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HUMAN PERFORMANCE CRITERIA FOR MILITARY NOISE EXPOSURE

David C. Hodge
Joseph Mazurczak

January 1975

HUMAN ENGINEERING LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

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A new research program is described whose objectives include: identification of aural performance requirements of soldiers in tactical situations; quantification of the effects of aural acuity deficits on such performance; and development of models to predict the effects of military noise exposure on soldiers' performance. It is shown that soldiers need to be able to hear in the 100 Hz to 12 kHz range. Hearing losses are usually first observed at 4-6 kHz. Speech reception is relatively unaffected by typical hearing loss patterns, and can be predicted fairly well from audiometric data. Materiel sound detection is unaffected by typical hearing losses. Personnel sound detection is probably affected by

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typical hearing losses, and cannot be predicted from audiometric data. The program's current emphasis is on the relation between hearing acuity and high-frequency personnel sound detection. A description of the test environment is included.

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David C. Hodge
Joseph Mazurczak

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APPROVED: JOHN D. WEISZ
Director
U. S. Army Human Engineering Laboratory

U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

CONTENTS

HUMAN PERFORMANCE CRITERIA FOR MILITARY NOISE EXPOSURE[1]

INTRODUCTION

This paper describes a new research program which we are beginning at the U. S. Army Human Engineering Laboratory (HEL), the objective of which is to re-state noise exposure criteria in terms of predictions about soldiers' performance.

From 1962 to 1971 our efforts in the Psychoacoustics Team of the Behavioral Research Directorate were concentrated on the temporary effects of noise exposure on human hearing, and the prediction of permanent losses of hearing. We conducted an extensive series of studies of TTS (temporary threshold shift) using military types of noise exposure (see 12, 15, 17, 18, 19, 22). The results of these studies, along with data from other sources, have been used to develop hearing damage-risk criteria (5, 7) and, more recently, design standards for Army materiel (13, 23).

Throughout our noise exposure program we received numerous requests for information and predictions about the functional significance of hearing loss. That is, what does a hearing loss do to the soldier in terms of his ability to perform some task? This question was most frequently raised in the context of TTS which, by definition, disappears after a suitable recovery period. The question was impossible to answer precisely, and most of our predictions had to be vague. Noise-induced hearing loss (temporary and permanent) from most types of military noise exposure is observed first at the upper end of the usual range of audiometric frequencies, viz., 4-8 kHz. Many people having such hearing losses are unaware of it; often there is little or no interference with their ability to communicate by speech. On the other hand, there is a substantial body of information, albeit partly anecdotal, which indicates that such hearing losses can and do interfere with certain types of military performance (6, 16). So we have begun a program to look at the hearing requirements of soldiers and the effects of hearing losses on their performance.

OVERALL OBJECTIVES

The overall objectives of this new program include (a) determining the scope of aural performance requirements of soldiers, (b) quantifying the effects of aural acuity deficits on soldiers' performance, and (c) ultimately, developing methods for predicting performance characteristics from either a knowledge of noise exposure parameters or a knowledge of the soldier's hearing acuity.

Scope of Aural Performance Requirements

To satisfy this objective, we will determine what types of things soldiers need to be able to do in a tactical situation, what range of hearing frequencies are involved, and the degree of hearing acuity required. As elaborated below, this objective has been at least partly achieved.

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[1] Based on a paper presented to the 8th International Congress on Acoustics, London, England, July 1974.

Effects of Aural Acuity Deficits

We are developing techniques and procedures for conducting research on the relation between hearing acuity and performance, and preliminary testing is in progress.

Development of Predictive Models

At present, given a knowledge of noise exposure parameters, reasonable predictions can be made about the extent of TTS that will result from a short exposure, as well as the likelihood of permanent hearing loss from years of exposure. When we have achieved the ability to predict performance from a knowledge of hearing loss or hearing acuity, the final step in the process will be to develop equations (models) allowing predictions to be made about performance levels as a function of noise exposure parameters.

AURAL PERFORMANCE REQUIREMENTS OF SOLDIERS

To analyze the performance requirements of soldiers, we looked at military tactics and operations, studied nearly the entire set of Army training and doctrine publications, reviewed several older reports relating to the problem (cf., 2, 6, 20), and generally tried to reduce military operations down to the smallest number of qualitatively different activities. "Qualitatively different" refers to the ranges of hearing frequencies required to perform the activities.

One type of performance is obvious: communication by speech. Except in a few situations where hand-signals are feasible, speech communications are essential to the conduct of military operations. And, incidentally, soldiers who are unable to communicate satisfactorily by speech (with and aid, if necessary) are not assigned to combat duties (1).

The second qualitatively different, function that soldiers have to be able to perform in a tactical situation is to determine that the enemy is present, or nearby. Soldiers exist primarily to engage an enemy, either in defensive or offensive tactics. In either case, it is essential that soldiers know when the enemy is present, or nearby. To this end, soldiers perform a variety of activities in field situations in which their primary objective is to discover the enemy's presence, observe his activities and, hopefully, discover his intentions. Sentries and other types of security guards perform these tasks from relatively fixed locations; the entent of enemy activity that might be of interest to them is, therefore, relatively limited. Reconnaissance patrols, by contrast, are mobile and go out in search of the enemy or for indications of his presence. Thus, the types of enemy activity to which patrols would be responsive are far broader, and possibly include virtually anything that the enemy might be doing in a tactical situation (including looking for us!).

In this context, two points should be made before proceeding further.

1. Man has other senses besides hearing. Vision, for example! Hearing is a very important modality, however, in that vision is often limited in tactical situations. (And, incidentally, we have specialized training (9) to acquaint military personnel with the proper use of their hearing in field situations.) Visibility may be limited in several ways. For one thing, half of the day is night! Also visibility is often limited by terrain and/or vegetation (10). Sound waves, unlike light waves, bend around obstacles; often we can hear farther than we can see (11). Also, since we don't want the enemy to see us, we try to remain hidden from him as much as possible. Thus, in concealing ourselves from him, we may inadvertently conceal him from ourselves!

2. We are very much dependent on man as an intelligence-gathering channel. There have been, it is true, many developments in battlefield sensors in the past few years. But it is also true that in many situations man is still our best source of information. One reason is that "mobility" is the key word in current tactical doctrine; many sensor systems are designed for use in relatively stationary situations and are thus incompatible with the mobility concept.

So, the soldier is out there listening. What's he listening for; what types of sounds might he be likely to hear? What types of sounds betray the enemy's presence, or enable discrimination between friendly and enemy activity?

The sounds of interest can be divided roughly into two classes: far sounds and near sounds. Far sounds come mainly from sources with relatively high sound outputs, such as heavy equipment and weapons fire. Far sounds are mainly important when the soldier is trying to detect the enemy at some great distance, say several kilometers. Near sounds, by contrast, come from sources whose sound outputs are relatively low in intensity; they are usually detectable only when the source is closer to the listener. These are largely the sounds of personnel movement and personnel activity, such as might occur when the enemy attempts to infiltrate our position.

Figure 1 shows the results of our preliminary analysis of the aural performance requirements of soldiers, in terms of the frequency ranges involved. Note the range of normal human hearing (roughly 20 Hz to 20 kHz), the range of frequencies involved in speech sounds (which can be reduced with little or no effect on intelligibility), and the ranges involved in detecting the sounds of enemy activity (far and near; materiel and personnel, respectively). In general we may conclude that soldiers need good hearing acuity over the range of 100 Hz to 12 kHz in order to perform their duties properly.

But let's take a closer look at these requirements.

1. Speech. As shown in Figure 2, the range of frequencies in speech sounds is roughly 100 Hz to 7 kHz. From everyday experience, we know that telephone bandwidth permits good speech intelligibility as a rule; so, at least in the US, this range can be reduced to 300 Hz to 3.5 kHz. Most current criteria for evaluating the degree of hearing impairment for speech utilize only the hearing levels at 0.5, 1 and 2 kHz (8). However, a variety of studies have shown that this range should be extended to include (at least) 3 kHz since there are consonant discrimination and masking factors which are not properly accounted for by the 0.5-2 kHz range (14, 21). Thus, we may conclude that (at least) the range of 300 Hz to 3.5 kHz is essential for good speech reception by soldiers.

2. Materiel Sounds. For aural detection of distant materiel the 100-300 Hz range is particularly important. This conclusion is derived, in part, from the results of listening tests (4). The conclusion may also be derived by considering how the sound spectra of heavy equipment are affected by transmission through the atmosphere. Many items of heavy equipment have peaked sound spectra with maxima in the lower octave bands (e.g., 63-125 Hz). Given the spectrum at some point near the source, we can calculate the spectral characteristics of the sound after it has travelled some distance, say a kilometer or more.

Figure 3 shows the results of such a calculation for the sound of a LANCE missile system erecting crane. The upper curve is the spectrum measured at 25 meters, and the lower solid curve is the calculated spectrum at 1600 meters. Two types of atmospheric attenuation are involved in the calculation. Spherical divergence (i.e., the inverse-square law) results in all frequencies being attenuated by about 6 dB per doubling of distance. Excess attenuation (27) is frequency-dependent, with the greatest attenuation at the higher frequencies. The lower, dashed

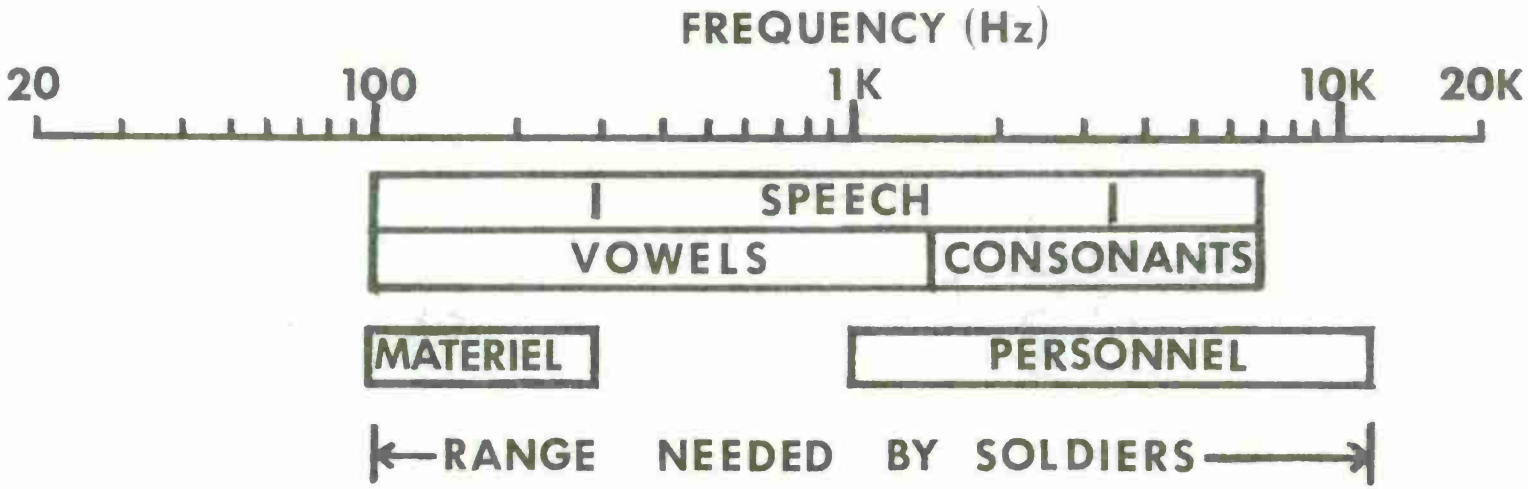

Figure 1. Hearing frequency ranges of importance to soldiers.

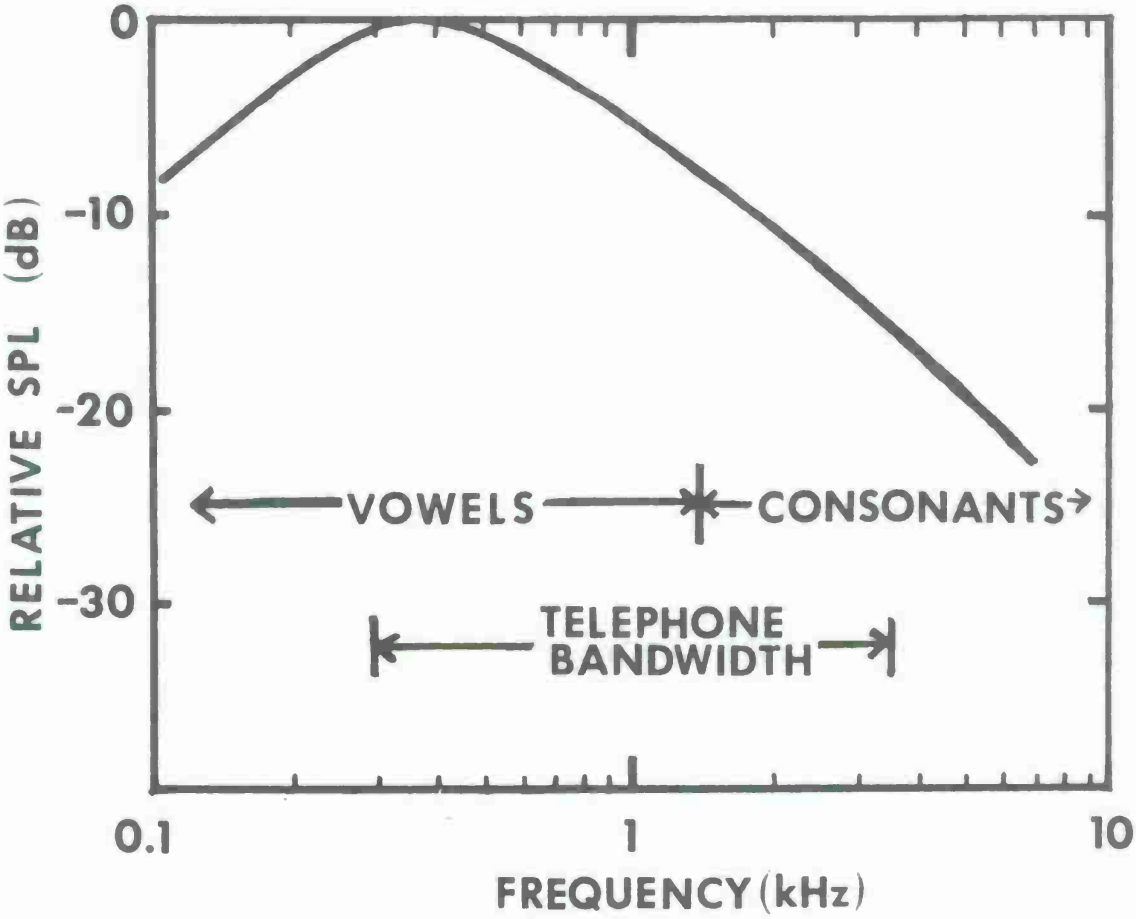

Figure 2. Spectrum of male speech

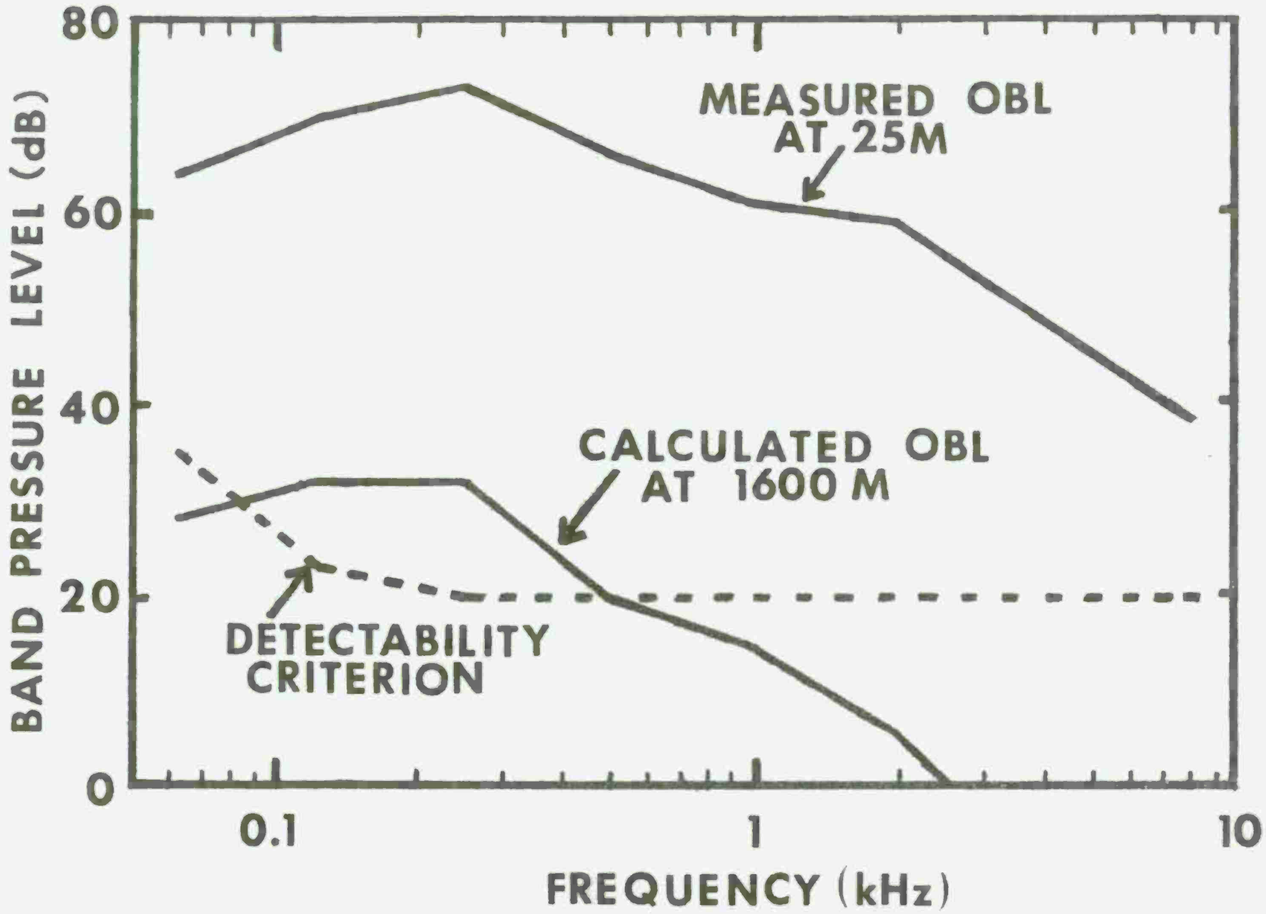

Figure 3. Spectral regions important for the distant detection of materiel sounds.
(Excess attenuation computed assuming 70° F. and 50% R. H.)

curve represents the aural detectability criterion being used for designing Army equipment (23). In order to be detected, a sound must exceed both the background noise level (assumed to be 20 dB in each octave band, at the listener's location), and the binaural, free-field threshold of hearing (25). In the case of the LANCE crane at 1600 meters, only the octave bands centered at 125 and 250 Hz exceed this detectability criterion.

3. Personnel Sounds. The range of interest appears to be 1-12 kHz, although some of our tape recordings also show some energy below 1 kHz. Black (2) concluded in 1958 that the sound of people walking across various types of terrain contained energy primarily in the 2-6 kHz range. Our conclusion came from an analysis of personnel sounds (movement and activity) contained on a sound recognition training aid tape recording (9) developed to familiarize personnel about to depart for Southeast Asia with sounds they might be expected to listen for in that environment. Figure 4 shows the results of our initial analysis (16) of 10 of the sounds. There appear to be two groupings of sounds, peaking at 4 and 8 kHz, respectively. One aspect of of our current program involves recording and analyzing further samples of combat-relevant sounds, to further define the spectral domain of such sounds.

TYPICAL PATTERNS OF HEARING AND HEARING LOSS

Let's now consider what we know about soldier's hearing in general, and the typical hearing losses induced by noise exposure. Figure 5 shows the means and standard deviations of the hearing level of Army personnel as a function of years of service. These data were computed from the tables presented by Walden, et al. (28). The upper curve is the average of 0.5, 1 and 2 kHz (the so-called "speech range"), while the lower curve is the average of 4 and 6 kHz (the "combat sound" range). The markers at 25 dB hearing level depict the "low fence" (8) where hearing impairment for speech is said to begin. The values on the extreme left are for soldiers just entering the Army; none of these men appear to have any difficulty with speech reception, and few have difficulties with their higher frequencies either. Note, however, how the two curves diverge with increased length of military service. After about 10-15 years of service, the mean plus one standard deviation for the "speech" curve is beginning to encroach on the impairment region (and it gets worse with further service). This means that about 18 percent of soldiers with 15 years service are impaired for speech reception. If we assume (perhaps inappropriately, at this point) that 25 dB hearing level is also the point where impairment for combat sound detection begins, then for the 10-15 year service group the mean minus one standard deviation is about 25 dB; thus this would indicate that about 72 percent of soldiers would be impaired for combat sound detection by the end of 15 years service. (Note that this analysis is based on the assumption that 25 dB hearing level is the low fence for impairment of detection performance; we will have to wait for the completion of our program's second phase before confirming the starting point for this type of impairment.)

Figure 6 shows some typical TTS data, for both impulse and steady noise exposure. Both curves show the same thing: TTS usually occurs first, or has the greatest magnitude, at the higher frequencies.

SUMMARY

a. Soldiers need to be able to hear in the 100 Hz to 12 kHz range.

b. Hearing loss is usually first observed at 4-6 kHz.

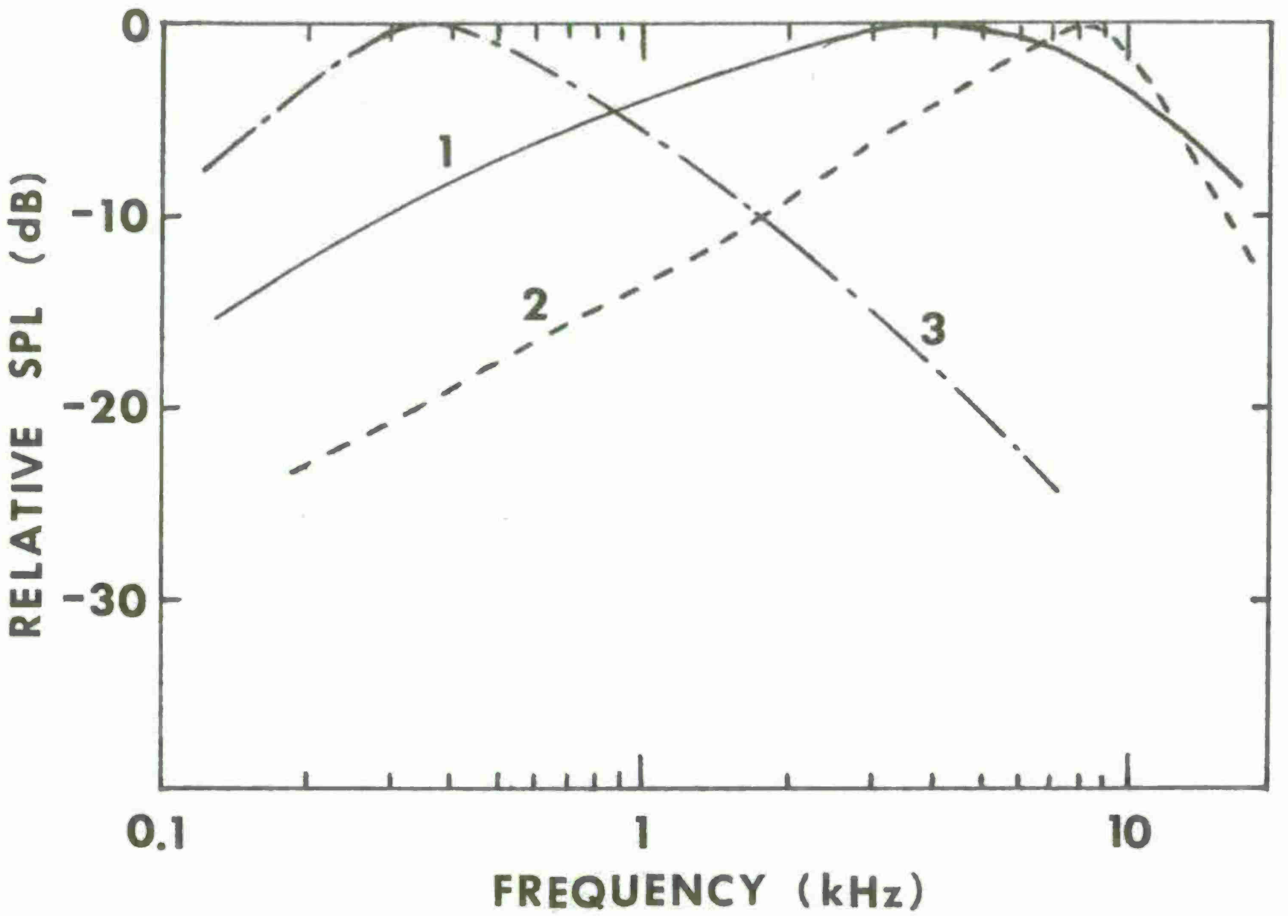

Figure 4. Spectra of personnel sounds and speech. 1: averaged spectra of five sounds peaking at 4 kHz (canoe paddle; canteen slosh; waves against boat; swimmer leaving water; fish jumping in water). 2: averaged spectra of five sounds peaking at 8 kHz (man walking in grass with and without shoes; loose cartridges; loose dog tags; clipping barbed wire). 3: male speech.

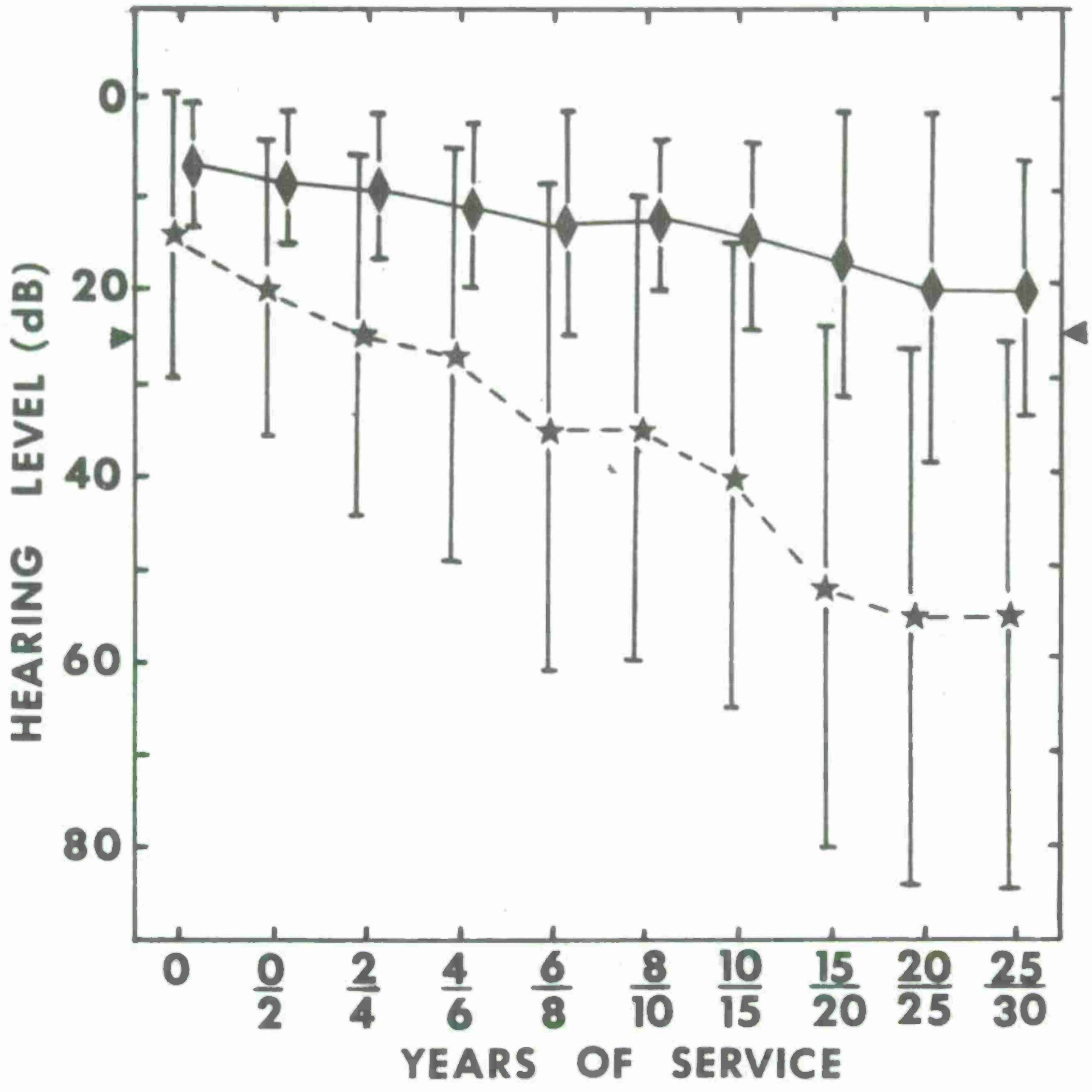

Figure 5. Means and standard deviations of hearing levels of Army personnel as a function of years of service. Upper curve: average of 0.5, 1 and 2 kHz. Lower curve: average of 4 and 6 kHz. (From Ref. 28.)

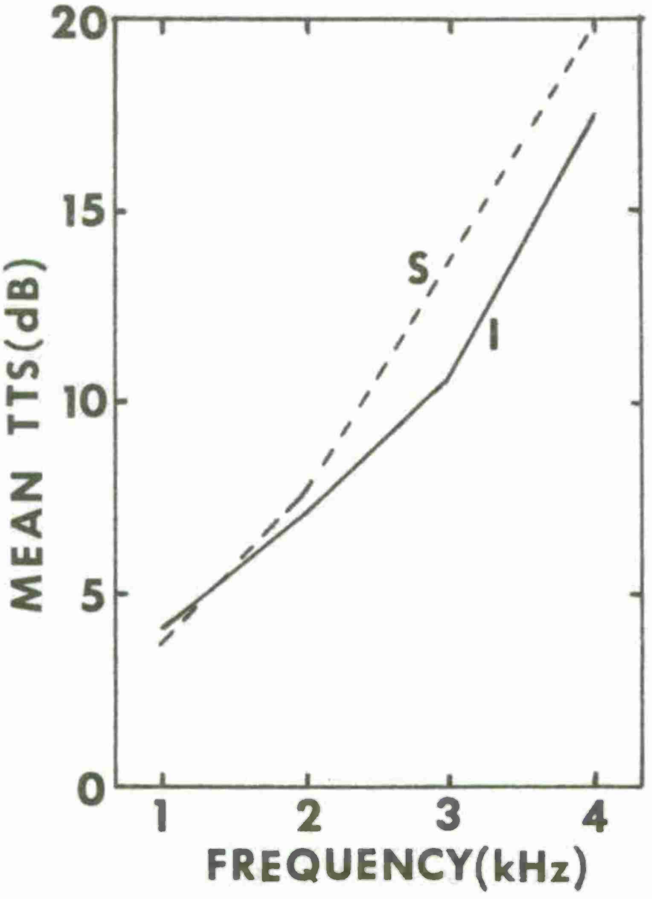

Figure 6. TTS from steady and impulse noise. S: 5-min. exposure to white noise at 90 dB sensation level. (From Ref. 24.) I: 25 gunfire impulses at 163 dB peak level. (From Ref. 3.)

c. Speech reception is relatively unaffected by typical hearing losses (particularly TTS), and can be predicted fairly well from audiometric data.

d. Materiel sound detection (at great distances) is unaffected by typical hearing losses.

e. Personnel sound detection is probably affected by typical hearing losses, and cannot be predicted from audiometric data.

f. Conclusion: We should concentrate on the relation between hearing acuity and ability to detect high-frequency personnel sounds; we are.

RESEARCH ON COMBAT SOUND DETECTION AS A FUNCTION OF HEARING ACUITY

Two aspects of this problem are being pursued. One involves recording and analyzing the spectra of selected personnel sounds in order to define the spectral domain of these sounds; the other involves preliminary experimental work with existing sound recordings.

Spectra of Personnel Sounds

Table 1 lists some of the variables of interest in developing a subpopulation of recorded personnel movement sounds for spectral analysis and listening tests. We plan to record and analyze sounds representing appropriate combinations of the variables to determine the spectral regions that may be important for detecting personnel movement sounds. (Example: the sound of one man wearing normal combat clothing, crawling over earth that is covered by short green vegetation.)

TABLE 1

Variables of Interest in Developing A Sub-Population of Personnel Movement Sounds

1. Mode of Movement	3. Vegetation
Walking	None
Running	Short
Crawling	Tall
Skiing	Green
Snowshoeing	Dry
Swimming	
2. Types of Terrain	4. Clothing Worn
Earth	Minimal
Pavement	Normal Combat
Gravel	No Shoes
Sand	Loose Items
Snow	5. Number of Personnel
Water	
Swamp	

Another subpopulation will include the sounds of personnel activity, other than movement, per se. Included here will be sounds that might be important if one were listening for an enemy attempting to infiltrate our position, e.g., barbed wire being cut. A study by Coles (6) indicated that soldiers with high-frequency hearing losses were impaired in their ability to detect such sounds.

Preliminary Listening Tests

Briefly, tape-recorded sounds are presented to subjects via circumaural earphones. A dedicated computer controls the signal level via a programmable attenuator, using the up-and-down psychophysical method. The subject knows when to listen and when to respond. The program runs until a preset number of detection threshold crossings has occurred; then it stops, and the detection threshold for that test run is computed and printed.

Sound Recordings

We are presently using sound segments taken from an Army training aid tape recording (9). Table 2 lists the personnel sounds (movement and activity) available. Ultimately, we will be using our own recordings.

TABLE 2

Personnel Sounds Available on Device 5H12[1]

Loose cartridges in the pocket of running man
Man walking in grass with shoes
Man walking in grass without shoes
Slap of a canoe paddle in water
Window pane being tapped out
Slosh of half-filled canteen as man runs
Man dragging a large object over dirt
Jingle of loose dog tags
Soft waves lapping against side of moving boat
Swimmer coming out of water
Barbed wire being cut

[1]Device 5H12 also contains a number of weapon and heavy materiel sounds.

Computer Control System

We have a terminal from a Grason-Stadler SCAT programming computer in our laboratory. This makes it possible to gather a great deal of data efficiently, without introducing human errors. Figure 7 shows the computer control system and other laboratory instrumentation.

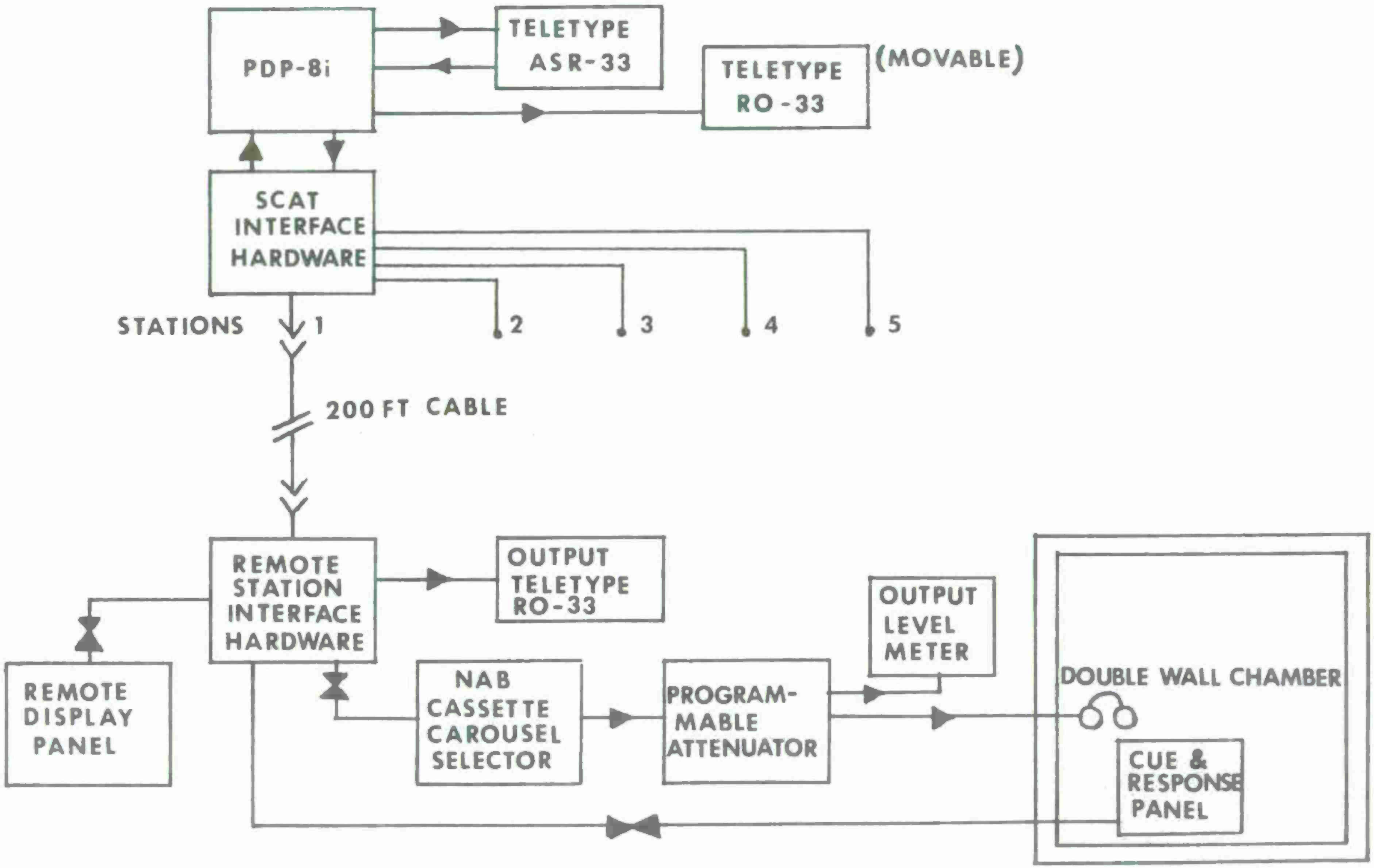

Figure 7. Instrumentation for studies of combat sound detection. For details of operation, see text.

Tape Reproducing System

The experimental paradigm requires a tape reproducing system having a wide, flat response, permitting a given sound segment to be played back repeatedly and automatically. The NAB cassette system, used by FM radio stations for playing repeated announcements, was selected. There are three tracks on the 1/4-inch tape: two for stereophonic signals, and a third for cue tones. A cue tone can, for example, be recorded at the end of a test sound segment and used to stop the tape drive at that point.

The NAB cassette tapes are recorded on an International Tapetronics recorder. They are played back on a Sono-Mag carousel deck. The carousel deck holds 24 cassettes, which are selected manually by the operator. (A random-access logic package is available should that feature become desirable in future studies.)

Earphones

Standard audiometric earphones, for which there are standardized calibration techniques and couplers, are not suitable for these experiments because most of them do not respond above 10 kHz. Circumaural earphones (e.g., conventional stereophonic phones) have the desired broad frequency response, but there are no standardized calibration procedures or couplers. (Some workers (cf., 26) doubt that standardized calibration procedures can be developed.) Measured on a flat-plate coupler, most stereo phones show large peaks and valleys in their response curves. We have been using Koss Pro-4AA phones for most of our preliminary tests, because their response on a flat-plate coupler was the least variable of the several dynamic phones tested.

Subject's Cue and Response Console

The subject is seated inside a double-walled IAC chamber, wears the circumaural earphones, and has a cue and response console. One display lights when he is supposed to listen; another lights when he is supposed to respond. Push-buttons allow him to respond "yes" or "no," i.e., that he did, or did not, hear a sound during the listening interval.

Current Preliminary Testing

We have made a number of simplifying assumptions about the listening task in order to begin the program with as simple a task as possible; this, we expect, will enable us to gain an understanding of the problems involved in sound detection.

1. We are measuring <u>detection</u> only.

2. The subject is assumed to be <u>alert.</u> We tell him when to listen and when to respond.

3. The sound presentation is <u>monaural.</u> This should permit us to correlate hearing level and detection threshold most easily.

4. The subject is listening in <u>quiet.</u>

We recognize this as a highly artificial listening situation, quite unlike the real world in which the soldier will be expected to perform. For example, he might not be alert, would ordinarily have two ears to listen with, and probably would have to contend with some sort of masking noise. Moreover, he will be as interested in identifying the sound as detecting it. We feel, however, that it is important to gain some basic understanding of the relation between hearing level and detection threshold in a simple listening situation before introducing what are likely to be confounding variables. Ultimately, or course, we expect to try stereophonic presentations, realistic masking sounds (rain, wind, etc.), and to measure signal levels needed for identification as well as detection. There may also be a possibility of conducting some field tests to verify conclusions reached in laboratory tests.

(Very) Preliminary Results

It has already become clear, after conducting only a few pilot tests, that pure-tone hearing levels do not explain all. Figure 8 shows the spectra for two sounds: those of a man walking in grass with, and without, shoes. These spectra are very similar: both peak in the 6.3 kHz band. Figure 9 shows the audiograms for two subjects tested in pilot experiments. One has normal hearing (usually defined as hearing levels no greater than 15 dB at any test frequency); the other has a severe hearing loss in the 4-7 kHz range. At 6 kHz, these two subjects differed by 65 dB in their hearing levels. Yet their detection thresholds for the two sounds differed by only about 18 dB. Obviously, then, the substantial difference in hearing level at 6 kHz does not explain the results.

I think that this example illustrates the complexity of the problem, and suggests that a number of different parameters must be looked at and a variety of analytic approaches taken in developing the relation between hearing acuity and personnel sound detection.

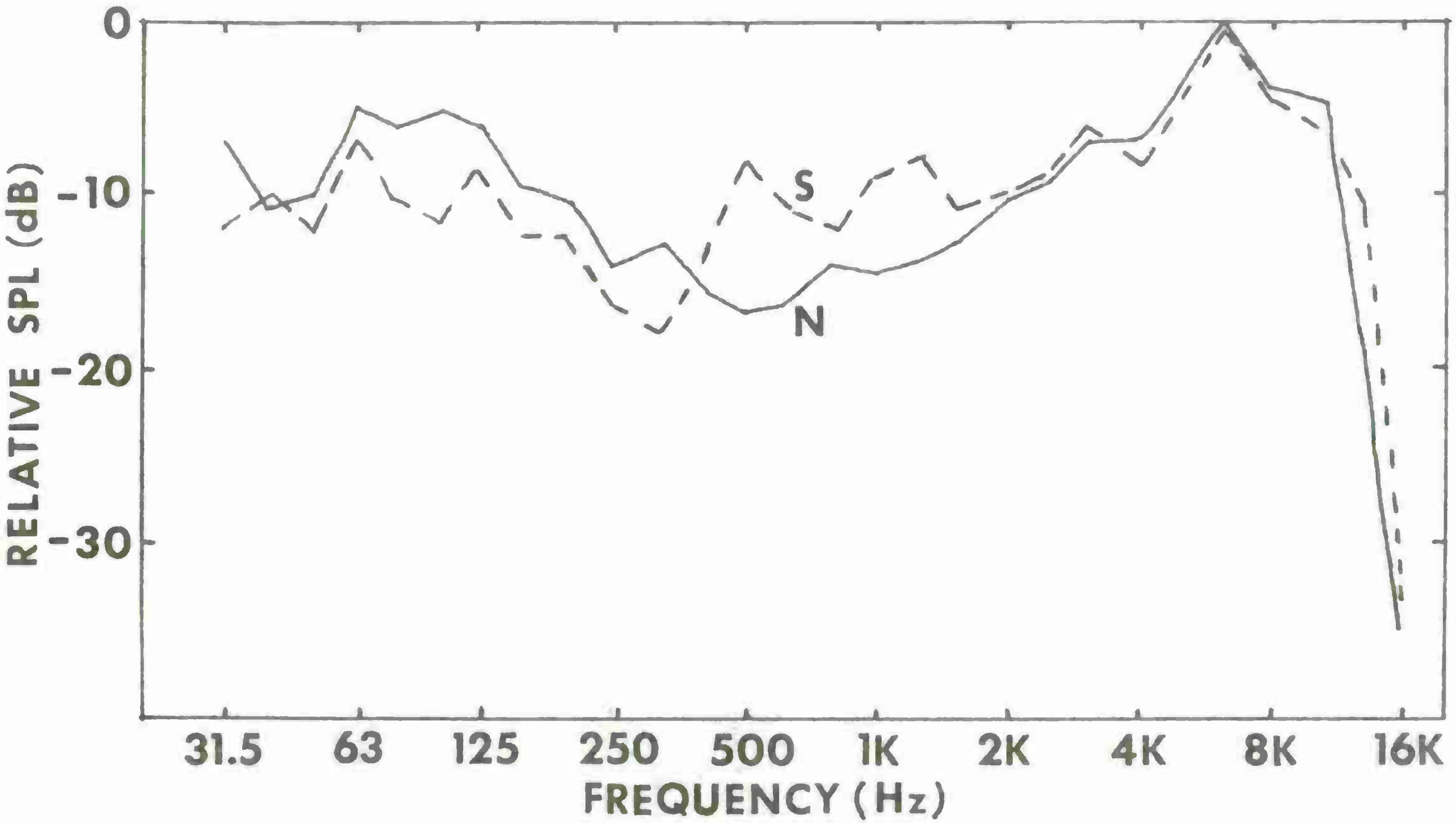

Figure 8. One-third octave spectra for two personnel movement sounds: A man walking in grass with (S) and without (N) shoes.

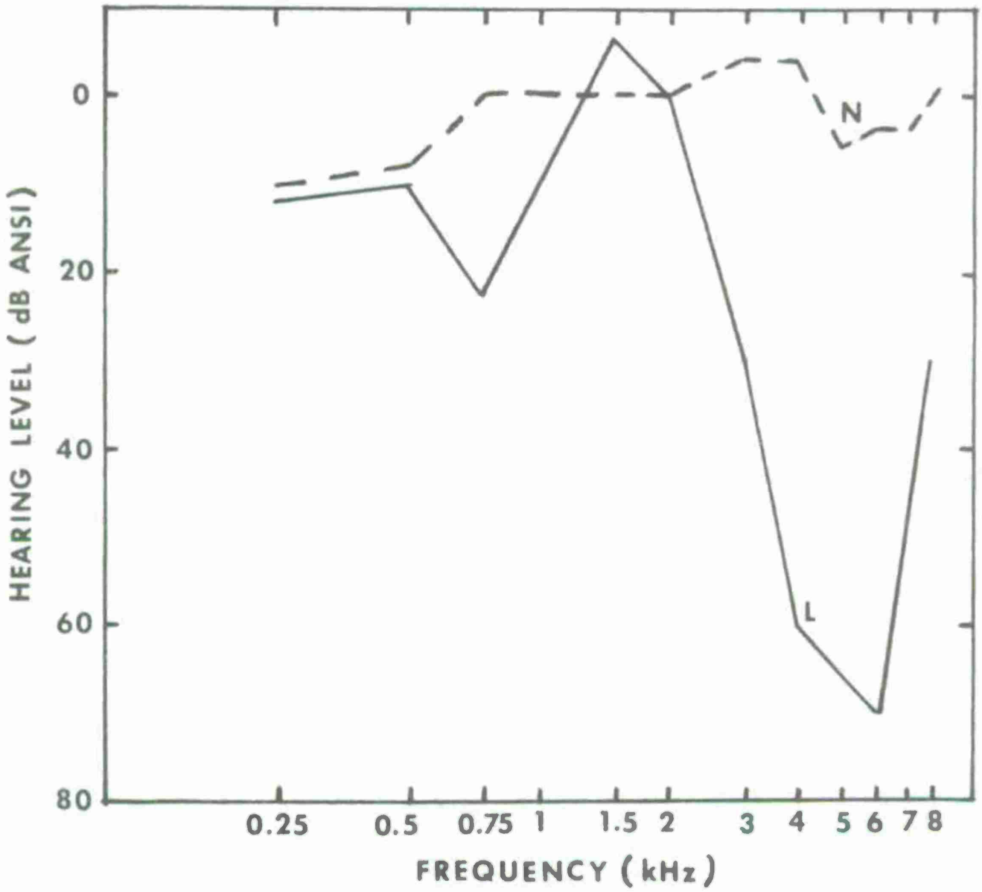

Figure 9. Audiograms for two test subjects. N: normal hearing. L: high-frequency hearing loss.

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