions.

In the course of the analyses of the relations among the dependent variables the characteristics of the PTS audiograms are described in detail. It is, therefore, convenient to include in this chapter a discussion of the important relations between PTS audiograms, the spectrum of the noise, TTS audiograms, and CTS audiograms.

$\overline{\text{PTS}}$ and PTS Audiograms

The degree to which knowledge of the value of $\overline{\text{PTS}}$ specifies a cat's PTS audiogram is examined below. In the course of this examination the frequency characteristics of the audiograms are described and inferences concerning the growth of PTS are made.

A PTS audiogram is shown in figure 32 for each of 34 cats that were exposed to the broad-band noise. For this figure the audiograms have been ordered with respect to the value of $\overline{\text{PTS}}$, and the rank of the $\overline{\text{PTS}}$ for each audiogram is shown by the arabic numeral in the upper left-hand corner of each panel. Also shown on each panel are the cat's number, the exposure condition, and the value of $\overline{\text{PTS}}$. On this figure C stands for continuous exposure while S stands for spaced exposures. The inter-exposure interval is IEI. Most of these audiograms were measured 84 days after the cessation of the noise exposures. Inspection of figure 32 suggests that the audiograms, when ranked as they are by $\overline{\text{PTS}}$, form a graded series of increasing severity. After examination of this series, it was decided that the major trends shown by the audiograms were most easily described if the audiograms were categorized into five classes. The class of each audiogram is given by the Roman numeral in the upper left-hand corner of each panel of figure 32, and the properties of each class are described below.

The first three panels show the audiograms for the cats in Class I. These audiograms are almost unaffected by the noise, and their $\overline{\text{PTS}}$'s range from -2.7 to 2.8 db.

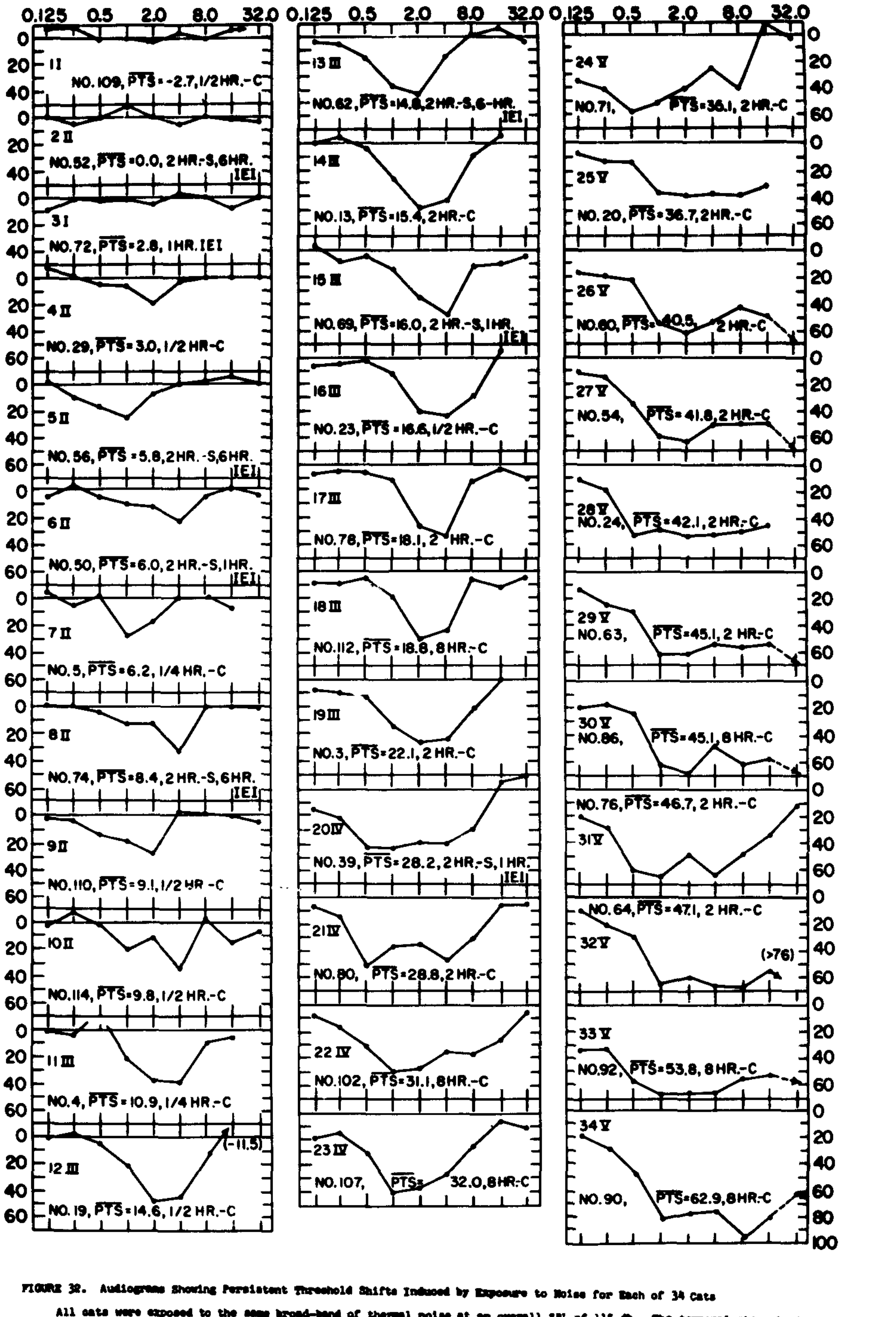

FIGURE 32. Audiograms Showing Persistent Threshold Shifts Induced by Exposure to Noise for Each of 34 Cats

All cats were exposed to the same broad-band of thermal noise at an overall SPL of 115 db. The temporal characteristics of the exposures did differ. The grid marks on the axis of ordinates are 10-db steps, and the grid marks on the axis of abscissas show the frequency of the test tones in kilocycles/second. See text and Appendix B for details.

Class II includes the seven cats shown on the panels ranked 4 through 10. The audiograms in this class have a dip at one of the octave steps in the mid-frequency range, 1.0, 2.0, or 4.0 kc, and $\overline{\text{PTS}}$ ranges from 3.0 to 9.8 db. For two of the cats, the dip is at 1.0 kc; for two others, the dip is at 2.0 kc; and, for the remaining three, it is at 4.0 kc. In all seven cases there is some PTS at 1.0 and 2.0 kc, while only three have significant PTS at 4.0 kc. A transition into the next category is represented by the audiogram for Cat No. 114 shown in panel 10; in this case the dip is broadening to include a range of two octaves.

The audiograms in Class III are shown in panels for ranks 11 through 29; for these nine cats, $\overline{\text{PTS}}$ ranges from 10.9 to 22.0 db. These audiograms are characterized by a dip that includes two of the octave steps. The dip includes 1.0 and 2.0 kc for one of the cats, while for the remaining eight it includes 2.0 and 4.0 kc.

The next four panels, ranks 20 to 23, show the audiograms of Class IV. In this class, $\overline{\text{PTS}}$ ranges from 28.0 to 32.0 db. The audiograms are characterized by large shifts throughout three or four octaves of the mid-frequency range; in Class IV, the shifts are not as great in either the low- or the high-frequency range as they are for the mid-frequencies.

The last eleven audiograms, ranks 24 to 34, were all placed in Class V. The $\overline{\text{PTS}}$'s in Class V range from 35.0 to 62.9 db, and the shapes of the audiograms are distinguished by severe shifts at either the high or the low frequencies as well as the mid-frequencies. Two of the cats present anomalous results. The shape of Cat No. 76's audiogram, rank 31, would place it in Class IV, but the large value of $\overline{\text{PTS}}$ places it in Class V. The histological findings for this animal are consistent with the large threshold shifts. The results for Cat 71, whose rank is 24, are difficult to interpret. This cat's audiogram has its largest shifts in the low- and mid-frequency range. The interpretation of this finding is complicated by the facts that this cat had a slight high-frequency loss before exposure to the noise, that it was probably the oldest of the cats used in these experiments, and surgical destruction of his left cochlea, unlike all other cats in these experiments, was not complete.

The mean audiogram for each of the five classes of audiograms is shown in figure 33. These mean audiograms reflect some of the trends noted in the series of individual cats. In summary, when $\overline{\text{PTS}}$ is less than about 3 db, the deviations from the zero line appear to be random. When $\overline{\text{PTS}}$ lies between 3 and 10 db, a dip which encompasses about one octave is expected in the neighborhood of 1.0 or 2.0 or 4.0 kc. A larger dip centered about 2.0 and 4.0 kc or 1.0 and 2.0 kc can be expected when $\overline{\text{PTS}}$ lies between about 11 and 23 db. For $\overline{\text{PTS}}$'s in the range from about 24 to 35 db, a dip with a broad maximum which covers three or four octaves can be expected. As $\overline{\text{PTS}}$ increases from 35 to 63 db, PTS's increase at all frequencies, but the greatest increases can be expected at the high frequencies.

The data presented in figures 32 and 33 support the hypothesis that knowledge of $\overline{\text{PTS}}$ specifies the PTS audiogram. We further suggest that the sequence of increasing severity shown in figure 32 may be taken as a picture of the development of PTS in an individual cat as the duration of the exposure is increased. It should be recognized that threshold shifts begin in the neighborhood of either 1.0 or 2.0 or 4.0 kc. The area of loss then spreads in the manner indicated by the series shown in the figure. Furthermore, we believe that if a new cat were given one of the exposures in these experiments, the best guess of the shape of his PTS audiogram would be made as follows. The mean value of $\overline{\text{PTS}}$ for the group of cats previously exposed should be determined; then, from figure 32 the audiogram of the cat with a value of $\overline{\text{PTS}}$ closest to the mean $\overline{\text{PTS}}$ should be taken as the predicted PTS audiogram. An alternative procedure would be to use the mean audiogram for the group of cats, which may include audiograms from several classes, and, thus, not reflect the most probable shape of the audiogram for an individual cat.

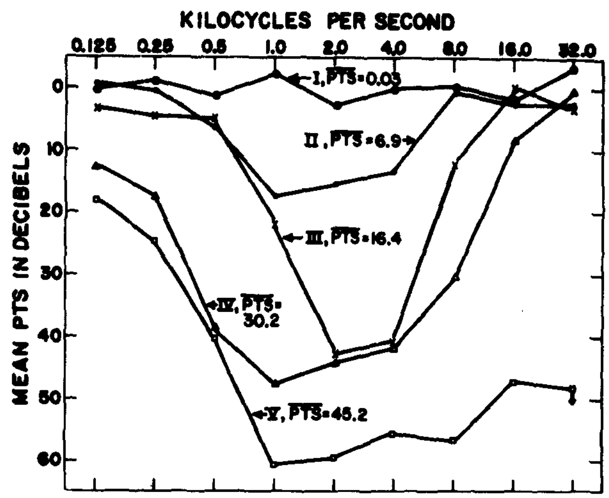

FIGURE 33. Audiograms Showing the Mean PTS for Each of the Five Classes of Severity

On the figure the class is indicated as well as the mean value of PTS.

We also wish to comment here that the audiograms shown in figures 32 and 33 support the common generalization that low frequencies are more resistant to acoustic trauma than are the mid and high frequencies; nonetheless, the large PTS's of up to 35 db at 125 cps and 250 cps or up to 61 db at 500 cps should not be ignored. These very severe PTS's were produced at low frequencies. In general, it should be noted that PTS's in the octaves below 4 kc are more frequent and greater than the shifts in the two octaves above 4 kc. For TTS audiograms produced by exposure to the spectrum quite the opposite is true. This difference is discussed in more detail later in the chapter.

The audiogram categories represented by Classes I to V appear to be sufficiently homogeneous and significant to warrant examination of the mean values of other dependent variables for each class. In the sections that follow, the division of the cats into Classes I to V is used for the examination of the period of recovery and the amount of recovery, for comparison of the behavioral and the histological findings, for comparison of the PTS audiograms with the spectrum of the noise, and for comparison of TTS, CTS, and PTS audiograms.

Period of Recovery

It will be recalled that the time required for the completion of recovery was measured as follows: the number of days required for the threshold shift to reach a value that was 6 db greater than the PTS was found by linear interpolation. Figure 34 shows the mean number of days of recovery for each of the classes of severity. The cats in Class I had no PTS, and, therefore, the days to recover from TTS are shown. For this class recovery is complete at every frequency in less than four days. The curves for Classes II and III, however, show a strong frequency effect. The mid frequencies recover over a longer period of time than do either the low or the high frequencies. The duration of the recovery period differs little for Classes IV and V. For these classes there is a suggestion that the low frequencies require a little more time for recovery than do the high frequencies.

A source of bias in all of the curves of figure 34 is that a few instances of recovery from pure TTS are being averaged with the recovery of the temporary component of CTS. When the instances of TTS were eliminated from the data, the mean curves shown in figure 34 were not appreciably altered.

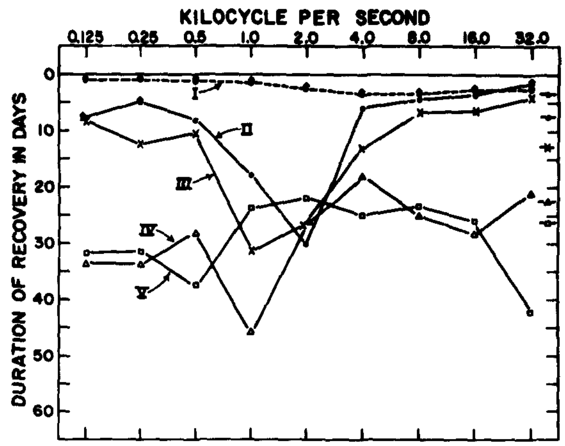

FIGURE 34. Mean Duration of the Recovery Period for Each Frequency of the Test Tone

The symbols on the far right of the figure are the mean number of days for the mean CTS, $\overline{CTS}$, to recover within 6 db of the $\overline{PTS}$. For this analysis the cats were placed in classes of severity of $\overline{PTS}$.

There is great variability in this measure of the duration of the recovery process, and, therefore, interpretations must be made with extreme caution. Nonetheless, it appears that the duration of the recovery period increases with increases in $\overline{PTS}$, at least up to values of 30 or 35 db for the latter variable. The symbols on the right-hand margin of figure 34 show the mean number of days for the average threshold shift at the octave steps from 125 to 16,000 cps ($\overline{CTS}$) to reach a value within 6 db of $\overline{PTS}$. This parameter also increases as the mean $\overline{PTS}$ increases.

Amount of Recovery

In table XII the mean amount of recovery is shown for each of the five classes. These amounts of recovery were calculated by subtracting the PTS from the CTS at one day after exposure; thus, the amount of recovery is defined as the size of the temporary component of the compound threshold shift measured at one day after exposure. If the cat did not respond to the audiometer's maximum output on the first post-exposure day, the threshold was taken as the maximum SPL of the audiometer, and a lower bound on the CTS was calculated. Mean values obtained using these lower bounds for individual cats represent lower bounds on the sample means. Many such instances can be noted in table XII and this fact degrades the usefulness of these particular measures. Nevertheless, it is clear that the amount of recovery—thus, the temporary component of CTS— increases from Classes I to IV. Whether or not there is an increase in the amount of recovery as one goes from Class IV to Class V cannot be determined.

Injury Ratings and PTS

To facilitate the comparison of behavioral audiograms and injury ratings, a plot showing injury ratings as a function of frequency was devised. This was accomplished by converting the locations for which the ratings were made into frequency by means of the map of the cat's cochlea given by Schuknecht (ref. 28). Thus, a plot showing injury ratings in a manner which corresponds to the familiar audiogram was made. The panels of figure 35 show the mean injury ratings for each of the behaviorally defined classes of severity. Comparison of figures 33 and 35 shows a remarkable correspondence between the two sets of data. The only gross discrepancy between these behavioral and histological "audiograms" is for Classes I and II. The behavioral audiograms for these two classes are clearly different, while the mean injury ratings appear to be identical.

TABLE XII

AMOUNT OF RECOVERY ($TS_1 - TS_{84}$) FOR EACH CLASS OF AUDIOGRAM

Audiogram Class		Frequency in Kilocycles/Second 0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	$\overline{PTS}$
I	$\bar{X}$	0.3	-4.6	-0.1	9.7	7.5	13.3	14.1	14.5	13.2	7.1
	σ_m	2.9	4.2	3.4	2.2	3.3	10.2	4.5	4.8	4.7	3.3
II	$\bar{X}$	5.6	16.8	18.6	30.8	37.8	21.0	18.0	12.8	14.6	19.8
	σ_m	3.8	6.8	6.2	5.9	5.1	6.8	6.9	3.9	8.5	4.2
III	$\bar{X}$	19.4	31.6	45.4	43.4	22.9	25.0*	39.8*	21.1	28.4	31.9
	σ_m	9.5	10.9	14.9	11.3	5.7	11.8	19.9	6.9	14.2	10.5
IV	$\bar{X}$	40.2	47.0	47.4*	42.0*	45.1*	44.0*	48.9*	49.5*	56.1*	45.5*
	σ_m	4.3	3.5	11.1	10.3	12.1	8.2	9.4	13.7	7.1	7.8
V	$\bar{X}$	46.3*	52.1*	52.8*	42.5*	37.4*	38.1*	33.4*	29.5*	33.0*	41.4*
	σ_m	4.2	3.9	5.6	2.9	2.0	4.2	4.2	5.9	10.9	2.3

* Lower bound on sample mean.

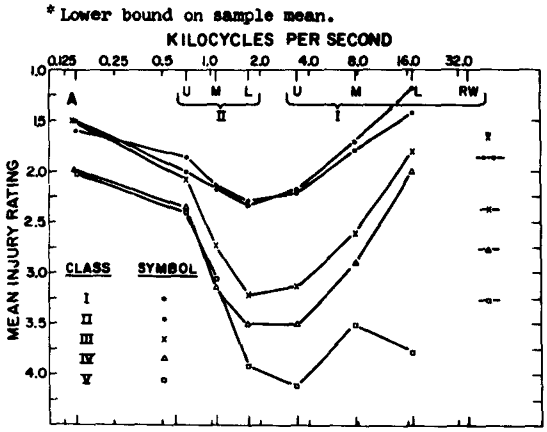

FIGURE 35. Mean Injury Ratings for the Five Classes of Severity of PTS.

The ordinates are the mean injury ratings for the cats in each of the severity classes. The abscissas are locations along the basilar membrane. For convenience these positions are mapped to the test-tone frequency that would give maximal stimulation at that point.

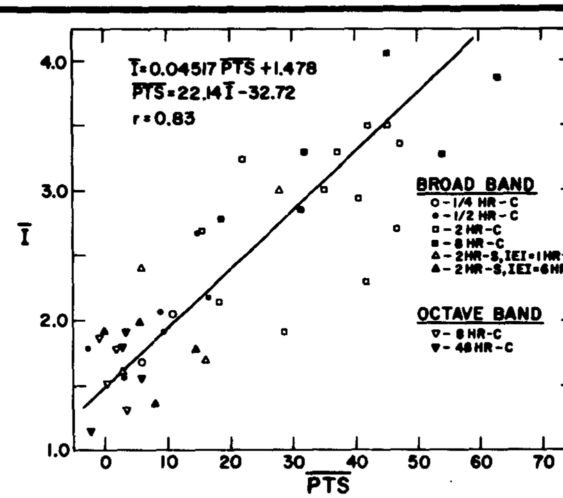

FIGURE 36. Scattergram Showing Relation Between the Mean Injury Rating, $\bar{I}$, and $\overline{PTS}$

Each point is for an individual cat. The ordinate is the mean of the injury ratings made at the several locations across the basilar membrane; the abscissas are $\overline{PTS}$'s, means of the PTS's at the eight frequencies which comprise the octave steps from 125 to 16,000 cps.

The relation between the behavioral threshold shift and the histological findings was examined in another way. In an attempt to use all of the data in evaluating this relation, $\overline{PTS}$ was correlated with the mean of the injury ratings along the length of the membrane. Figure 36 shows the scattergram. On this graph each point shows the $\overline{PTS}$ and the mean injury rating ($\overline{I}$) for a particular cat. For these correlations the cats exposed to the low-frequency noise are included. The linear R for this relation is 0.83. The line shown in figure 36 is the least squares fit that minimizes the squared perpendicular distances between the points and the line. By this equation,

$$\overline{PTS} = 22.14\ \overline{I} - 32.72, \text{ or}$$

$$\overline{I} = 0.045\ \overline{PTS} + 1.48.$$

A similar plot was made for the mid-frequency range. The average PTS at 1.0, 2.0, and 4.0 kc was compared with average injury rating in the upper part of Turn I and the lower and middle portions of Turn II. The linear R was 0.776, and the best fitting straight line was

$$PTS = 34.72\ I - 68.47, \text{ or}$$

$$I = .029\ PTS + 1.97.$$

By these equations, $\overline{PTS}$ increases about 22 db for each unit increment to the average injury rating, while for the mid-frequency range the corresponding slope is about 35 db. Zero $\overline{PTS}$ is associated with an average injury rating of 1.48, while for the mid-frequencies zero PTS is associated with an average injury rating of 1.97. These intercepts reflect the fact that slight injuries were found in the middle of the basilar membrane when no threshold shifts were measured. Since all of these animals were exposed to noise, no control specimens were available; thus, this particular finding needs to be confirmed in experiments which include the appropriate control animals.

The results given above show, on the average, a close correspondence between the shapes of the behavioral audiograms and the pattern of injury ratings along the length of the basilar membrane. Furthermore, the average injury ratings for whole cochleas are highly correlated with $\overline{PTS}$. Nonetheless, many discrepancies between histological and functional measures remain. For example, it is clear from knowledge of the traveling wave in the cochlea that exact predictions of behavioral audiograms cannot be expected until rules are established for relating the extent of injuries along the basilar membrane as well as their severity to the threshold for a particular test frequency. In previous investigations by Eldredge and Associates (refs. 11-14) electrophysiological measures of cochlear function have been correlated with histological changes. These experiments suggest that the kinds of injuries observed histologically strongly depend on the sound pressure of the deafening stimulus, whereas equivalent functional changes are observed for both moderate and intense pressures if the duration of the exposure is appropriately adjusted. In general, a lowering of the correlation between any functional measures and histological measures can be expected if the spectrum of the deafening stimulus is allowed to vary within the series of experiments.

Comparison of TTS, CTS, and PTS Audiograms

It was previously noted that after exposure to the spectrum of the present experiments, the TTS auidograms peak at 4.0 kc. In addition TTS spreads more to frequencies above than frequencies below 4.0 kc. Showing this relation, quantitatively, are 14 of 16 cats that had greater values of TTS at 8.0 kc than at 2.0 kc.

PTS audiograms after more severe exposures to the same spectrum show quite another picture. In this case the shifts are larger below 4.0 kc than they are above it. If one examines the audiograms in Classes II to V shown in figure 32 it can be seen that 28 of the 31 cats have greater values of PTS at 2.0 than at 8.0 kc. This is true even though for large PTS all mid- and high-frequencies tend to have similar losses.

What is the shape of the CTS audiogram during the first hours after a severe exposure to the noise? Does it have the frequency characteristics typical of TTS audiograms, a TTS audiogram added to a PTS audiogram, or a PTS audiogram? Unfortunately it was often impossible to measure CTS audiograms during the first and second day after an exposure. Data that we were able to obtain during the first 6 to 48 hours after exposure suggest that CTS audiograms have the appearance characteristic of PTS audiograms. These limited data suggest that CTS audiograms form a series similar to that for PTS audiograms; that is, the shape of the CTS audiogram seems to depend on its average value at the time the audiogram was determined.

Shown in figure 37 are four examples of recovery of the temporary components of CTS audiograms. An example is taken from each of the classes of severity. It can be seen that changes in the audiogram during recovery follow the general course of moving from severe to less severe along the graded series of audiograms like that previously shown in figure 32 and described in this chapter.

To summarize, if a cat is exposed to a spectrum for a duration only sufficient to produce TTS and, later, is exposed to the same spectrum for a duration sufficient to produce PTS, then the TTS and PTS audiograms can be expected to differ in both their contours and the locations of the maximum shifts. In addition, there will be no obvious correspondence between the temporary components of a CTS audiogram and a TTS audiogram even though both are produced by the same spectrum. These findings do not support the hypothesis that PTS produced by a traumatic noise is simply due to an extension of the processes responsible for large values of TTS; rather these findings suggest that both PTS and the temporary component of CTS, when they are produced by traumatic exposures to sound, depend on processes different from those that are responsible for TTS.

Relation of PTS Audiograms to the Spectrum

One explanation of the difference between TTS and PTS audiograms is that they depend on different measures of the spectrum of the exposure stimulus. A simple hypothesis of this type is that the PTS's at the various test frequencies are proportional to the levels of the noise in narrow bands centered about each test frequency, while TTS's are proportional to the levels in noise bands of lower frequency than the test stimulus. One might add in both cases that the spectrum levels should be corrected by the transmission characteristics of the ear and that these characteristics can be approximated by including the audibility curve or the critical-ratio curve or both in such a formulation.

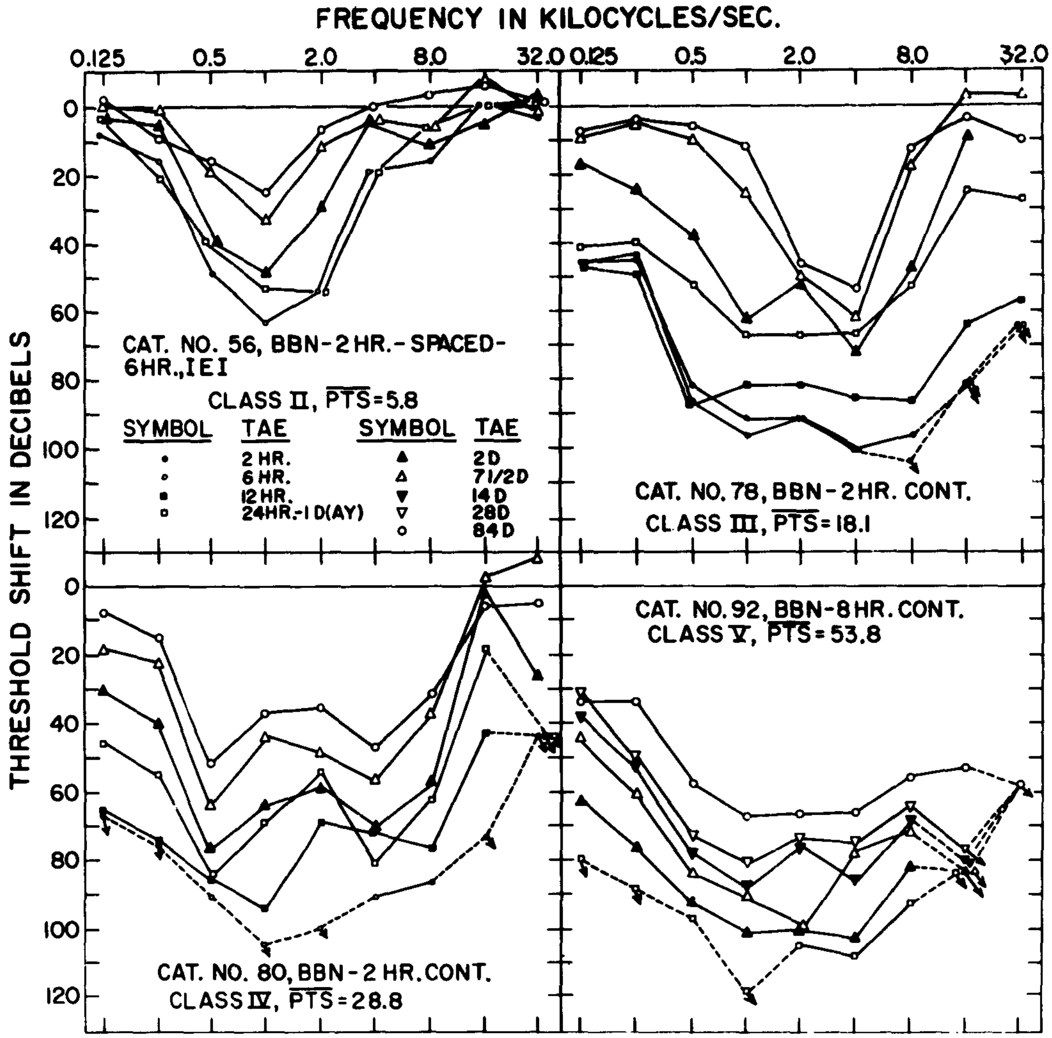

FIGURE 37. The Progressions from CTS Audiograms Measured Shortly After Exposure to the Stable PTS Audiogram

Changes in the shape of the audiograms as the temporary component of the CTS diminishes are exemplified by these four cats.

In this section we wish to evaluate a simple form of the hypothesis that PTS's are proportional to the spectrum levels of the exposure stimulus at the corresponding frequencies. This hypothesis is described as the spectrum matching hypothesis. It states that where significant permanent threshold shifts are present, the post-exposure audibility curve can be matched by the spectrum of the noise minus a constant. For this form of the hypothesis, the additive constant is determined by the duration of the exposure and by a cat's susceptibility to the noise. That is, both individual differences and the duration of the exposure are treated as additive factors which are constant across test-tone frequencies. This simple form of the spectrum matching hypothesis can be rejected for experiments which vary the bandwidth of the spectrum as shown by the comparison of narrow and broad-band exposures in Chapter VIII of this report. The possibility remains that in the case of the broad-band noise a strong correlation existed between the spectrum levels and the post-exposure thresholds. This possibility was tested in the following way.

At those frequencies for which PTS was greater than 5.0 db, the difference between the spectrum level of the noise and the post-exposure threshold was calculated for each of the 34 cats exposed to the broad-band noise. The mean of these differences, $\overline{C}$, was calculated for each cat. Since the PTS audiogram is the difference between the pre- and post-exposure audibility curves, the spectrum matching hypothesis was evaluated by fitting the PTS audiograms in accordance with the equation

$$PTS' = (B - \overline{C}) - \beta_o, \text{ and if } [(B - \overline{C}) - \beta_o] < 0, \text{ then } PTS' = 0.$$

PTS' is the fitted value of PTS. $\underline{B}$ is the spectrum level of the noise at the appropriate frequency. β_o is the SPL of the threshold stimulus before exposure to the noise. The constant $\overline{C}$ has a single value for each cat. Of course, the quantity $(B - \overline{C})$ is the fitted post-exposure threshold.

To evaluate this form of the spectrum matching hypothesis, the correspondence between PTS' and PTS was examined for each cat. In some cases the fit was excellent, while in others it was poor. The test frequency showing maximum PTS was not always predicted. Overall, the root-mean-square of differences between the predicted and the obtained PTS's was about 9.6 db, and the average difference was 8.0 db. Table XIII shows the correspondence between PTS' and PTS for the five classes of audiograms. The agreement is generally fair except for Class III where it is poor.

TABLE XIII

CORRESPONDENCE BETWEEN OBSERVED PTS AND PTS' FITTED TO THE DATA ON THE BASIS OF A SPECTRUM MATCHING HYPOTHESIS

		Frequency in kc/second									
Class		0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	PTS
I	PTS	0.0	-1.2	1.1	-2.4	2.8	0.0	-0.4	1.5	-3.2	0.03
	PTS'	6.0	2.9	0.4	4.5	4.1	0.0	0.4			
II	PTS	-0.4	0.6	6.4	17.3	15.6	13.3	-0.4	2.6	2.3	6.9
	PTS'	-0.6	0.0	6.9	19.5	13.6	5.8	-3.2			
III	PTS	3.6	4.6	5.0	22.0	42.9	40.8	11.9	0.2	2.6	16.4
	PTS'	-0.2	5.0	17.6	32.0	37.0	29.8	20.4			
IV	PTS	12.5	17.2	38.6	47.5	44.2	42.0	30.2	8.0	0.25	30.0
	PTS'	0.0	13.9	37.1	47.3	54.4	43.7	31.2			
V	PTS	17.9	24.5	39.9	60.7	59.5	55.3	56.4	47.1	>48.6	45.2
	PTS'	4.7	32.3	49.0	61.3	65.5	55.4	50.6			

Calculations similar to those reported above were made using the estimated masked thresholds in place of the spectrum level of the noise. This change, in effect, includes both the audibility curve and the critical-ratio curve, determined for the cat by Watson (ref. 41), as corrections on the spectrum level. The fitted PTS audiograms obtained in this manner were no better or worse than those previously obtained.

We believe that the simple spectrum matching hypothesis presented above fails for several reasons. It does not include changes in the spectrum produced by the intra-aural muscles. It assumes that noise bands are mapped onto the basilar membrane in the same positions as the corresponding pure tones, which according to Tonndorf (ref. 35) is incorrect. The assumptions that the constant of proportionality between spectrum level and PTS has unit value and that it is independent of exposure duration need investigation.

It should be possible to specify precisely the relation between the spectrum and PTS, if data are accumulated which are free from the unknown effects of the intra-aural muscles. Information which would help bridge the gap from the pattern of the spectrum to the PTS audiogram could be obtained from experiments performed on either the cochlea or models of it that determine the relations among the measures of the motion of the basilar membrane and the severity of traumatic injury.

Further Comments on the Relations Between TTS, CTS, and PTS

For man, after exposure to intense transients or to most noises of broad bandwidth, TTS, CTS, and PTS all seem to show a characteristic maximum near 4 kc for both traumatic exposures of short duration and high intensity and for long term exposures to less severe levels. There are instances, however, of such severe exposures that produce either PTS's or very severe TTS's which seem to have the frequency characteristics of a cat's PTS audiogram. For cat, it has been shown by the data of Lindquist, Neff, and Schuknecht (ref. 20), of Schuknecht, Neff, and Perlman (ref. 30) and of the present report that exposures to gunshot, or broad-band noise, or blows to the head produce PTS audiograms that in most instances show more loss below 4 kc than above it. The opposite is true for the cat's TTS audiograms.

To account for these findings we suggest the following hypotheses:

1. Threshold shifts that are due to underlying temporary and permanent injuries produced by traumatic exposures of relatively short duration (order of seconds and hours) are proportional to the spectrum levels of the traumatic noise after its transformation by the mechanical mechanisms of the ear. One property of this hypothesized relation is that the maximum of the transformed spectrum should be the point of maximum PTS.

2. Threshold shifts that are due to fatigue-like processes also have a simple relation to the spectrum of the exposure stimulus. This relation, however, involves some parameter which increases with frequency, thus moving the location of maximum threshold shift to a frequency higher than the maximum of the transformed spectrum. A TTS experiment which illustrates this position was conducted by Miller (ref. 22).

3. Continued or repeated severe fatiguing of the ear over a period of many years produces PTS audiograms with the frequency characteristics of TTS audiograms. This kind of PTS corresponds to the noise-induced threshold shift described by Davis (ref. 6). A recent study by Nixon and Glorig (ref. 26) casts doubt on this hypothesis. They examined the growth of PTS, corrected by presbycusis, at both 2.0 kc and 4.0 kc in men exposed to industrial noise over periods of many years.

The spectrums of the noises were such that short exposures (8 hours) to them probably produced TTS audiograms with maximums near 4 kc and little or no TTS at 2.0 kc. The spectrum levels nonetheless were maximum between 0.3 and 0.6 kc. The overall levels of these noises were such that PTS accumulates slowly over periods of years. The data of Nixon and Glorig show that initially PTS is greatest at 4.0 kc and it appears to reach an asymptotic level after ten years of exposure. On the other hand the PTS at 2.0 kc shows little or no growth during the first ten years of exposure. These data for the first ten years of exposure are consistent with the hypothesis that TTS audiograms and PTS audiograms have the same shape for noise-induced deafness. During the period beyond ten years, however, continued exposure to the most intense noise of the Nixon and Glorig study produces marked increases in the PTS at 2.0 kc even though the PTS's at 4.0 kc remain constant. Thus, the final shape of the PTS audiogram is probably different from the shape of the TTS audiogram, the losses being greater in the range important for speech perception in the case of PTS than in the case of TTS.

4. The hypotheses stated above are subject to modification by consideration of the intra-aural muscles, which provide an unknown and changing frequency distortion of the exposure stimulus, and species differences which include structural and acoustical differences in all parts of the ear.

XI. SUMMARY

Aural effects of exposure to intense noise were investigated by behavioral measurements of the auditory sensitivity of cats before and after such exposures and by histological examination of their cochleas.

Procedures for the training and the audiometric testing of the cat are described in detail. The results of extensive determinations of the cat's audibility curve for sound fields are reported and a standard audibility curve is offered for the use of future investigators.

Terms that are useful in the description of the deafening effects of exposure to intense sound are defined as follows. A threshold shift is computed as the difference in decibels between pre- and post-exposure thresholds. Threshold shifts that are measured at post-exposure times that exceed a few seconds and that decline in time to zero are denoted as temporary threshold shifts (TTS's). If, after exposure to intense sound, threshold shifts are measured that are stable and persist over a period of several weeks, then these threshold shifts are said to be persistent threshold shifts (PTS's) and permanent injury to the auditory mechanism is inferred. Threshold shifts that have both temporary and fresh persistent components are defined as compound threshold shifts (CTS's). Average values of CTS or PTS over the frequency range from 125 to 16,000 cps are denoted in this report by the symbols $\overline{\text{CTS}}$ and $\overline{\text{PTS}}$.

The broad-band noise that was used as an exposure stimulus is described in detail. The noise had nearly equal octave-band levels in the bands centered at 850, 1700, and 3400 cps, with lower levels above and below this region.

Exposure of the cat to this noise either at an overall SPL of 115 db for 1/8 hour or at 105 db for 1/4 hour results in TTS audiograms that have the same general features as those measured in man; the maximum TTS is at 4 kc and TTS is greater above 4 kc than below it. Recovery from large values of TTS is similar to that for man. The cat is more susceptible than man to TTS; it is estimated that, if man and cat are to have equal TTS, then the exposure must be approximately 18 db greater in energy for man than for cat.

Cats also were exposed to the broad-band noise at an overall SPL of 115 db without interruption for periods of 1/4, 1/2, 2, or 8 hours. These exposures produced PTS's whose magnitudes depended on the duration of the exposure, the test-tone frequency, and the susceptibility of the individual cat. Mean values of $\overline{\text{PTS}}$ were 5.6 db and 8.5 db for the 1/4-hour and 1/2-hour exposures, while values of 35.0 db and 40.6 db were found for the 2-hour and 8-hour exposures. The growth of PTS with increasing duration of exposure is described in detail in the text.

The effects of distributing the 2-hour exposure into 16 doses of 1/8 hour each were investigated. A different inter-exposure interval was used in each of four conditions; these were 0, 1, 6, or 24 hours. Average values of $\overline{\text{PTS}}$ were 38, 13, 6, and 2 db, respectively. Thus, the greater the inter-exposure interval the smaller the PTS's. If PTS's are to be reduced to near-zero values for all cats, a small duty-cycle of 1.0 to 0.5 percent seems to be required for exposure schedules similar to those used in these experiments.

The behavior of the temporary component of CTS was examined for cats exposed to the broad-band noise. The following conclusions are limited by the facts that it was often impossible to measure threshold shifts during the first several days after exposure and that PTS's exceed 70 db in only one cat. The size of the temporary component at 24 hours after exposure (the difference between CTS at one day after exposure and PTS) increased with the severity of the exposure, and it was positively correlated with PTS. Recovery from the temporary component of CTS is most rapid during the first few post-exposure days; thereafter, the rate of recovery gradually slows. The period of recovery increases with the severity of the exposure and it is also positively correlated with the magnitude of the PTS. This period ranged from a few days up to approximately two months. The recovery processes seem to have stopped after the first two post-exposure months.

The PTS audiograms produced by either continuous or spaced exposures to the broad-band noise had characteristic shapes. For small average values of PTS, the PTS audiogram has a dip which includes one octave in the neighborhood of 1.0 or 2.0 or 4.0 kc depending on the cat. As the average value of PTS increases, the dip widens to include first two and then three or four octaves of the range from 500 to 8,000 cps. For average values of PTS greater than 35 db, sizable PTS's can be expected at all frequencies, the largest usually being at frequencies above 250 cps. The shapes of CTS audiograms seem to depend on their average values in a manner similar to that described for PTS audiograms.

PTS and CTS audiograms produced by exposure to the broad-band noise have greater shifts below 4.0 kc than above it, while the opposite is true for TTS audiograms produced by the same spectrum. Thus, PTS's and CTS's produced by traumatic exposure to sound seem to depend on underlying processes which differ from those responsible for TTS.

The auditory effects of an octave-band of noise (300-600 cps) were also investigated using the cat as a subject. A band-pressure level of 105 db was used, since it matched the level of the corresponding band of the broad-band noise whose overall level was 115 db. The masking pattern of the octave-band was determined and this pattern was as expected except for unexplainably large amounts of masking found at 125 cps. Exposure to the octave band for 8 hours produced small but definite threshold shifts throughout the frequency range, and these shifts declined to near-zero values by the seventh post-exposure day. Exposure to this noise for 48 hours produced TTS audiograms that had two dips, one between 0.25 and 1.0 kc and the other between 4.0 and 16.0 kc. No PTS's were measured, but slight to moderate injuries were noted in the histological findings. Further investigations of the effects of prolonged continuous exposures to low-frequency noise are needed, but the present results suggest that some variable related to bandwidth is a determiner of PTS and injury, at least for low frequencies.

A scale for the histological evaluation of injuries is presented, and using this scale injuries were rated at seven locations in each cochlea. An ordering of injuries from slight changes in Deiters' cells to marked changes in both Deiters' and external hair cells appears to have emerged. The pattern of injury ratings along the basilar membrane is highly similar to the pattern of the behavioral audiograms, if both are placed on an anatomical-frequency scale. The Pearson correlation coefficient for the average injury rating for the whole cochlea and the cat's average PTS was 0.85.

The data available for man show that the typical human adult would suffer no persistent threshold shifts if exposed to any one of the conditions used in the present experiments. We hypothesize that if the level of the noise be increased by approximately 18 db, then results similar to those described for the cat would be found in man.

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APPENDIX A

GRADES OF INJURY FOR EACH SPECIMEN AND AN EXPLANATION OF DATA

Grades of Injury

CAT NO.	EXPOSURE	TURN apex	TURN II upper	TURN II middle	TURN II lower	TURN I upper	TURN I middle	TURN I lower
Trained								
4	1/4 hr. b.b.n.	1.5	2.5	3.0	2.5	2.5	2.0	1.5
5	c. 115 db	1.5	1.5	2.5	2.0	1.5	2.0	1.5
Trained								
19		1.5	2.0	2.0	3.0	4.0	4.0	3.0
23	1/2 hr.	1.5	1.5	2.5	3.0	3.5	3.0	2.0
29	b.b.n.	1.0	1.5	1.5	2.0	2.5	1.5	1.5
109	c.	1.5	2.0	2.5	2.0	2.0	1.5	1.0
110	115 db	2.0	2.0	2.0	2.5	2.5	2.0	1.5
114		1.5	2.0	2.5	2.0	2.0	2.0	1.5
Trained								
3		1.5	2.0	3.0	4.5	5.0	4.5	3.0
13		1.5	2.0	2.5	4.0	4.5	3.0	2.0
20		2.0	2.5	3.0	4.0	4.0	3.5	3.5
24	2 hrs.	2.5	2.5	3.0	4.5	5.0	3.5	3.0
54	b.b.n.	1.5	1.5	2.0	3.0	2.5	2.0	3.5
60	c.	1.5	1.5	2.0	2.5	4.5	4.0	4.5
63	115 db	2.0	2.5	4.0	4.0	3.5	4.0	4.5
64		2.5	3.0	3.5	4.0	3.5	3.0	4.0
71		1.5	2.5	3.0	4.0	4.5	3.5	2.0
76		2.0	2.0	3.0	4.5	4.0	2.0	1.5
78		1.5	2.0	3.5	3.0	2.0	1.5	1.5
80		1.5	1.5	2.0	2.0	3.0	2.0	1.5
Untrained								
A.r.		1.5	1.5	2.0	3.0	2.5	2.0	1.5
l.		2.0	2.0	2.5	3.0	2.5	2.0	1.0
D.r.	2 hrs.	2.0	2.5	2.5	3.5	3.0	3.5	2.0
l.	b.b.n.	1.5	1.5	2.0	3.0	2.0	2.0	1.5
E.r.	c.	1.0	1.5	2.0	3.5	2.5	2.0	1.5
l.	115 db	2.0	2.0	3.0	3.5	2.5	2.0	1.5
F.r.		1.5	2.0	2.5	3.0	2.0	1.5	1.5
l.		1.5	2.0	2.0	3.0	4.0	5.0	3.0
G.r.		2.0	2.5	3.0	3.5	3.5	4.0	1.5
l.		2.0	2.5	3.5	3.5	4.0	4.0	2.0
Trained								
86		3.0	3.0	4.0	5.0	4.5	4.0	5.0
90	8 hrs.	2.0	3.0	3.5	4.0	4.5	5.0	5.0
92	b.b.n.	1.5	2.0	2.5	3.5	4.5	4.0	5.0
102	c.	2.0	2.5	3.5	4.0	3.0	3.0	1.0
107	115 db	2.5	3.0	3.0	4.0	4.0	3.5	3.0
112		2.0	3.0	3.5	4.0	3.0	2.5	1.5
Trained								
39	2 hrs. b.b.n.	2.0	2.5	4.0	4.0	3.5	3.0	2.0
50	s. 16 doses	1.5	2.5	3.0	3.5	3.0	2.0	1.5
69	7-1/2 min. IEI = 1 hr.	1.5	1.5	2.0	2.5	2.0	1.5	1.0
72	115 db	1.5	2.0	2.0	3.0	2.0	1.5	1.0
Trained								
52	2 hrs. b.b.n.	1.5	2.0	2.0	2.0	2.5	2.0	1.5
56	s. 16 doses	2.0	2.0	2.5	2.5	2.0	1.5	1.5
62	7-1/2 min. IEI = 6 hrs.	1.5	2.0	2.5	2.5	1.5	1.5	1.0
74	115 db	1.0	1.5	1.0	1.5	2.0	1.5	1.0
Trained								
61	8 hrs.	1.0	1.0	1.5	2.0	1.5	1.5	1.0
70	n.b.n.	1.0	2.0	2.0	2.0	1.5	1.0	1.0
79	c.	1.5	1.5	2.5	2.5	2.0	1.5	1.0
99	105 db	1.5	2.0	2.5	2.5	2.0	1.5	1.0
Trained								
53	48 hrs.	1.5	1.5	2.5	3.5	2.0	1.5	1.0
59	n.b.n.	1.0	1.0	1.5	1.5	1.0	1.0	1.0
75	c.	1.5	1.5	2.5	2.0	1.5	1.0	1.0
98	105 db	1.5	1.5	2.C	3.0	2.0	1.5	1.0

Abbreviations: c, continuous; s, spaced; b.b.n., broad band of noise; n.b.n., narrow band of noise (300-600 cps); I.E.I., inter-exposure interval.

APPENDIX A (cont'd)

EXPLANATION OF DATA

Trained cats 4 and 5 -
Exposure: A broad band of continuous noise at 115 db for 1/4 hour.
Results: Usually mild injury to supporting cells.

Trained cats 19, 23, 29, 109, 110, and 114 -
Exposure: A broad band of continuous noise at 115 db for 1/2 hour.
Results: Mild injury to supporting cells with some involvements of external hair cells particularly in two specimens.

Trained cats 3, 13, 20, 24, 54, 64, 71, 80, 60, 63, 76, and 78 -
Exposure: A broad band of continuous noise at 115 db for 2 hours.
Results: Injuries in lower part of the first turn for four specimens show loss and degeneration of external and internal hair cells and supporting cells with collaspe of the tunnel of Corti. The similar areas in four other specimens reveal slight to moderate changes such as swelling of supporting, with or without some deformation, of external hair cells. In the upper part of the first turn and into the middle of the second turn, the damage is in fair agreement for most specimens.

Untrained cats A, D, E, F, and G -
Exposure: A broad band of continuous noise at 115 db for 2 hours. Animals sacrificed within 2 to 4 hours following exposure. Both ears were exposed.
Results: Only relatively mild changes are usually present in the lower part of the first turn, such as slight swelling of supporting cells. These changes become somewhat greater in the middle and upper part of the first turn and for three specimens severe injuries are present in this location. Definite hair cell and other cell injuries of moderate degree are in evidence in the lower part of the second turn for all specimens. These become less in the middle and upper part of the second turn.

Trained cats 86, 90, 92, 102, 107, and 112 -
Exposure: A broad band of continuous noise at 115 db for 8 hours.
Results: In three cochleas the organ of Corti was lifted from the basilar membrane in the lower part of the first turn. In one, there was moderate injury and in two, slight changes at the same location. For all specimens the damage became more severe or maintained its severity into the middle of the second turn. For the remainder of the apical turn the injuries were moderate to slight.

Trained cats 39, 50, 69, and 72 -
Exposure: Sixteen doses, 7.5 minutes each (or 2 hours total) with 1-hour inter-exposure interval.
Results: The extreme ends of the basal and apical turns reveal only slight or mild injuries such as supporting cell changes. In the upper part of the first turn and into the middle of the second turn, there is considerable variation in degree of injury for the different specimens. It ranges from supporting cell changes to marked organ of Corti damage for one specimen.

Trained cats 52, 56, 62, and 74 -

Exposure: Sixteen doses, 7.5 minutes each (or 2 hours total) with 6-hour inter-exposure interval.

Results: The injuries for all specimens are slight or relatively mild. There is a tendency for the greatest degree of injury to occur in the upper part of the first turn and lower and middle parts of the second turn. It is primarily supporting cell changes with some evidence of slightly altered hair cells.

Trained cats 61, 70, 79, and 99 -

Exposure: A narrow band of low frequency (300-600 cps) continuous noise at 105 db for 8 hours.

Results: Very mild injuries are present chiefly in the upper part of the first turn and throughout the second turn for each specimen. These are primarily supporting cell changes with slight, if any, hair cell damage. As a group, the findings are fairly consistent.

Trained cats 53, 59, 75, and 98 -

Exposure: A narrow band of low frequency (300-600 cps) continuous noise at 105 db for 48 hours.

Results: Moderate external hair and supporting cell injury is present for two specimens in the lower part of the second turn with only mild changes in nearby areas. One specimen is practically within normal limits while the remainder show slight injuries in the lower and middle parts of the second turn.

APPENDIX B

PRE-EXPOSURE THRESHOLDS IN SPL AND FINAL THRESHOLD SHIFTS (PTS)

CAT NO.	EXPOSURE	DAYS AFTER NOISE	Frequency in kc/second 0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	$\overline{PTS}$
3**	1/4 hr	P	44.8	19.8	4.0	-8.5	-14.0	-19.2	-25.8+	-20.5	-	
	b.b.n.	46	-3.8	-5.0	3.0	8.8	-5.0	3.8	-1.2	-2.5	-	-0.2
4	c. 115 db	P	44.8	19.8	25.8	-6.0	-20.2	-13.0	-27.0+	-16.8	-	
		152	1.9	3.8	-13.1	21.9	28.1	28.8	10.0	5.6	-	10.9
5		P	44.8	19.8	12.0	-8.5	-19.0	-13.0	-23.2+	-19.8	-	
		149	-4.4	5.0	-1.9	26.9	18.1	0.0	-1.9	7.5	-	6.2
19	1/2 hr	P	44.8	21.0	-0.5	-16.0	-24.0	-19.2	-24.5+	-5.5	-	
	b.b.n.	118	0.0	-2.5	4.4	21.2	47.5	45.0	12.5	-11.2	-	14.6
23	c. 115 db	P	34.8	13.5	-0.5	-16.0	-15.2	-15.5	-28.8+	-5.5	-	
		118	6.9	5.0	3.1	11.9	40.6	43.8	27.5	-5.6	-	16.6
29		P	48.5	19.8	-1.8	-12.2	-27.8	-18.0	-22.0+	-13.0	-	
		75	-8.1	-1.9	5.0	6.2	18.8	3.8	0.0	0.0	-	3.0
109		P	31.6	19.4	7.4	-9.1	-23.6	-7.8	-14.6	2.0	38.0	
		84	-7.0	-8.7	1.3	0.8	3.4	-3.0	0.8	-5.5	-13.5	-2.7
110		P	25.6	20.4	-4.6	-10.1	-16.6	-15.8	-15.6	-6.0	15.0	
		84	4.0	5.0	16.0	20.0	29.0	-2.0	-1.0	2.0	6.0	9.1
114		P	22.6	23.4	9.4	-11.1	-13.6	-13.8	-12.6	-5.0	12.0	
		84	3.0	-8.0	2.0	21.0	12.0	35.0	-2.0	15.0	7.0	9.8
3	2 hr	P	41.0	14.8	7.0	0.2	-19.0	-15.5	-27.0+	-23.0	-	
	b.b.n.	118	7.5	10.0	13.1	34.4	46.4	44.4	20.6	0.0	-	22.0
13	c. 115 db	P	44.8	19.8	4.5	-8.5	-12.5	-16.5	-18.2+	-9.2	-	
		145	0.0	-3.8	5.0	26.9	48.5	43.5	8.8	-5.6	-	15.4
20		P	44.8	19.8	4.0	-13.5	-14.0	-10.5	-18.4+	-11.8	-	
		171	8.1	21.9	23.0	48.1	50.6	48.8	49.4	43.8	-	36.7
24		P	44.8	21.0	3.2	-6.0	-19.0	-19.2	-23.2+	-14.2	-	
		117	11.2	19.4	53.8	48.8	53.8	53.1	50.6	46.2	-	42.1
54		P	31.6	16.4	1.4	-9.1	-15.6	-7.8	-8.6	-3.0	11.0	
		84	11.8	15.0	35.0	58.8	63.2	51.0	50.0	50.0	68.5*	41.8
60		P	32.6	13.9	3.9	-12.1	-14.6	17.3	-17.1	-6.5	12.5	
		84	17.0	19.5	22.5	55.0	62.1	54.3	43.5	50.0	67.0*	40.5
63		P	39.1	16.9	3.4	-12.1	-17.1	-19.3	-17.1	-0.5	11.5	
		84	13.9	25.5	31.0	62.2	62.5	54.5	56.7	55.0	68.0*	45.2
64		P	29.6	10.4	1.4	-12.1	-19.6	-13.8	-27.6	-12.0	3.0	
		84	10.0	21.0	29.0	65.2	60.0	67.0	68.2	56.0	76.5*	47.0
71		P	34.6	21.4	7.4	-2.1	-3.6	8.2	-3.6	15.0	38.0	
		84	35.0	41.0	56.0	51.6	40.6	25.6	40.4	-9.2	3.0	35.1
76		P	31.6	16.9	7.9	-8.6	-7.6	-13.8	-13.6	2.5	18.5	
		84	20.1	28.7	61.0	66.0	49.1	64.4	49.2	35.0	12.5	46.7
78		P	23.1	16.9	6.9	-6.6	-12.6	-17.3	-16.6	-4.5	15.0	
		84	7.5	4.5	6.5	11.5	46.0	53.5	12.0	3.5	10.0	18.1
80		P	34.6	22.4	-0.6	-2.1	-3.6	-20.8	-15.6	3.0	36.0	
		84	8.0	15.0	51.4	37.0	35.0	47.0	31.0	6.0	5.0	28.8

APPENDIX B (cont'd.)

CAT NO.	EXPOSURE	DAYS AFTER NOISE	Frequency in kc/second 0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	PTS
86	8 hr	P	27.6	18.4	9.4	-1.1	-14.6	0.2	-17.6	-2.0	11.0	
	b.b.n. c.	84	19.0	17.0	24.0	63.1	69.1	48.1	62.1	58.5	68.5*	45.1
90	115 db	P	26.6	17.4	7.4	-9.1	-15.6	-10.8	-17.6	-6.0	16.0	
		84	18.0	28.0	47.0	82.4	77.5	75.5	94.6	80.5	63.5*	62.9
92		P	23.6	11.4	-1.6	-14.1	-19.6	-17.8	-15.6	-5.0	10.0	
		84	33.1	33.0	57.1	67.0	66.0	66.1	55.2	52.5	57.5*	53.8
102		P	28.6	18.4	9.4	-8.1	-18.6	-2.8	-16.6	4.0	17.0	
		84	8.0	17.0	31.0	49.0	47.0	35.0	36.0	26.0	-5.0	31.1
107		P	30.6	16.4	3.4	-11.1	-20.6	-9.8	-4.6	-1.0	18.0	
		84	19.0	15.0	29.0	60.0	56.0	46.0	25.0	6.0	11.0	32.0
112		P	28.6	15.4	9.4	-4.1	-10.6	-10.8	-10.6	-11.0	15.0	
		84	9.0	9.0	5.0	18.0	50.0	43.0	5.0	11.0	4.0	18.8
39	2 hr	P	30.6	18.4	8.4	-6.1	-15.6	-6.8	-18.6	-4.0	9.0	
	b.b.n. s.	84	15.0	22.0	43.0	44.0	39.0	40.0	29.0	-6.0	-10.0	28.2
50	16 doses	P	31.6	23.4	6.4	-9.1	-12.6	-17.8	-18.6	-6.0	9.0	
	7-1/2 min 1 hr. IEI	84	4.0	-5.0	4.0	9.0	11.0	22.0	4.0	-1.0	3.0	6.0
69	115 db	P	28.6	14.4	9.4	-3.1	-15.6	-15.8	-6.6	-3.0	12.0	
		84	-4.0	9.0	4.0	14.0	35.0	48.0	12.0	10.0	4.0	16.0
72		P	29.6	15.4	2.4	-13.6	-27.6	-12.8	-21.6	-9.0	8.0	
		84	9.0	1.0	2.0	1.0	5.0	-3.0	-1.0	8.0	0.0	2.8
52	2 hr	P	26.6	10.4	0.4	-7.1	-16.6	-11.8	-18.6	-7.0	10.0	
	b.b.n. s.	84	-2.0	4.0	0.0	-9.0	0.0	6.0	-1.0	2.0	4.0	0.0
56	16 doses	P	31.6	20.4	5.4	-12.1	-9.6	-4.8	-15.6	-5.0	13.0	
	7-1/2 min 6 hr. IEI	84	-2.0	9.0	16.0	25.0	7.0	0.0	-3.0	-6.0	-1.0	5.8
62	115 db	P	27.6	14.4	8.4	-8.1	-14.6	-1.8	-13.6	1.0	17.0	
		84	4.0	6.0	17.0	38.0	44.0	16.0	-1.0	-6.0	5.0	14.8
74		P	43.6	22.4	5.4	-10.1	-16.6	-15.8	-19.6	-8.0	12.0	
		84	1.0	0.0	4.0	13.0	13.0	34.0	1.0	1.0	1.0	8.4
60**	2 hr	P	32.6	13.9	3.9	-12.1	-14.6	17.3	-17.1	-6.5	12.5	
	b.b.n. s.	109	-5.0	-0.5	6.5	0.0	-1.4	6.5	0.5	-0.5	3.5	0.8
63**	16 doses	P	39.1	16.9	3.4	-12.1	-17.1	-19.3	-17.1	-0.5	11.5	
	7-1/2 min 24 hr. IEI	109	0.5	1.5	3.0	0.0	1.5	10.5	0.5	-3.5	-1.5	1.8
76**	115 db	P	31.6	16.9	7.9	-8.6	-7.6	-13.8	-13.6	2.5	18.5	
		109	7.0	3.5	-6.5	2.5	4.0	8.0	12.0	-2.5	-4.5	3.5
78**		P	23.1	16.9	6.9	-6.6	-12.6	17.3	-16.6	-4.5	15.0	
		109	6.5	3.5	1.5	0.5	-4.0	-1.5	4.0	-1.5	0.0	1.1

APPENDIX B (cont'd.)

CAT NO.	EXPOSURE	DAYS AFTER NOISE	Frequency in kc/second 0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	PTS
61	8 hr	P	25.6	10.4	-2.6	-10.1	-18.6	-29.8	-15.6	-12.0	11.0	
	n.b.n.	84	-2.0	-2.0	5.0	2.0	-1.0	12.0	7.0	7.0	7.0	3.5
	c.											
70	105 db	P	24.6	14.4	6.4	-3.1	-5.6	-13.8	-16.6	-3.0	17.0	
		84	2.0	3.0	4.0	1.0	-10.0	2.0	0.0	2.0	9.0	0.5
79		P	26.6	17.4	10.4	-5.1	-18.6	-17.8	-19.6	-3.0	20.0	
		84	-2.0	-1.0	-3.0	-5.0	6.0	17.0	5.0	1.0	1.0	2.2
99		P	32.6	13.5	0.4	0.9	-15.6	-9.8	-22.6	-7.0	14.0	
		84	-2.0	3.0	4.0	-3.0	-1.0	-10.0	4.0	-2.0	8.0	-0.9
53	48 hr	P	22.6	6.4	-1.6	-7.1	-22.6	-24.8	-21.6	-13.0	3.0	
	n.b.n.	84	2.0	3.0	2.0	8.0	-3.0	-3.0	8.0	8.0	12.0	3.1
	c.											
59	105 db	P	24.6	9.4	1.4	-4.1	-16.6	-22.8	-21.6	-6.0	14.0	
		84	-1.0	-1.0	-1.0	-10.0	-2.0	6.0	2.0	-10.0	2.0	-2.1
75		P	29.6	14.4	6.4	-11.1	-15.6	-17.8	-19.6	-10.0	14.0	
		84	5.0	3.0	6.0	4.0	5.0	12.0	4.0	8.0	15.0	5.9
98		P	29.6	13.4	-2.6	-8.1	-16.6	-15.8	-19.6	-6.0	11.0	
		84	4.0	4.0	9.0	4.0	1.0	-4.0	-2.0	4.0	12.0	2.5

+ In these instances frequency was 8.8, not 8.0 kc/second   P = pre-exposure
* No response at audiometer's maximum.
** Later used in 2-hour continuous exposure.

Aerospace Medical Division, 6570th Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio
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