NTID300.7

EFFECTS OF NOISE ON PEOPLE

DECEMBER 31, 1971

U.S. Environmental Protection Agency
Washington, D.C. 20460

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Prepared by

THE CENTRAL INSTITUTE FOR THE DEAF
under
CONTRACT 68-01-05000

for the

U.S. Environmental Protection Agency
Office of Noise Abatement and Control
Washington, D.C. 20460

PREFACE

This manuscript was prepared by Dr. James D. Miller, Central Institute for the Deaf, St. Louis, Missouri and has been reviewed and approved for publication by the following members of the NAS-NRC Committee on Hearing, Bioacoustics, and Biomechanics: Hallowell Davis, Karl D. Kryter, William D. Neff, Wayne Rudmose, W. Dixon Ward, Harold L. Willima, and Jozef J. Zwislocki. Of course, the final responsibility for the contents of this paper lies with Dr. Miller as author.

FOREWORD

It has not been demonstrated that many people have had their lives shortened by noise. While undoubtedly there have been accidental injuries and deaths when auditory warning signals were misunderstood or not heard because of the effects of noise, the prevalence of these has not been evaluated. Perhaps the stress of continued exposure to high levels of noise can produce disease or make one more susceptible to disease, but the evidence is not convincing. There are only hints of relations between exposure to noise and the incidence of disease. In other words, the effects of noise on people have not been successfully measured in terms of "excess deaths" or "shortened lifespan" or "days of incapacitating illness." The only well-established effect of noise on health is that of noise-induced hearing loss.

There is clear evidence to support the following statements about the effects on people of exposure to noise of sufficient intensity and duration.

Noise can permanently damage the inner ear with resulting permanent hearing losses that can range from slight impairment to nearly total deafness.

Noise can result in temporary hearing losses and repeated exposures to noise can lead to chronic hearing losses.

Noise can interfere with speech communication and the perception of other auditory signals.

Noise can disturb sleep.

Noise can be a source of annoyance.

Noise can interfere with the performance of complicated tasks and, of course, can especially disturb performance when speech communication or response to auditory signals is demanded.

Noise and other acoustical considerations can reduce the opportunity for privacy.

Noise can adversely influence mood and disturb relaxation.

In all of these ways noise can affect the essential nature of human life--its quality. It is for these reasons that the recitation of facts and hypotheses that follow may be of some importance.

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INTRODUCTION

An old riddle asked, "What comes with a carriage and goes with a carriage, is of no use to the carriage and yet the carriage cannot move without it?" The answer: "A noise."

And yet (sound) is of great use to us and to all animals. Many events of nature, whether the meeting of two objects or the turbulent flow of air, radiate a tiny part of their energy as pressure waves in the air. A small fraction of the energy that is scattered enters our ears, and we hear it and thus we know of the event. Hearing is a late development in evolution but it has become the sentinel of our senses, always on the alert.

But hearing does more. The ear and the brain analyze these sound waves and their patterns in time, and thus we know that it was a carriage, not footsteps that we heard. What is more, we can locate the position of the carriage, and tell the direction in which it is moving.

. . . . . .

Many birds and animals have also learned to signal one another by their voices, both for warning and for recognition. But we humans, with good ears and also mobile tongues and throats, and above all, our large complex brains, have learned to talk. We attach arbitrary and abstract meanings to sounds, and we have language. We communicate our experiences of the past and also our ideas and plans for future action. For human beings, then, the loss of hearing brings special problems and a special tragedy. ... human society creates a special problem even for those with perfect hearing—the problem of unwanted sound, of noise, which is as much a hazard of our environment as disease germs or air pollution.

. . . . . . All of (these subjects) are important. Sounds may be small and weak, but civilization could not have grown without them.

(Introduction by Hallowell Davis, M.D., to Sound and Hearing, 1965, Time, Inc., courtesy of TIME-LIFE BOOKS.)

Biologically, man has not changed for many thousands of years. His responses to sound today rest on the same biological heritage as they did in the far distant past. The ear, the auditory nervous system, and the interrelations between the auditory system and the remainder of man's bodily and behavioral functions developed to meet the demands for adaptation to the environment—the environment of the past.

It is interesting to contrast the visual and auditory systems in this regard. With each day there are and have been enormous, sustained changes in the amount of light at any point on the surface of the earth. Visual animals that engage in important activities during both day and night developed visual mechanisms that function, without damage, during sustained periods that differ greatly in luminance. Daily changes of luminance equivalent to about 100 decibels have occurred for as long as the earth has rotated on its axis. The eyes are provided with lids that can block out light, pupils which vary in size and thus control the amount of light entering the eyes, and sensory receptors that have mechanisms to alter their sensitivity with these very large changes in luminance.

The situation for sound and hearing is quite different. As the ear developed it did not need to contend with large daily variations in average sound levels. Indeed, one imagines that only rarely were intense sounds sustained for very long periods of time. To be sure, the ear had to be able to withstand the intense but brief sounds of thunder, the moderately intense sounds of windstorms and sustained rain, but these rarely lasted more than a few hours. In general, the evolving ear did not have to cope with either frequent, very intense sounds or even moderately intense sounds that were maintained day after day. Only near some beaches, waterfalls, or areas with sustained winds would moderately intense sound levels have continued for prolonged periods of time. It is interesting in this regard that ancient travelers noted that villagers who lived near the cataracts of the Nile appeared to have hearing loss (Ward, 1970a).

Hearing evolved to play a role in both individual and social adaptation to the environment. For individual efforts at survival, hearing is indeed the "sentinel of our senses, always on the alert." By hearing, man can detect a sound-making object or event, day or night. Often man can localize the direction of an object or event and sometimes identify it by its sound alone. To increase the chances of identifying objects or events and to insure appropriate preparation for response, evolution has closely tied hearing to man's activating and arousal systems. These systems energize us. In addition, specific auditory-muscular reflexes cause one to orient his head and eyes in an appropriate direction to aid recognition and identification of the sound-making object or event.

Hearing is also involved in <u>social</u> mechanisms of adaptation to the environment. With our voices and ears we can "communicate our experiences of the past and also our ideas and plans for future action." In addition, language, dialect, and manner of speech are important determiners of the actions and cohesiveness of social groups.

The close ties of hearing to arousal, muscular actions, and social relations provide the biological foundations for the mood-influencing and esthetic properties of auditory experience. For hearing not only serves as an ever-vigilant warning system and as the avenue of speech reception, but also acts to influence man's moods, feelings of well-being, and esthetic sensibilities. Many of these responses to sound are culturally determined and represent learned attitudes, but surely there are biological bases for development of music with its associated emotional responses along with the muscular responses of rhythmic movement and dance. Some of these biological bases stem from adaptative interrelations between the auditory system and the arousal and muscular systems. Others may be simply accidents of the evolution of the auditory system.

Thus, it is clear that sound is of great value to man. It warns him of danger and appropriately arouses and activates him. It allows him the immeasurable advantage of speech and language. It can be beautiful. It can calm, excite, and it can elicit joy or sorrow. The recent discovery that five-day-old infants will work to produce a variety of sounds (Butterfield and Siperstein, 1970) only reinforces our everyday observations that man enjoys hearing and making sounds.

But not all sound is desirable. Unwanted sound is noise. The definition of noise includes a value judgment, and for a society to brand some sounds as noises requires an agreement among the members of that society. Sometimes such agreements can be achieved readily. Other times considerable analysis and debate is required before agreement can be reached.

For example, while machines are useful and valuable, they often produce as a by-product too much sound, noise. On the other hand, since machines can be dangerous, undoubtedly they should make enough sound to warn us of their approach or of the danger from their rapidly moving, powerful parts. But how much and what kinds of sound? Also, sounds that are valuable in one location may travel to places where they may not only serve no desirable purpose, but they may interfere with and disrupt useful and desirable activities. Some sounds seem to serve no useful purpose, anywhere or anytime to anyone. These sounds are unwanted and they clearly are noises. Other sounds are noises only at certain times, in certain places, to certain people. It is these complexities that require considerable analysis and thought to enable us to reach agreement about what is noise and what is not. Scientists and citizens have engaged in such analysis and thought and some of the results of their efforts are described in this report.

The effects of noises of such low frequency (infra-sound) or of such high frequency (ultra-sound) that they cannot be heard by people are not considered in this paper. Furthermore, this paper is not addressed to the extent of the noise problem either in terms of the number of people affected or in terms of the resulting social or economic costs of noise. Rather it is the relations between the properties of noise and its effects on people that are presented.

PART I. AUDITORY EFFECTS

Preliminary Statement

The auditory system is exquisitely sensitive to sound. The acoustical power at the eardrum associated with a sound so loud as to produce discomfort (120 decibels) is only about 1/10,000 of a watt. The sound power of the same sound impinging over the entire surface of the body is of the order of 1.0 watt. Furthermore, the boundary between the skin of the body and the surrounding air is such that little of the acoustical power of audible sound is actually transmitted into the body. Even for very loud sounds only a small amount of acoustical power actually reaches the body. Therefore, it is not surprising that noise has its most obvious effects on the ear and hearing since these are especially adapted to be sensitive to sound.

One set of auditory effects is noticeable after a noise has passed; these are temporary hearing loss, permanent hearing loss, and permanent injury to the inner ear. Another set of auditory effects is noticeable while a noise is present; these are masking and interference with speech communication. Both of these sets of adverse auditory effects are discussed below.

Section 1. EAR DAMAGE AND HEARING LOSS

Introduction

Exposure to noise of sufficient intensity for long enough periods of time can produce detrimental changes in the inner ear and seriously decrease the ability to hear. Some of these changes are temporary and last for minutes, hours, or days after the termination of the noise. After recovery from the temporary effects, there may be residual permanent effects on the ear and hearing that persist throughout the remainder of life. Frequent exposures to noise of sufficient intensity and duration can produce temporary changes that are chronic, though recoverable when the series of exposures finally ceases. Sometimes, however, these chronically maintained changes in hearing lose their temporary quality and become permanent.

The changes in hearing that follow sufficiently strong exposure to noise are complicated. They include distortions of the clarity and quality of auditory experience as well as losses in the ability to detect sound. These changes can range from only slight impairment to nearly total deafness.

A. Ear Damage

How ear damage from noise is studied. Conclusive evidence of the damaging effects of intense noise on the auditory system has been obtained from anatomical methods applied to animals. One group of animals is exposed to noise and a comparable control group is not. After a wait of a few months, both groups of animals are sacrificed and their inner ears are prepared for microscopic evaluation. The primary site of injury is found to be in the receptor organ of the inner ear. Modern quantitative methods allow an almost exact count of the numbers of missing sensory cells in the inner ears of noise-exposed animals. These can be compared to the numbers of missing cells in the inner ears of control animals. Other signs of injury such as changes in the accessory structures of the inner ear can also be observed.

These anatomical methods are limited for two reasons. The integrity of crucial structures, such as the connections between the hairs of the hair cells and the tectorial membrane, cannot be evaluated, and also the functional properties of cells that are clearly present cannot be assessed. That is, when a cell is clearly present, the anatomist can only guess at its functional state. The absent cell is clearly identifiable and the interpretation of its function is obvious.

The inner ears of human beings have also been examined. Some patients with terminal illness have volunteered their inner ears to temporal bone banks. Such specimens are collected at the time of a post-mortem examination. The anatomist tries to relate the condition of the human ear to the patient's case history after making allowances for post-mortem changes in the inner ear and possible pre-mortem changes associated with the terminal illness or its treatment. In spite of these difficulties, observations of human cochleas are extremely important and in combination with animal experiments provide a fairly clear description of the damaging effects of noise on the inner ear.

Because of the limitations of anatomical methods and the lack of complete knowledge of the relations between hearing abilities and the anatomy of the auditory system, it is not possible to predict completely the hearing changes from the anatomical changes. However, physiological observations which include measurement of changes in biochemical state and electrical responses of the cochlea and auditory nerve help to reveal the functional changes produced by exposure to noise.

Kinds of ear damage and major findings. The outer ear, eardrum, and middle ear are almost never damaged by exposure to intense noise. The eardrum, however, can be ruptured by extremely intense noise and blasts (von Gierke, 1965). The primary site of auditory injury from excessive exposure to noise is the receptor organ of the inner ear. This has been known for many years, and excellent illustrations of such damage were published near the turn of the century (Yoshii, 1909).

The receptor organ of the inner ear is the organ of Corti, and its normal structure is illustrated in cross-section in Panel A of Figure 1. Here one can identify the auditory sensory cells (hair cells) and the auditory nerve fibers attached to them, as well as some of the accessory structures of the receptor organ. A brief account of the function of the organ of Corti is as follows. Through a complicated chain of events, sound at the eardrum results in an up-and-down movement of the basilar membrane. The hair cells are rigidly fixed in the reticular lamina of the organ of Corti which in turn is fixed to the basilar membrane. As the basilar membrane is driven up and down by sound, a shearing movement is generated between the tectorial membrane and the top of the organ of

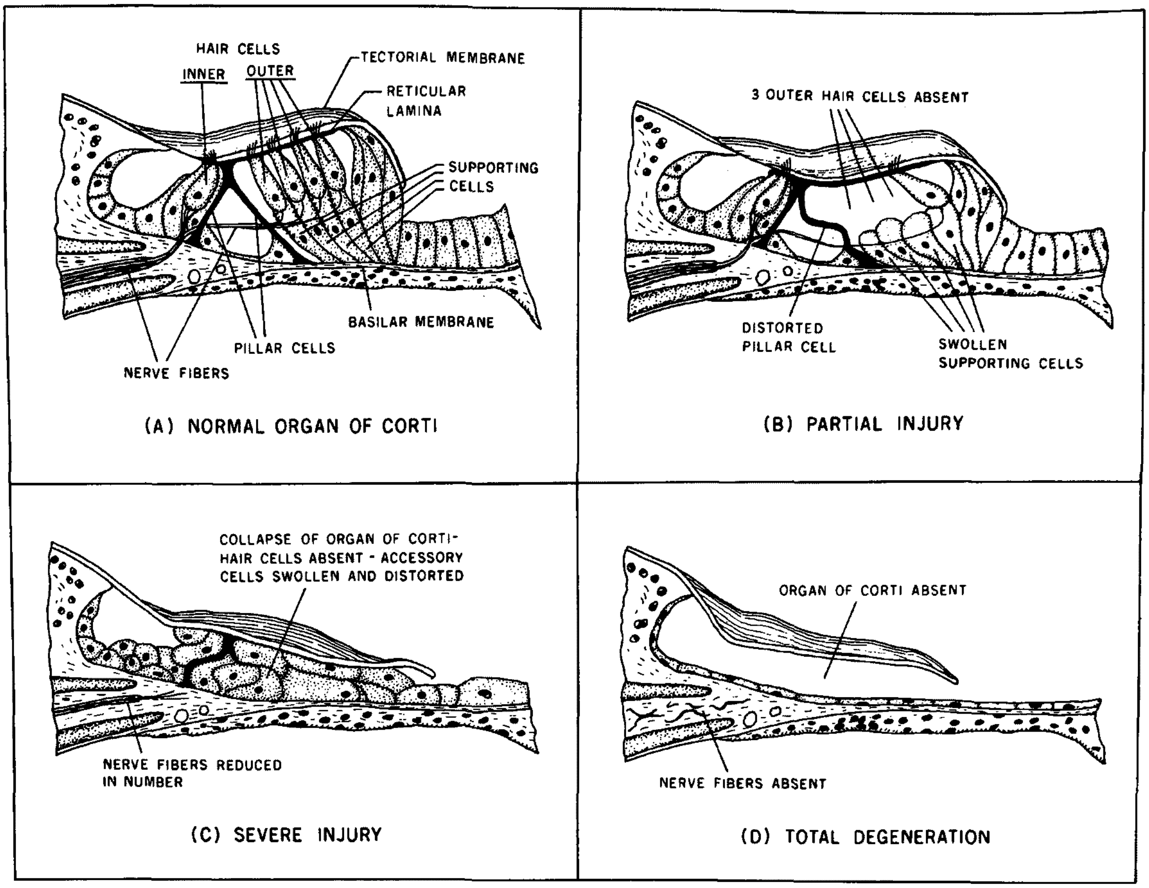

Figure 1. Drawings of the human organ of Corti are shown that illustrate the normal state, Panel A, and increasing degrees of noise-induced permanent injury, Panels B, C, and D.

Corti. This movement bends the hairs at the top of the hair cells. This bending, in turn, causes the hair cells to stimulate the auditory nerve fibers. As a result, nerve impulses arise in the nerve fibers and travel to the brain stem. From the brain stem, the nerve impulses are relayed to various parts of the brain and in some unknown way give rise to auditory sensations. The point to be made is that the integrity of the sensory cells and the organ of Corti is important for normal hearing.

Excessive exposure to noise can result in the destruction of hair cells and collapse or total destruction of sections of the organ of Corti. In addition, auditory neurons may degenerate. Figure 1 illustrates these injuries. The injury illustrated in Panel B includes absence of 3 outer hair cells, distortion of a pillar cell, and swelling of the supporting cells. In Panel C there is a complete collapse of the organ of Corti with the absence of hair cells, distortion of the accessory structures, and a reduction in the number of nerve fibers. This section of the organ of Corti is almost certainly without auditory function. The injury shown in Panel D is obvious; there is complete degeneration of the organ of Corti.

On Figure 2 are shown actual photomicrographs of cross-sections of the organ of Corti from post-mortem human specimens. These photographs were provided by Dr. Harold F. Schuknecht of the Massachusetts Eye and Ear Infirmary of Boston, Massachusetts. The organ of Corti in Panel A of Figure 2 is essentially normal and can be compared with the drawing on

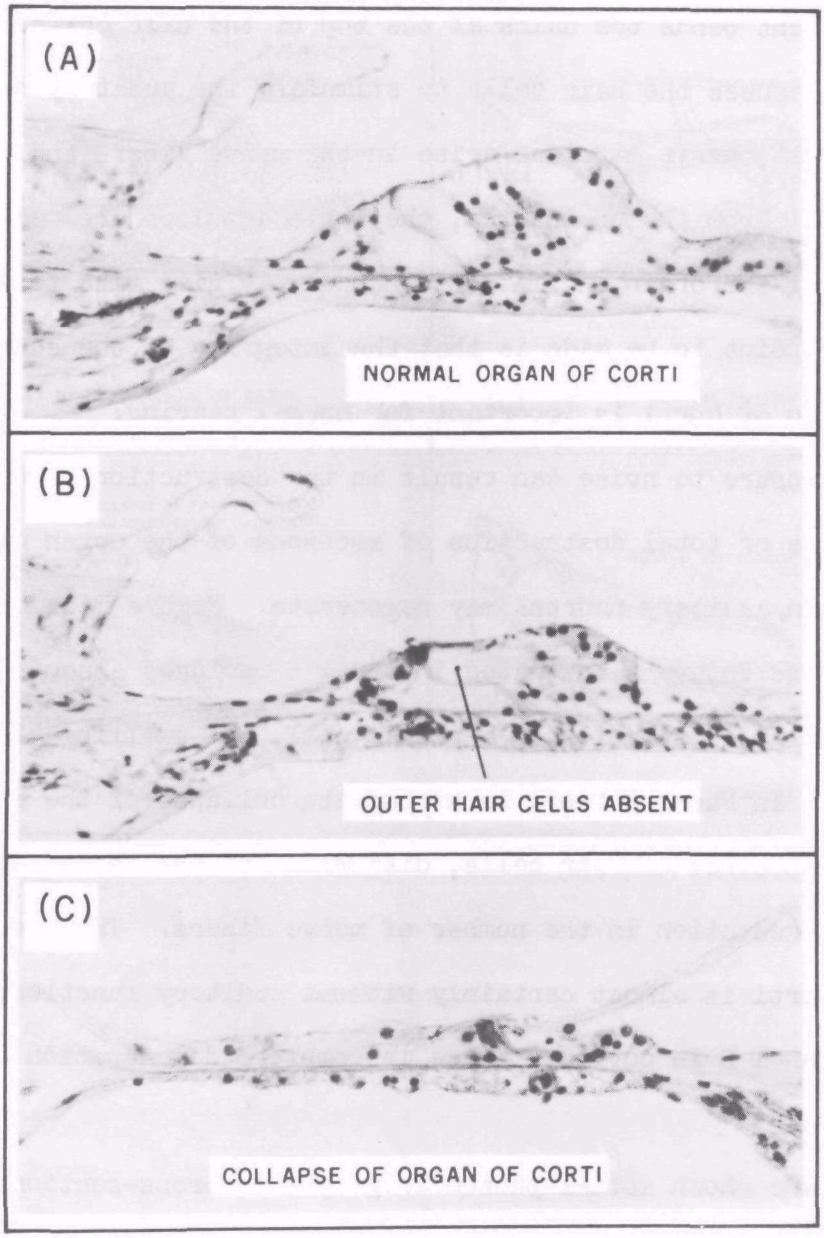

Figure 2. Photomicrographs of cross-sections of the human organ of Corti are shown: Panel A, normal; Panels B and C, injuries most probably produced by exposure to noise. Similar injuries have frequently been seen in experimental animals after exposure to noise. (These photographs were provided by Dr. Harold F. Schuknecht of the Massachusetts Eye and Ear Infirmary of Boston, Massachusetts.)

Panel A of Figure 1. Shown on Panel B of Figure 2 is a cross-section of the organ of Corti from a man who worked for a few years in small compartments of boilers where for prolonged periods of time he was exposed to the noise of riveting machines. In this cross-section the inner hair cell is present but only one outer hair cell can be seen where one would normally expect to see four. The example in Panel C is from a man who worked in the noisy environment of a steel factory. There is collapse of the organ of Corti with complete absence of normal receptor cells.

The injuries on Figures 1 and 2 are from selected locations within the ear. For proper perspective it is important to know that the human organ of Corti is about 34 millimeters in length with about 395 outer hair cells and 100 inner hair cells per millimeter (Bredberg, 1968). These total about 17,000. Thus, the five hair cells shown in a single location represent but a small fraction of the receptor organ. The magnitude of injury to the inner ear and the associated hearing loss depend not only on the severity of the injury at any one location but also on the spread of the injury along the length of the organ of Corti.

The loss of hearing abilities depends, in a complicated way, on the extent of the injury along the organ of Corti. Total destruction of the organ of Corti for one or two millimeters of the total 34 millimeters may or may not lead to measurable changes in hearing. Recent evidence from human cases and animal experiments suggests that the loss of sensory cells must be quite extensive in the upper part of the cochlea (that part which is important for the perception of low-frequency sounds) before this damage is reflected as a change in threshold. In the lower part of the cochlea (that part which is important for the perception of high-frequency sounds) losses of sensory cells over a few millimeters are sometimes reflected in changes in hearing (Bredberg, 1968).

The mechanism by which over-exposure to noise damages the auditory receptor is not well understood. Very intense noise can mechanically damage the organ of Corti. Thus, loud impulses such as those associated with explosions and firing of weapons can result in vibrations of the organ of Corti that are so severe that some of it is simply torn apart. Other very severe exposures to noise may cause structural damage that leads to rapid "break-down" of the processes necessary to maintain the life of the cells of the organ of Corti. Such an injury is an acoustic trauma.

Over-exposure to noise of lower levels for prolonged periods of time also results in the degeneration of the hair cells and accessory structures of the organ of Corti. Such injuries are called noise-induced cochlear injuries. Many theories have been proposed to explain noise-induced cochlear injuries. One notion is that constant over-exposure forces the cells to work at too high a metabolic rate for too long a period of time. As a result the metabolic processes essential for cellular life become exhausted or poisoned, and this leads to the death of the cells. In a sense, the receptor cells can die from overwork.

No matter what theory is eventually found to be correct, certain facts are established beyond doubt. Excessive exposure to noise leads to the destruction of the primary auditory receptor cells, the hair cells. There can be other injuries to the organ of Corti that can range from mild distortion of its structure to collapse or complete degeneration. The auditory neurons may also degenerate. All of these cells are highly specialized. Once these cells are destroyed, they <u>do not regenerate</u> and <u>cannot</u> be stimulated to regenerate; they are lost forever.

B. Hearing Loss

<u>How hearing loss due to noise is studied</u>. Experiments on hearing loss are sometimes done with animals because one would not deliberately deafen a human subject. For these experiments it is necessary to train the animal subjects so that their ability to detect faint tones can be measured. The measure of this ability is the intensity level of the faintest tone that can be detected. This is called the hearing threshold level. The greater the hearing threshold level, the poorer the ability to hear. The hearing thresholds of trained animals are measured by methods similar to those used with human patients. After the animal's normal thresholds have been measured, it is exposed to noise under controlled laboratory conditions. After the cessation of the noise, changes in the animal's thresholds are measured. Subsequently, its ears are evaluated by physiological and anatomical methods.

Experiments with human subjects are limited to exposures to sound that produce only temporary changes in the hearing mechanism. In such experiments, measures of some auditory capability are made prior to exposure and also at various specified times after its termination. One of the advantages of laboratory studies is the fact that precise measures of hearing are made before and after exposures to a noise whose properties are exactly known.

Measurements of the effects of noise on human hearing are also collected in field and clinical case studies. These data are subject to considerable error, but several well-done field studies have been completed or are now in progress. Threshold measurements are made on persons who are regularly exposed to noise. These exposures usually occur in an occupational setting. Noise levels are measured and the progress of hearing thresholds is followed. While it is true that the actual occupational exposures vary from day to day and moment to moment within a day, some rather clear trends emerge when a sufficient number of persons are carefully studied. For comparison, similar measurements are made on persons whose life patterns include very little exposure to noise.

Well-done studies of individual patients in the clinic have suggested hypotheses and have also been an important source of data.

<u>Temporary, compound, and permanent threshold shifts—single exposures</u>. The primary measure of hearing loss is the hearing threshold level. The hearing threshold level is the level of a tone that can just be detected.

The greater the hearing threshold level, the greater the degree of hearing loss or partial deafness. An increase in a hearing threshold level that results from exposure to noise is called a threshold shift.

Some threshold shifts are temporary and they diminish as the ear recovers after the termination of the noise. Frequently-repeated exposures can produce temporary threshold shifts that are chronic though recoverable when the exposures cease. When a threshold shift is a mixture of temporary and permanent components, it is a compound threshold shift. When the temporary components of a compound threshold shift have disappeared (that is, when the ear has recovered as much as it ever will), the remaining threshold shift is permanent. Permanent threshold shifts persist throughout the remainder of life.

Temporary threshold shifts can vary in magnitude from a change in hearing sensitivity of a few decibels restricted to a narrow region of frequencies (pitches) to shifts of such extent and magnitude that the ear is temporarily, for all practical purposes, deaf. After cessation of an exposure, the time for hearing sensitivity to return to near-normal values can vary from a few hours to two or three weeks. In spite of efforts in many laboratories, the laws of temporary threshold shifts have not yet been completely determined. There are large numbers of variables that need to be explored. Also, there are probably several different underlying processes that influence the measured threshold shifts. It may be necessary to sort out the influence of each of these underlying processes before the laws of noise-induced temporary threshold shifts will be completely understood.

Nonetheless, certain generalizations seem to be correct (Ward, 1963). Noises with energy concentrations between about 2000 and 6000 hertz probably produce greater temporary threshold shifts than noises concentrated elsewhere in the audible range. In general, A-weighted sound levels must exceed 60-80 decibels before a typical person will experience temporary threshold shifts even for exposures that last as long as 8-16 hours. All other things being equal, the greater the intensity level above 60-80 decibels and the longer the time in noise, the greater the temporary threshold shift. However, exposure durations beyond 8-16 hours may not produce further increase in the magnitude of the shift (Mills *et al.*, 1970; Mosko *et al.*, 1970). It is also an interesting property of temporary threshold shifts that such shifts are usually greatest for test tones 1/2-1 octave above the frequency region in which the noise that produces the shift has its greatest concentration of energy. Finally, there is less temporary shift when an exposure has frequent interruptions than when an exposure is continuous.

People differ in their susceptibility to temporary threshold shifts. Unfortunately, these differences in susceptibility are not uniform across the audible range of frequencies (pitches). Indeed, one person may be especially susceptible to noises of low pitch, another to noises of medium pitch, and another to noises of high pitch. In general, women appear to be less susceptible to temporary threshold shifts from low-frequency noises than are men, and this relation is reversed for high-frequency noises (Ward, 1966; Ward, 1968a).

An impression of the quantitative facts of temporary threshold shifts can be obtained from Figures 3 and 4. All of the dashed lines indicate extrapolations based on current research. While it is likely that the general trends shown on these figures will be verified by additional research, the exact values cannot be expected to be accurate. For short durations of exposures to high intensities there may even be some changes in the rank ordering of the initial segments of curves. Nonetheless, these graphs provide an adequate summary of reasonable extrapolations of available data.

Consider Figure 3. The time in noise is plotted along the horizontal axis, while the amount of threshold shift measured in decibels at two minutes after the cessation of the exposure is plotted on the vertical axis. These curves represent probably the worst possible situation in that the noise is in the region, 2400-4800 hertz, to which the ear is most susceptible, and the test tone is at 4000 hertz where threshold shifts are often large. Certain facts are obvious from the graph. The

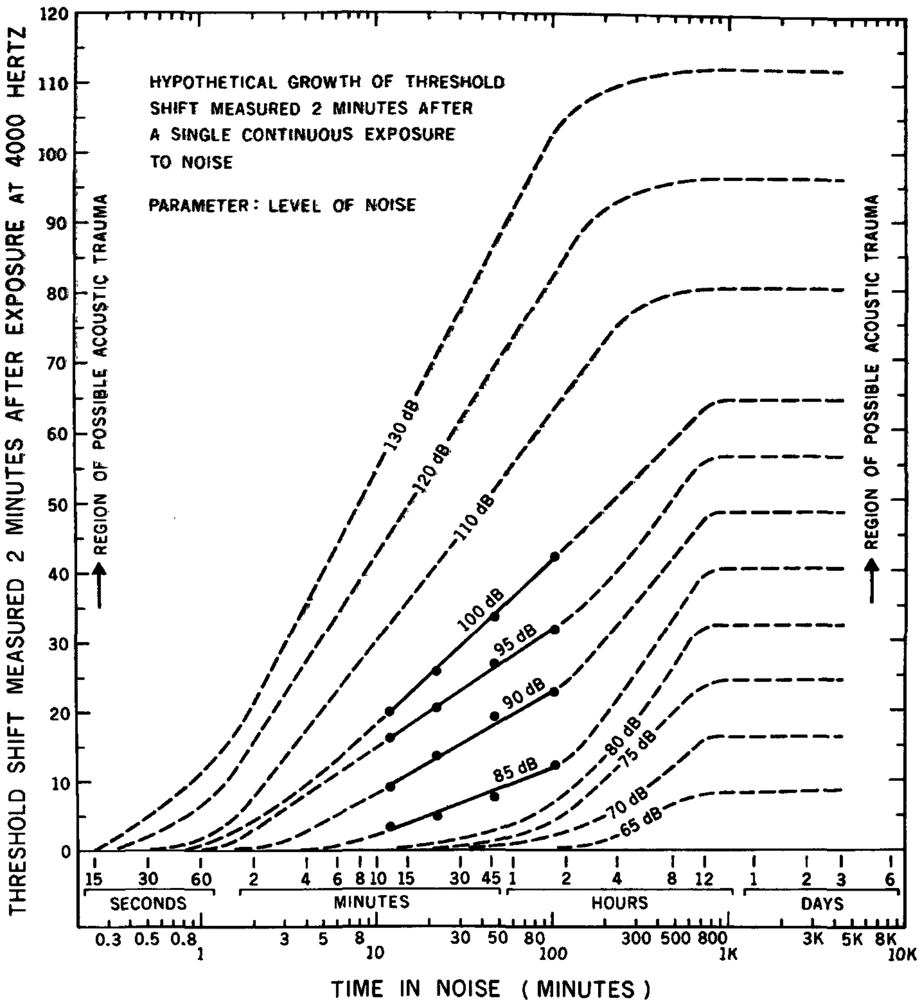

Figure 3. Hypothetical growth of threshold shift after various single and continuous exposures to noise. These curves represent predictions for an average, normally-hearing young adult exposed to a band of noise or pure tone centered near 4000 hertz. These are "worst-case" conditions as the ear is most susceptible to noise in this region. These hypothetical curves were drawn to be consistent with current facts and theory. They are for an average ear; wide differences among individuals can be expected. In many cases extrapolations had to be made from appropriately corrected data from animals (cats and chinchillas). The data points are from Ward, Glorig, and Sklar (1959a). Other relevant data can be found in papers by Botsford (1971), Carder and Miller (In press), Davis et al. (1950), Miller et al. (1963), Miller et al. (1971), Mills et al. (1970), Mosko et al. (1970), and Ward (1960, 1970b).

more intense the noise, the more rapidly threshold shifts accumulate as the time in noise is extended. When the noise is only 65 decibels, a typical person has to be exposed for several hours before any significant threshold shift can be detected. However, when the noise is very intense, say 130 decibels, a typical person exposed for only 5 minutes reaches dangerous levels of threshold shift. Notice that the combinations of intensity level and duration that produce threshold shifts greater than about 40 decibels are said to be in the region of possible acoustic trauma. In this region, for some people, the normal processes of the ear may "break down" and permanent threshold shifts—hearing loss—may result from even a single exposure to noise. Remember, however, that these relations are for the worst possible situation where the noise is concentrated in the region from 2400 to 4800 hertz. While exposures to other noises lead to qualitatively similar changes in hearing thresholds and to similar risks, the quantitative relations (even when the noise is measured in A-weighted sound level) may be different.

Recovery from threshold shifts after the cessation of an exposure to noise depends on a variety of factors and is not completely understood. Sometimes recovery from a threshold shift is complete in 50 or 100 minutes. Such rapid recovery from a threshold shift has been observed when the threshold shift is small, less than 40 decibels, and the duration of the exposure is short, less than 8 hours (Ward, et al., 1959a). Less rapid recovery from threshold shifts is illustrated on Figure 4. The straight

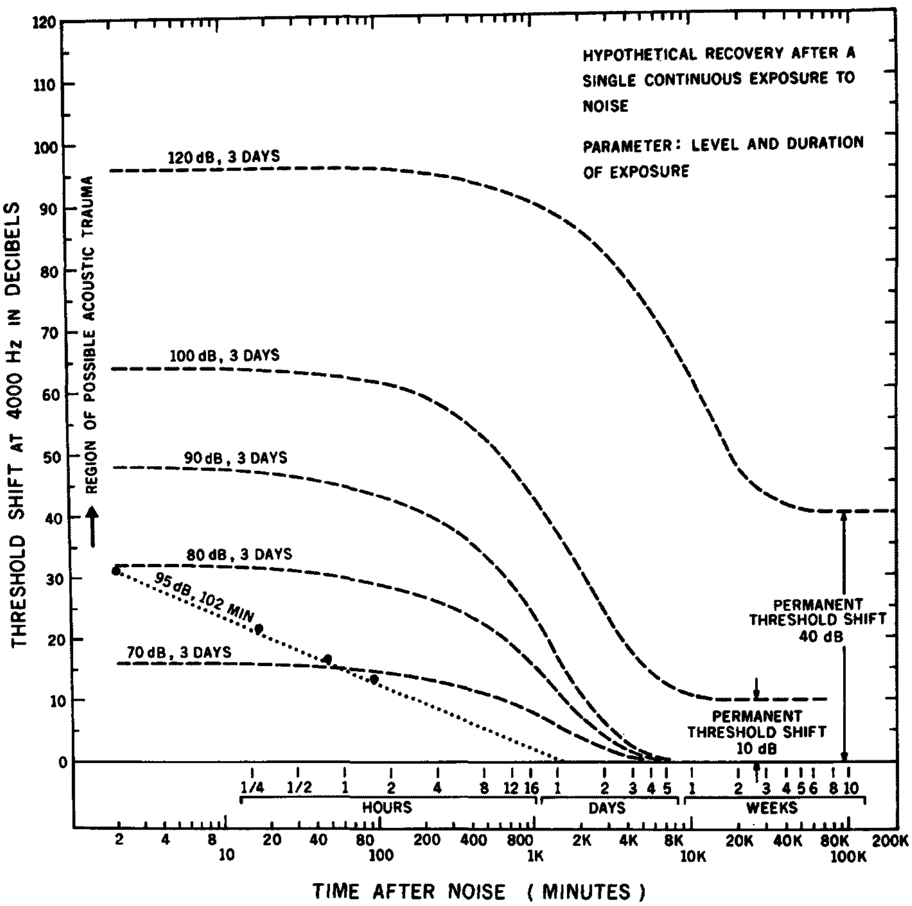

Figure 4. Hypothetical recovery from threshold shift after various single and continuous exposures to noise. See legend of Figure 3 for additional explanation.

dotted line indicates the course of recovery from a threshold shift that has often been assumed (Ward _et al._, 1959a, 1959b; Kryter _et al._, 1966). The data points (filled circles) represent the decline of threshold shift after an exposure at 95 decibels for 102 minutes as actually measured for human listeners. The accuracy of the extrapolation of the dotted lines beyond the data points is unknown. Clearly, however, recovery from the exposure of 95 decibels for 102 minutes (dotted line) is more rapid than recovery from the exposures for 3 days (dashed lines).

The slow recovery from noise-induced threshold shifts illustrated on Figure 4 by the dashed lines probably holds whenever the exposure is severe either in terms of the total duration or in terms of the amount of threshold shift present a few minutes after the termination of the noise. Recovery from temporary threshold shift appears to be very slow when the initial threshold shift exceeds 35-45 decibels (Ward, 1960), when the exposure lasts as long as about 12 hours (Mills _et al._, 1970; Mosko _et al._, 1970), or after some long but intermittent exposures to noise (Ward, 1970b). For example, it has been shown that exposure to a noise with an A-weighted sound level of about 80 decibels for two days results in small temporary threshold shifts that do not completely disappear for several days (Mills _et al._, 1970).

Very severe exposures to noise can produce compound threshold shifts from which complete recovery is impossible. After recovery from the temporary component of a compound threshold shift, there remains a permanent threshold shift. Some examples are shown on Figure 4. The ear's recovery from compound threshold shifts is often quite slow and this recovery probably represents a "healing" process. There can be no additional recovery (healing) beyond two to twelve weeks after an exposure (Miller et al., 1963).

Noise-induced permanent threshold shifts--repeated exposures. Sometimes people encounter single exposures to steady noises that produce permanent threshold shifts. This only happens rarely as people usually will not tolerate such severe exposures (see Figures 3 and 4).

More commonly, noise-induced permanent threshold shifts accumulate as exposures are repeated on a near-daily basis over a period of many years. The best examples of such cases are from field studies of occupational deafness.

An unusually thorough study was done of jute weavers (Taylor et al., 1965). These weavers were all women with little exposure to noise other than that received on the job. The noise exposures had been nearly constant in the mills for almost 52 years, and employees who had worked in the mills for 1-52 years were available for testing. All audiometry (measurement of hearing thresholds) was done with a properly calibrated instrument by a trained physician. Hearing thresholds were measured after a weekend away from the noise. This means that about 2-1/2 days of recovery were allowed and probably only a small recoverable component remained in the measured threshold shift (see Figure 4). Since the noise in the mill had an A-weighted sound level of about 98 decibels, a working-day exposure of eight hours would be expected to produce 35-65 decibels of temporary threshold shift in a typical, young adult female for a test tone of 4000 hertz. In 2-1/2 days, this threshold shift would be expected to decay to within about five decibels of normal (see Figures 3 and 4). Of course, wide variations can be expected. What happens when such an exposure is repeated about five days a week, 50 weeks a year, year after year? The results are shown on Figure 5. These thresholds are typical for the jute weavers and the expected changes with age have been subtracted.

Evidently, as the exposures are repeated year after year, the ear becomes less and less able to recover from the temporary threshold shift present at the end of each day. It also seems likely that as the exposures are repeated, the amount of threshold shift present at the end of each day's work might creep upward toward the asymptote appropriate to the level of the noise as indicated on Figure 3.

In any case, as the exposures are repeated, the noise-induced temporary threshold shifts become permanent or nearly so. It is also significant that on weekdays there are only 16 hours of recovery between work exposures. Therefore, from the <u>first day</u> of <u>employment</u>, most of these weavers will be living with a chronic threshold shift of 25-55 decibels at 4000 hertz (see Figures 3 and 4). Only on Saturday and Sunday will their hearing be near normal even during the first year of employment.

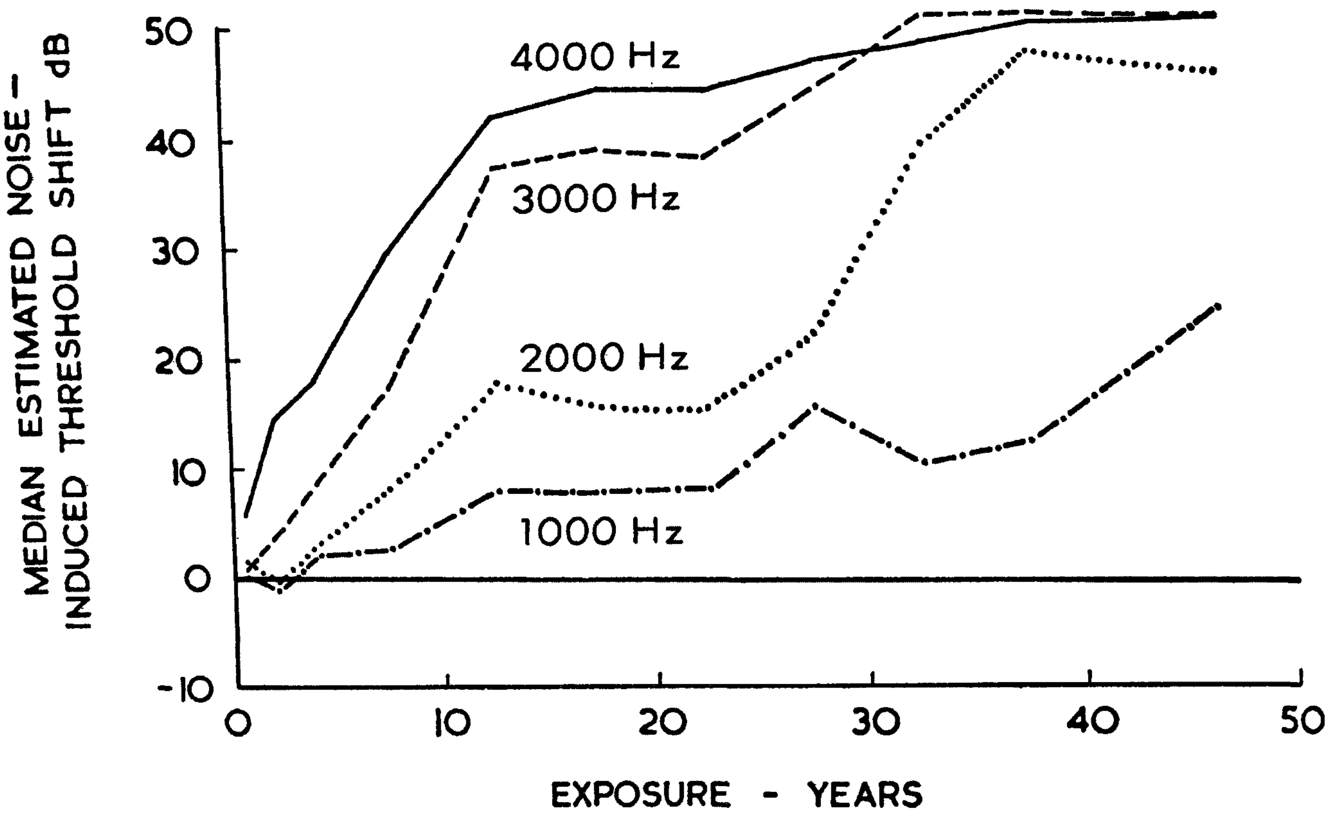

Figure 5. Median noise-induced threshold shifts for jute weavers with one to over 40 years of occupational exposure to noise with an A-weighted sound level of about 98 decibels. These threshold shifts have been corrected for the expected changes in thresholds with age in persons who are not exposed to noise. (From Taylor et al., 1965, with permission of the authors and the Journal of the Acoustical Society of America.)

As the years roll by, these jute weavers become partially deaf even on the weekends.

Similar data have been gathered on male workers in noisy industries in the United States (Nixon and Glorig, 1961). Age-corrected threshold shifts at 4000 hertz are shown for these workers on Figure 6. The average

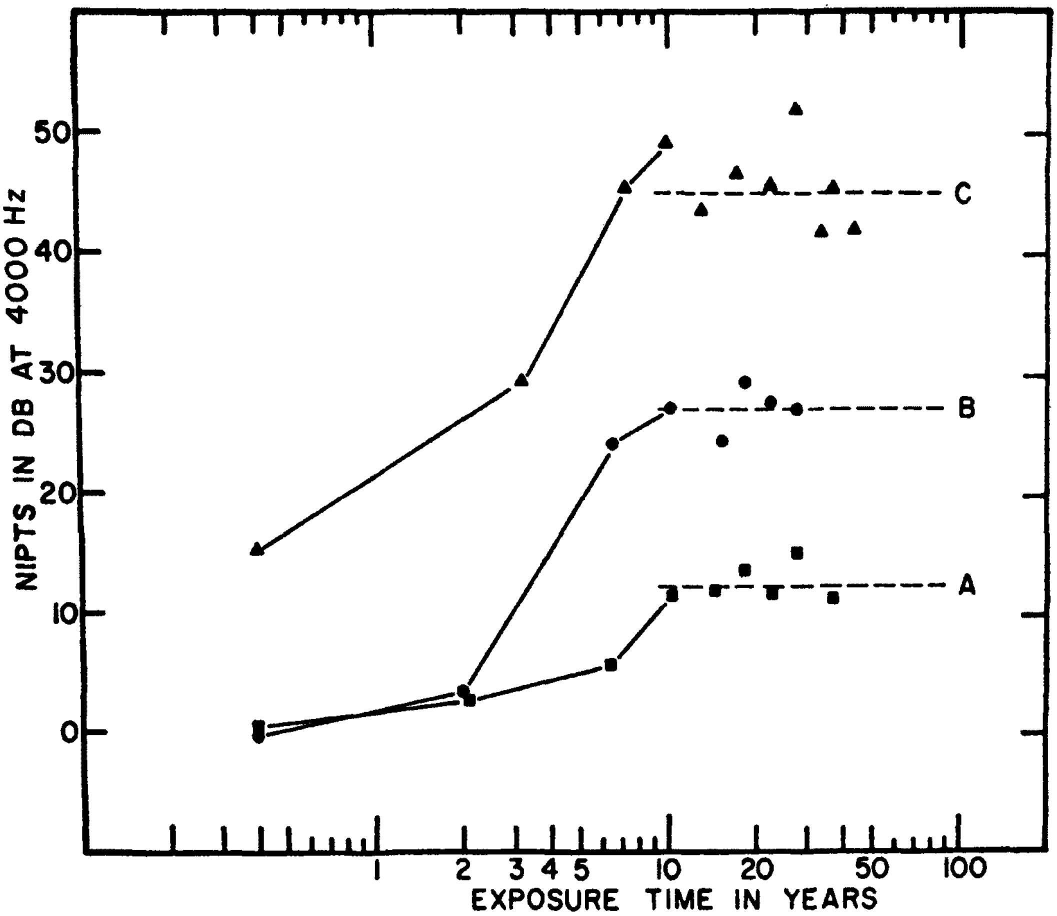

Figure 6. Noise-induced permanent threshold shifts (NIPTS) plotted against years of occupational exposure to noise for workers in three levels of noise. These threshold shifts have been corrected for the changes with age found in persons without occupational exposure to noise. The graphs are for a test tone of 4000 hertz and the data points are medians. The average A-weighted sound levels were 83 decibels for group A, 92 decibels for group B, and 97 decibels for group C. (Reprinted from Nixon and Glorig, 1961, with permission of the authors and the Journal of the Acoustical Society of America.)

A-weighted noise levels for the workers in environments A, B, and C were about 83, 92, and 97 decibels, respectively. Presumably, most of the threshold shifts were measured 2-1/2 days after the last workday and probably contain temporary components of less than 7-10 decibels.

The important points to notice on Figure 6 are: (a) there is an orderly relation between the median amount of noise-induced threshold shift and the intensity level of the noise; and (b) the amount of threshold shift at 4000 hertz from these occupational exposures shows no further increase after about ten years of exposure although the threshold shifts for lower frequencies (not shown) continue to increase.

The results shown on Figures 5 and 6 are medians. These orderly trends do not reflect the large differences among individual ears in susceptibility to noise-induced hearing loss. In fact, within a group of similarly exposed people some will exhibit very large threshold shifts while others will exhibit only small threshold shifts. The extent of these differences is shown on Figure 7. Some of the differences between similarly exposed people are due to differences in susceptibility to noise, and some are due to actual differences in the noise levels encountered. In an industrial situation the measurement of noise is an average over space and time, and, therefore, all workers do not necessarily receive the same exposure.

Threshold shifts from impulsive noise. Intense impulsive noise can be particularly hazardous to hearing. The reason is that in addition to the processes involved in noise-induced threshold shifts there is the added risk of a "breakdown" in the inner ear. Permanent threshold shift due to acoustic trauma may result. Since an acoustical impulse may contain only a small amount of total energy because of its limited duration,

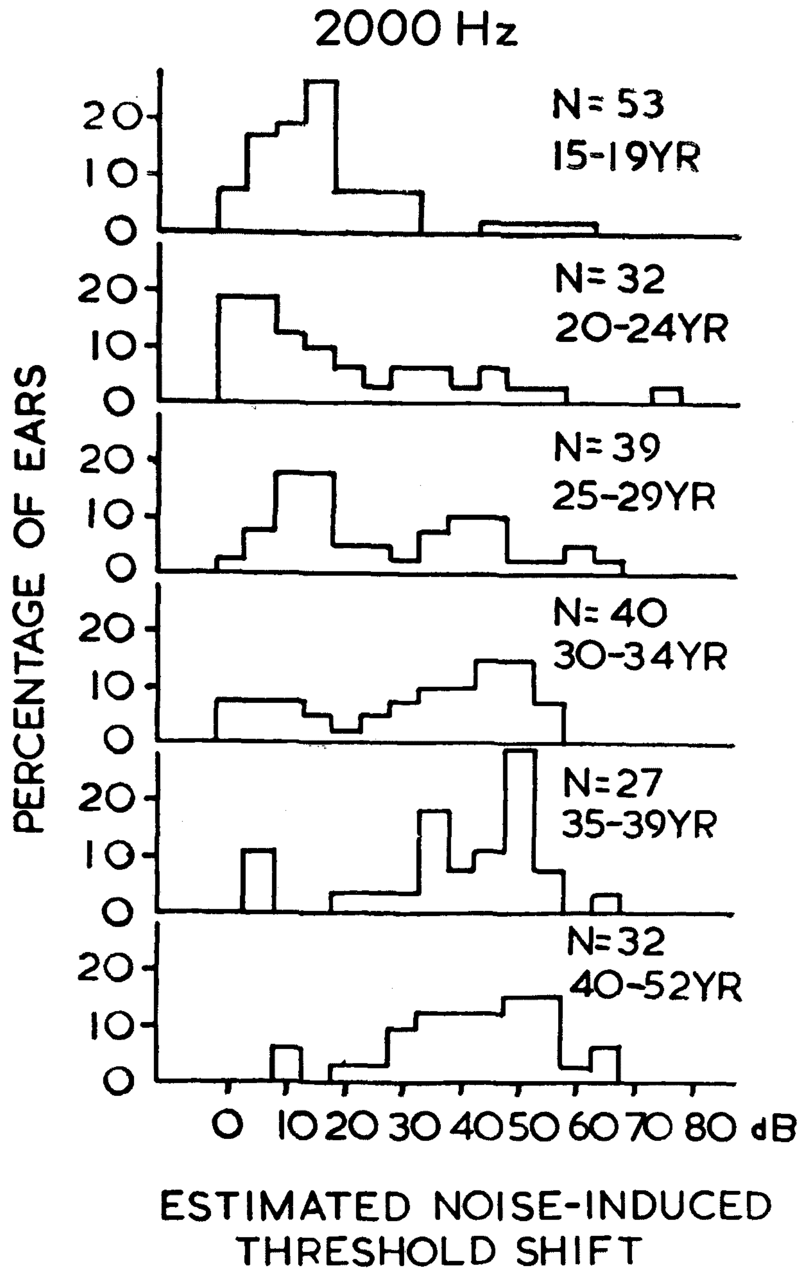

Figure 7. The distribution of noise-induced threshold shifts of jute weavers exposed for various numbers of years (parameter). The test frequency is 2000 hertz. Notice the large differences among people with regard to the effects of noise on the magnitude of the threshold shift. (Reprinted from Taylor et al., 1965, with the permission of the authors and the Journal of the Acoustical Society of America.)

the predicted threshold shift might be small. At the same time, a single impulse because of its high amplitude might rip or tear a crucial tissue barrier (say the reticular lamina which protects the hair cells and nerves from the fluids of scala media) and a considerable degeneration of the organ of Corti may result. Therefore, it is unlikely that description of impulsive noise in terms of <u>equivalent</u> spectrum and energy of "steady sounds" will be successful in predicting the enormous variability in response to impulses with high peak levels. With these impulses occasional cases of sudden severe hearing loss are observed, and these can be explained in terms of direct mechanical injury. It may be possible that expressing impulses in terms of <u>equivalent</u> spectrum and energy with steady sounds may be successful in predicting median trends (Kryter, 1970).

When a gun is fired or a hammer strikes metal, very large peak sound pressures may be generated at the eardrum. To follow the time course of an impulse accurately, one records the output of a good microphone on an oscilloscope. Idealized waveforms of impulse noises are shown on Figure 8. On Figure 9 are shown the combinations of peak sound pressure and duration that can be allowed if as many as 100 impulses were delivered to the ear over a period of four minutes to several hours each day. It is presumed that only 5% of the persons receiving a criterion exposure would have temporary threshold shifts that exceed ten decibels at 1000 hertz or below, 15 decibels at 2000 hertz, or 20 decibels at 3000 hertz or above. Details

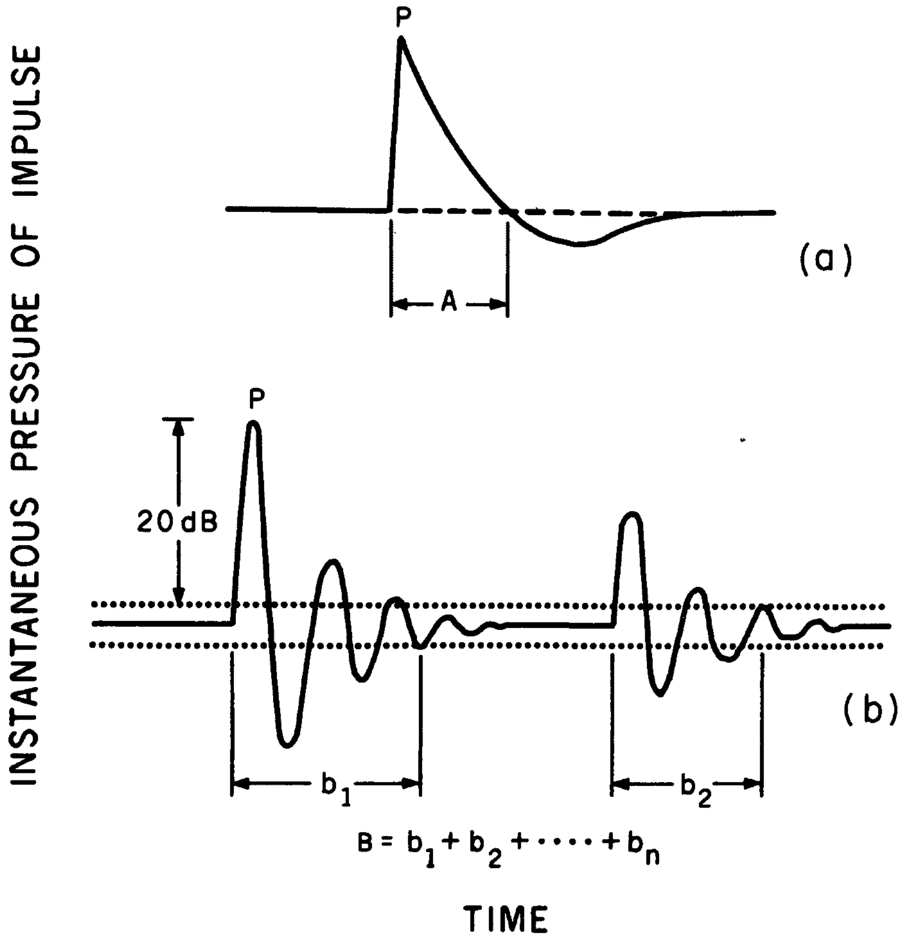

Figure 8. Idealized pressure waveforms of impulse sounds. On line (a) is shown a single, well-damped impulse. Its duration is taken as the time period indicated by the letter A. On line (b) is shown an impulse that has several oscillations. Also shown is a single reflection. Its duration is taken as the time period $B = b_1 + \ldots + b_n$. The amplitudes of both types of impulse noises is taken as the peak value, P, expressed in decibels. For more details see Ward (1968b).

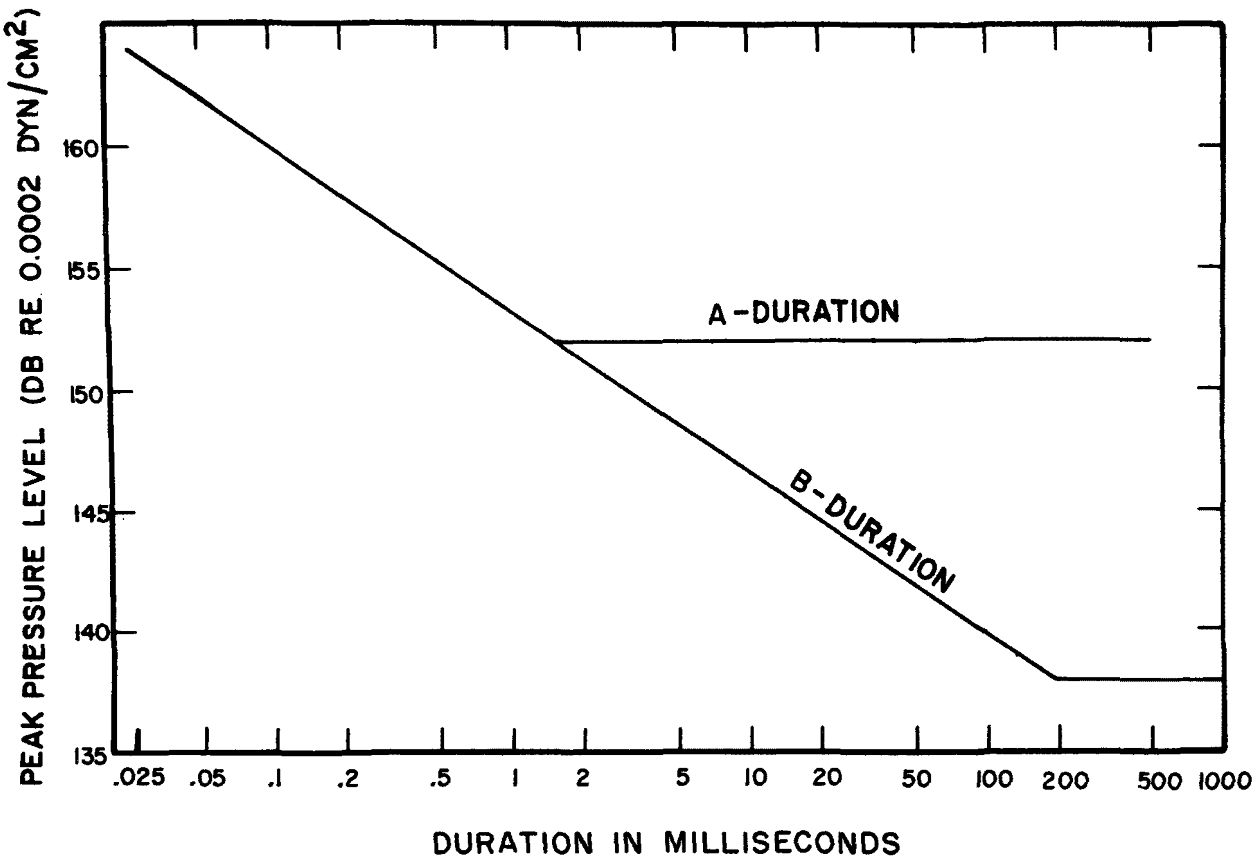

Figure 9. Upper limits of acceptable exposure to impulse noise as defined by Working Group 57 of the NAS-NRC Committee on Hearing, Bioacoustics, and Biomechanics (Ward, 1968b).

of these criteria and their derivation can be found elsewhere (Ward, 1968b).

Samples of permanent threshold shifts produced by a single firecracker explosion or the repeated firing of guns are shown on Figures 10 and 11.

C. Implications of Ear Damage and Hearing Loss

Interpretation of noise-induced hearing loss. There has been and continues to be considerable debate about the implications and significance of small amounts of ear damage and hearing loss. The most recent statement of the Committee on Hearing of the American Academy of Ophthalmology and Otolaryngology on Hearing Handicap is given on Figure 12. Prior to 1965, this group had used the terms hearing impairment, hearing handicap, and hearing disability almost synonymously and in accordance with the categories displayed in Figure 12.

In 1965, this committee offered these definitions of terms related to hearing loss. Hearing Impairment: a deviation or change for the worse in either structure or function, usually outside the normal range. Hearing Handicap: the disadvantage imposed by an impairment sufficient to affect one's efficiency in the situation of everyday living. Hearing Disability: actual or presumed inability to remain employed at full wages.

By these definitions, any injury to the ear or any change in a hearing threshold level that places it outside of the normal range constitutes a

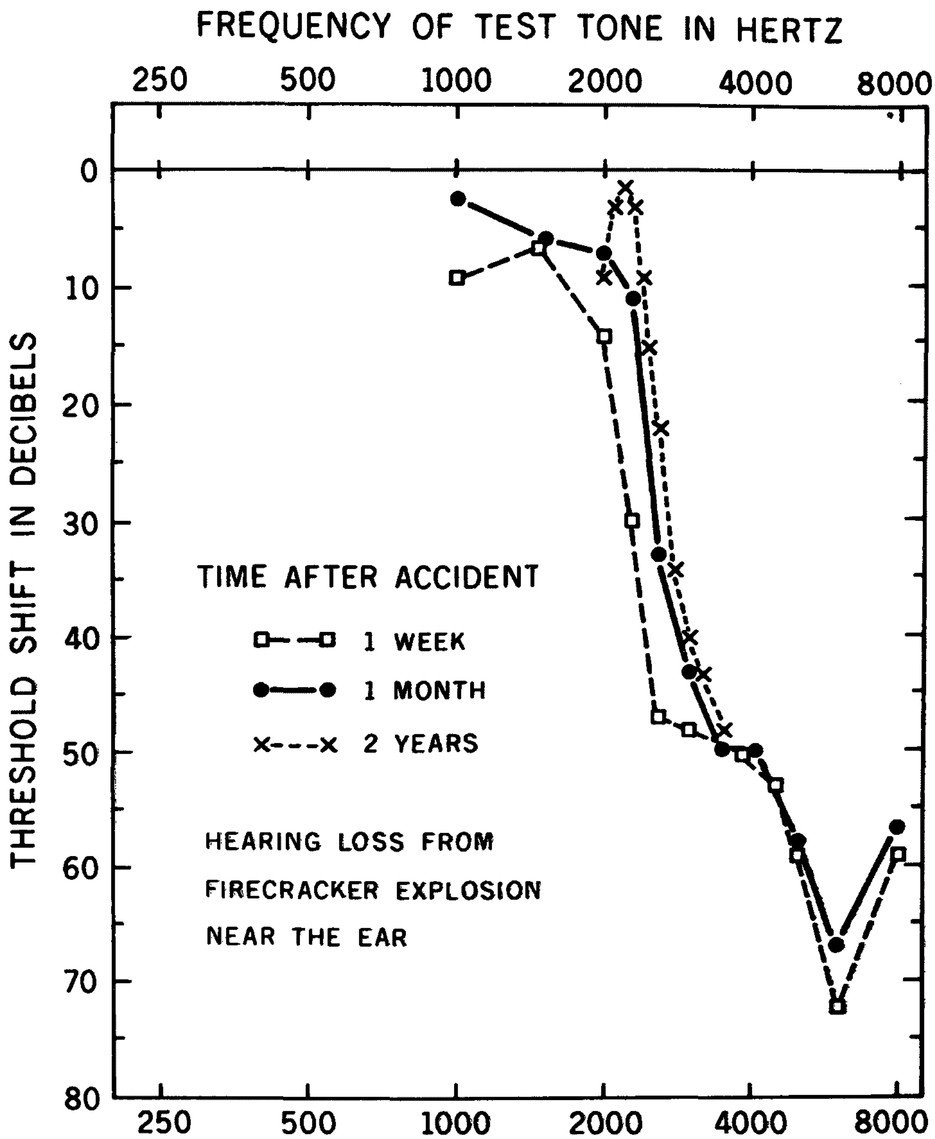

Figure 10. Permanent threshold shifts produced by a single exposure to a firecracker explosion. The change in hearing is shown by the difference between the thresholds taken before and after the accident. The firecracker was an ordinary flashlight cracker about two inches in length and 3/16 inch in diameter. It was about 15 inches from the patient's right ear when it exploded. (After Ward and Glorig, 1961, with the permission of the authors and Laryngoscope.)

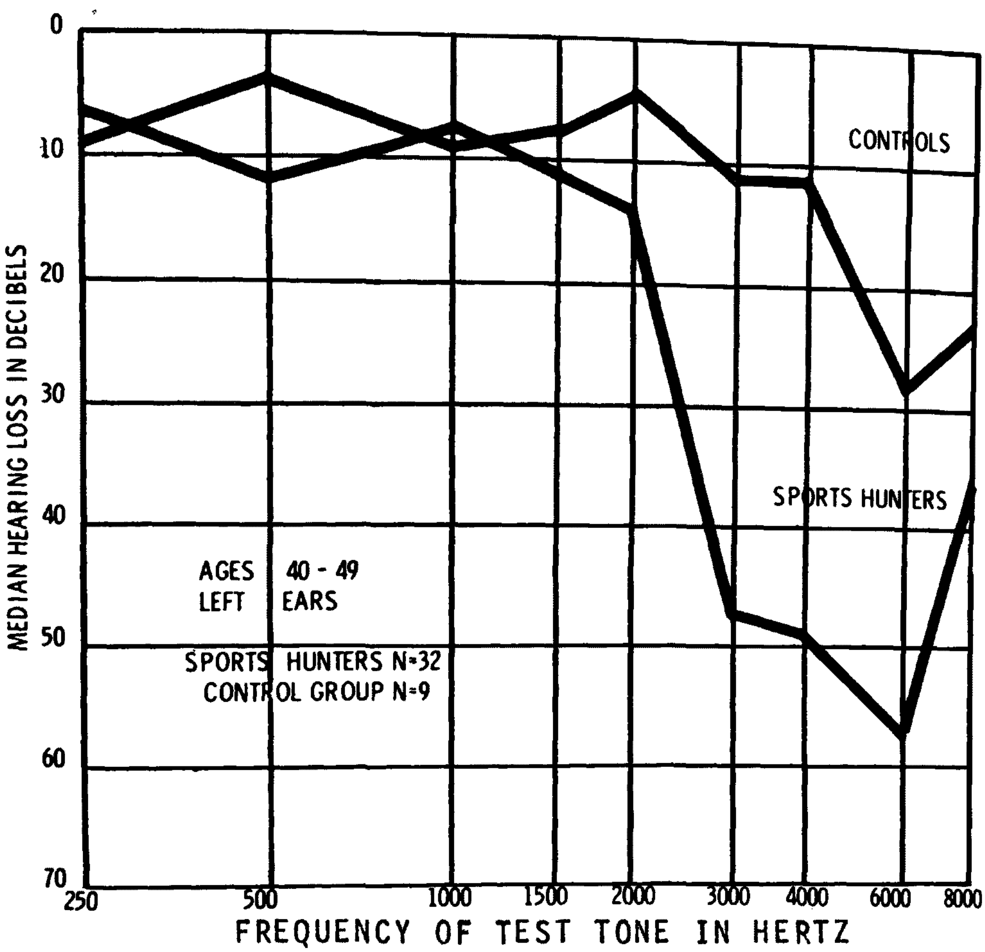

Figure 11. Median hearing loss in habitual sports shooters and age-matched controls. (From Taylor and Williams, 1966, with the permission of the authors and Laryngoscope.)

CLASS	DEGREE OF HANDICAP	AVERAGE HEARING THRESHOLD LEVEL FOR 500, 1000 AND 2000 Hz IN THE BETTER EAR		ABILITY TO UNDERSTAND SPEECH
		MORE THAN	NOT MORE THAN	
A	Not significant		25 dB	No significant difficulty with faint speech
B	Slight Handicap	25 dB	40 dB	Difficulty only with faint speech
C	Mild Handicap	40 dB	55 dB	Frequent difficulty with normal speech
D	Marked Handicap	55 dB	70 dB	Frequent difficulty with loud speech
E	Severe Handicap	70 dB	90 dB	Can understand only shouted or amplified speech
F	Extreme Handicap	90 dB		Usually cannot understand even amplified speech

Figure 12. Guideline for the relations between the average hearing threshold level for 500, 1000, and 2000 hertz and degree of handicap as defined by the Committee on Hearing of the American Academy of Ophthalmology and Otolaryngology. (From Davis, 1965, with the permission of the author and the Transactions of the American Academy of Ophthalmology and Otolaryngology.)

hearing impairment. Whether a particular impairment constitutes a *hearing handicap* or a *hearing disability* can only be judged in relation to an individual's life pattern or occupation.

The guideline for the evaluation of hearing handicap shown on Figure 12 uses only thresholds for tones in the region most important for the reception of speech (500, 1000, and 2000 hertz), and judgments of handicap are based on the associated ability to understand connected speech in quiet surroundings. While most authorities agree that a person in Category B or worse has a hearing handicap, there is debate over whether handicap exists when a person in Category A also has large hearing threshold levels above 2000 hertz.

Examples of audiograms that would fall into Category A and also exhibit large hearing threshold levels above 2000 hertz are shown on Figures 10 and 11. Notice that the guideline of Figure 12 indicates that such audiograms do not represent a significant handicap. Those who question the guideline of Figure 12 rally certain facts. For example, some individuals with sizable hearing threshold levels above 2000 hertz may experience considerable difficulty in understanding speech in moderate levels of background noise even though their average hearing threshold levels at 500, 1000, and 2000 hertz do *not* exceed 25 decibels (Niemeyer, 1967). Also, persons with hearing loss primarily above 2000 hertz may not be able to distinguish the sounds of certain consonants. Sometimes hearing loss above 2000 hertz may be especially important to a person; for example, piccolo players or specialists concerned with bird song may experience handicap whereas many others might not.

More generally, individuals will react differently to a hearing loss. One may be particularly upset by his inability to understand his children; another may feel handicapped by his inability to participate in rapid verbal patter; and others may miss the sounds of music or those of nature.

There is little room for controversy over the question of handicap when losses become as severe as those of Category C of Figure 12. Persons with losses this severe or worse are aware that they have lost part or all of a precious gift.

Hearing aids and noise-induced hearing loss. People with partial deafness from exposure to noise do not live in an auditory world that is simply "muffled." Even those sounds that are heard may be distorted in loudness, pitch, apparent location, or clarity. While a hearing aid sometimes can be useful to a person with noise-induced hearing loss, the result is not always satisfactory. The modern hearing aid can amplify sound and make it audible, but it cannot correct for the distortions that often accompany injury to the organ of Corti.

Presbyacusis and environmental noise. With age, people almost uniformly experience increasing difficulty in understanding speech. Undoubtedly, some of this loss is due to the degeneration of neurons in the brain which generally accompanies advancing age. Some of this loss is due to changes in middle or inner ears. Some of the changes in the inner ear are due to normal aging processes; some are undoubtedly due to toxic drugs; some are due to disease processes; and some are due to incidental, recreational, and occupational exposures to noise. Clear evidence is available that noises with A-weighted sound levels above 80 decibels can contribute to inner ear damage and eventual hearing handicap if such noises are frequently and regularly encountered. Beyond this, the evidence does not warrant stronger statements about the role of noise in progressive hearing loss with age. Theoretical grounds do suggest that <u>frequent</u> exposures of <u>sufficient duration</u> to noises with A-weighted sound levels greater than 70-80 decibels could contribute to the "normal loss of hearing with age."

At least some aspects of hearing loss with age seem to add to hearing loss from noise exposure (Glorig and Davis, 1961). This means that a small loss of hearing from exposure to noise may be insignificant when one is middle-aged, but might, when combined with other losses due to age, become significant as one reaches an advanced age.

D. Prevention of Ear Damage and Hearing Loss from Noise

Hearing loss and ear damage due to noise can be eliminated if exposures to noise are: (1) held to sufficiently low levels; (2) held to sufficiently short durations; or (3) allowed to occur only rarely.

The regulation of the acoustic environment in such a way that hearing loss and ear damage from noise are eliminated poses several problems. For example, the chances that a person will develop a hearing impairment due to noise depends on the pattern of exposure from all sources of noise that he happens to encounter. Some of these exposures from particular sources may be innocuous in isolation. But these same noises, which are innocuous by themselves, may combine with noises from other sources to form a total sequence of noises sufficient to produce hearing impairment (Cohen et al., 1970). While it may be possible to control the total exposure in an occupational setting during a day's work, it is nearly impossible to control an individual's activities and exposure to noise while he is away from work. Thus, one must turn to the regulation of sources of noise.

In general, any source with an A-weighted sound level of 70-80 decibels has the potential to contribute to a pattern of exposure that might produce temporary threshold shifts (see Figure 3) and this could lead to permanent hearing impairment. Therefore, it seems desirable to have as few sources as possible that expose people to A-weighted sound levels in excess of 70-80 decibels. But people can tolerate many brief exposures in excess of 70-80 decibels if they are widely spaced in time. For example, a shower bath may have an A-weighted sound level of about 74 decibels, but one would have to shower for over an hour before a temporary threshold shift would appear (see Figure 3). Clearly, regulation must not eliminate all sources of noise with A-weighted sound levels in excess of 70-80 decibels. On the other hand, if such sources are allowed to proliferate without bound, then vast numbers of persons will suffer chronic threshold shifts.

Sources with A-weighted sound levels in excess of 80 decibels have the potential to contribute to the incidence of hearing handicap. The argument about regulation of such sources runs exactly parallel to that of the previous paragraph.

Finally, from studies of hearing loss from occupational exposures to noise, one can identify exposures that, in and of themselves, increase the incidence of hearing handicap (Kryter *et al.*, 1966; Radcliff, 1970). Sources that provide exposures as severe as these should be avoided, eliminated, or controlled.

Part of the problem of the evaluation of hearing hazard from various sources of noise is this. While knowledge has accumulated about the effects of schedules of noise exposure such as those encountered in the occupational setting, very much less is known about the effects of other, irregular schedules such as those associated with occasional use of home tools and recreational devices (snowmobiles, for example). Here much more research is needed.

Another approach to the protection of hearing from noise is the use of ear plugs and earmuffs when hazardous noises are encountered. Effective devices are available for this purpose, but they must be carefully selected and properly used. In spite of the effectiveness of earplugs and earmuffs, people will often refuse or neglect to use them for reasons of appearance, discomfort, and bother.

Section 2. MASKING AND INTERFERENCE WITH SPEECH COMMUNICATION

Introduction

Man has a formidable ability to "hear out" one sound from a background of other sounds. For example, often one can hear the doorbell over a background of music and conversation. But there are very definite limits to this ability to "hear out" a signal. Unwanted sounds, noises, can interfere with the perception of wanted sounds, signals. This is called masking. By masking, an auditory signal can be made inaudible or the signal can be changed in quality, apparent location, or distinctiveness. Masking has been studied extensively in the laboratory, and, consequently, the effects of noise on the perception of auditory signals can be calculated for many environmental conditions. Descriptions of the masking of auditory signals by noise can be found elsewhere (Hirsh, 1952; Jeffress, 1970; Kryter, 1970; Scharf; 1970, and Ward, 1963).

Much of the research on auditory masking has been motivated by auditory theory. From their research, scientists hope to learn the basic laws of the analytic capacities of human hearing. The study of the masking of speech by noise has been undertaken to meet both practical and theoretical goals. While it is important for everyday life to be able to understand generally the perceptibility of auditory signals, most would agree that the understanding specifically of the problem of speech perception has great significance for the quality of human life. If speech is totally drowned out by a masker, the speech is said to be inaudible or below the threshold of detectability. If the presence of the speech can be detected, but it is indistinct or difficult to understand, the speech is said to be above the threshold of detectability and to have poor intelligibility or discriminability. Intelligibility or discriminability refers to the clarity or distinctness with which speech can be heard over a background noise and it is usually measured in the percentage of messages that a listener can understand.

A. Interference with Speech Communication

Speech and understanding speech. A talker generates a complicated series of sound waves. This series is called the speech stream. It is not possible to assign a particular acoustic pattern to each of the "sounds" of the English language in a one-to-one fashion. Rather, the "speech stream" carries the cues for the "sounds" of English and the listener decodes the "speech stream" by a complicated, synthetic process that not only relies on the acoustic cues carried by the "speech stream," but also relies on the listener's knowledge of the language and the facts of the situation. Not all of the cues carried by the "speech stream" are known. Also, the synthetic processes by which the "speech stream" is decoded and "heard as speech" are not fully understood. Nonetheless, much is known about which regions of the audible range of frequencies carry the cues for the intelligibility of speech.

Cues in the speech stream can be found at frequencies as low as about 100 hertz to as high as about 8000 hertz. Most of the acoustical energy of the speech stream is concentrated between 100 and 6000 hertz. But, the most important cue-bearing energy falls between about 500 and 2000 hertz. The speech stream carries much extra information. It is redundant. Therefore, speech can be heard with high intelligibility even when some of the cues have been removed.

How speech reception in noise is studied. There are many variables that influence the accuracy of speech communication from talker to listener in an experiment. The characteristics of the talker; the test materials; the transmission path from talker to listener; the background noise; the spatial locations of the talker, noise source, and listener; and the integrity of the listener's auditory system all can be important. The outcome of such an experiment is usually measured in the percentage of messages understood, and this percentage is taken as a measure of intelligibility or discriminability of the speech. Other measures are sometimes used. Among these are ratings of the quality or the naturalness of speech, recognition of the talker, or recognition of the personality or psychological state of the talker.

In no one experiment are all of the variables studied. Rather, most are held constant and the effects of a few are evaluated. The experiments of Miller et al. (1951) provide a good illustration. Only two subjects were used and they alternated roles as talker and listener. The subjects were located in different rooms and could only communicate via a microphoneamplifier-earphone system which passed only frequencies between 200 and 3000 hertz. Noise could be added into this communication link and the ratio of speech power to noise power could be controlled. In one experiment, the test materials were one-syllable words. The talker always said, "You will write_______," with the test item read at the blank. He monitored his voice level with an appropriate meter and, thus, the speech intensity at the microphone was held constant. The level of the speech and noise at the listener's ear was controlled by the experimenter through appropriate adjustments of the electronic equipment. Of major interest in this experiment were the relations between the speech power and noise power, the number of possible messages (one-syllable words), and the percentage of messages understood. For some tests, the message could be one of two alternatives known to the listener; for other tests the message could be one of four, eight, sixteen, thirty-two, two hundred fifty-six, or any of one thousand possible one-syllable words. The results are shown on Figure 13.

It can clearly be seen that the more intense the speech in relation to the noise the greater the percentage of messages correctly understood. Also, the fewer the number of alternative messages the greater the percentage of correctly understood messages. It is important to realize that the absolute percentage of correct messages transmitted for each speech-to-

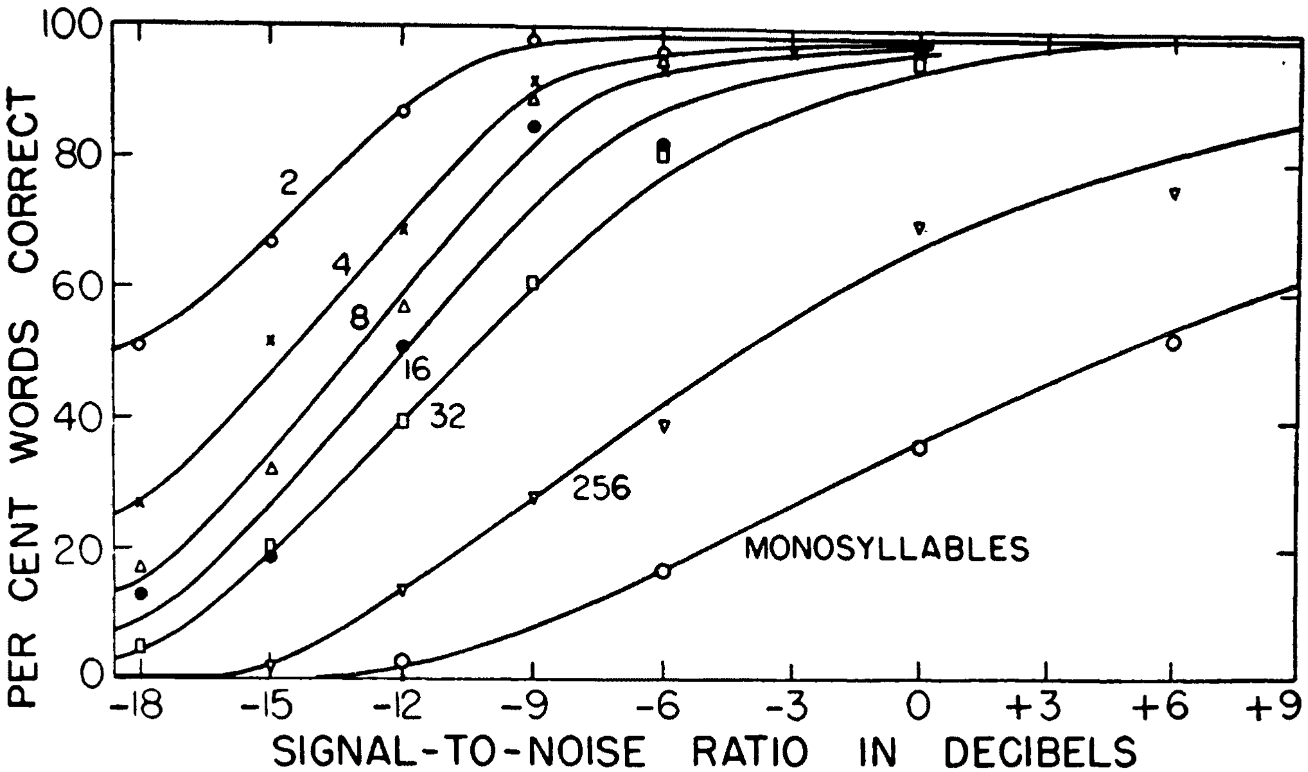

Figure 13. The dependence of the accuracy of speech communication on the relations between the intensity level of the speech in relation to the intensity level of the noise. The several curves are for various numbers of possible messages. When the message could be one of two possible words, the scores were high. When the message could be one of approximately 1000 one-syllable words, the scores were low. (From Miller et al., 1951, with permission of G. A. Miller and the Journal of Experimental Psychology.)

noise ratio will depend on the talker, the exact nature of the noise, its spectrum and intensity, and on the way in which the speech and noise intensities are measured.

<u>The major effects of noise on speech communication</u>. Many of the facts of speech communication in noise can be understood in terms of a single graph. This graph is given on Figure 14 and in simplified form on Figure 15. The vertical axis is the A-weighted sound level of background noise measured in decibels. The horizontal axis is the distance between talker and listener in feet. The regions below the contours are those combinations of distance, background noise levels, and vocal outputs wherein speech communication is practical between young adults who speak similar dialects of American-English. The line labelled "expected voice level" reflects the fact that the usual talker unconsciously raises his voice level when he is surrounded by noise. Consider the example of a talker in the quiet who wishes to speak to a listener near a running faucet. The A-weighted sound level of the background noise may be about 74 decibels for the listener. If the talker is 20 feet away, it is clear from Figures 14 and 15 as well as from everyday experience that communication would be difficult even if the talker were to shout. But, if the talker were to move within one foot of the listener, communication would be practical even when a normal voice is used. It can be seen that at 15-20 feet, distances not uncommon to many living rooms or classrooms, A-weighted sound levels of the background noise must be below 50 decibels if speech communication is to be nearly normal.

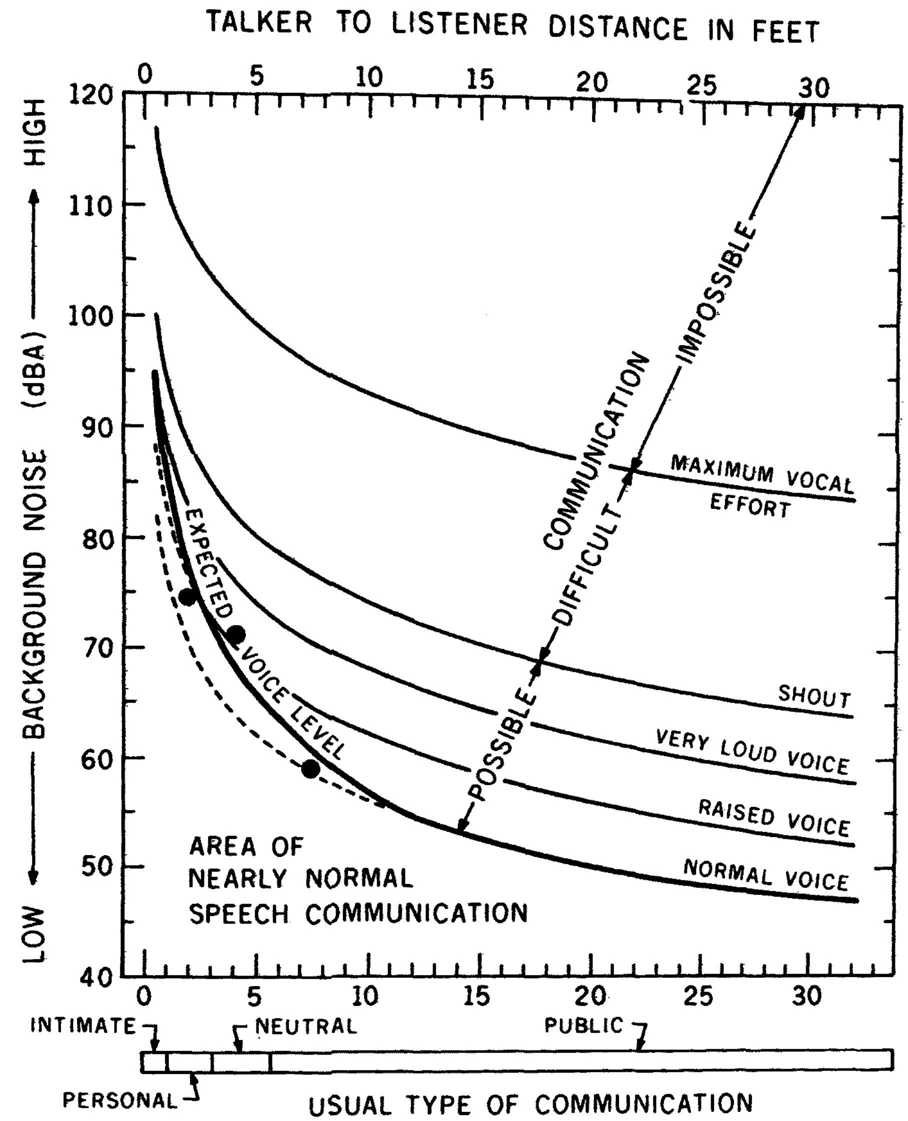

Figure 14. Quality of speech communication as dependent on the A-weighted sound level (dBA) of the background noise and the distance between the talker and listener. (Modified from Webster, 1969.) The heavy data points represent scores of 90% correct with tests done with phonetically balanced lists of one-syllable words (Waltzman and Levitt, 1971). The types of speech communication typical of various talker-listener distances are based on observation (Hall, 1959).

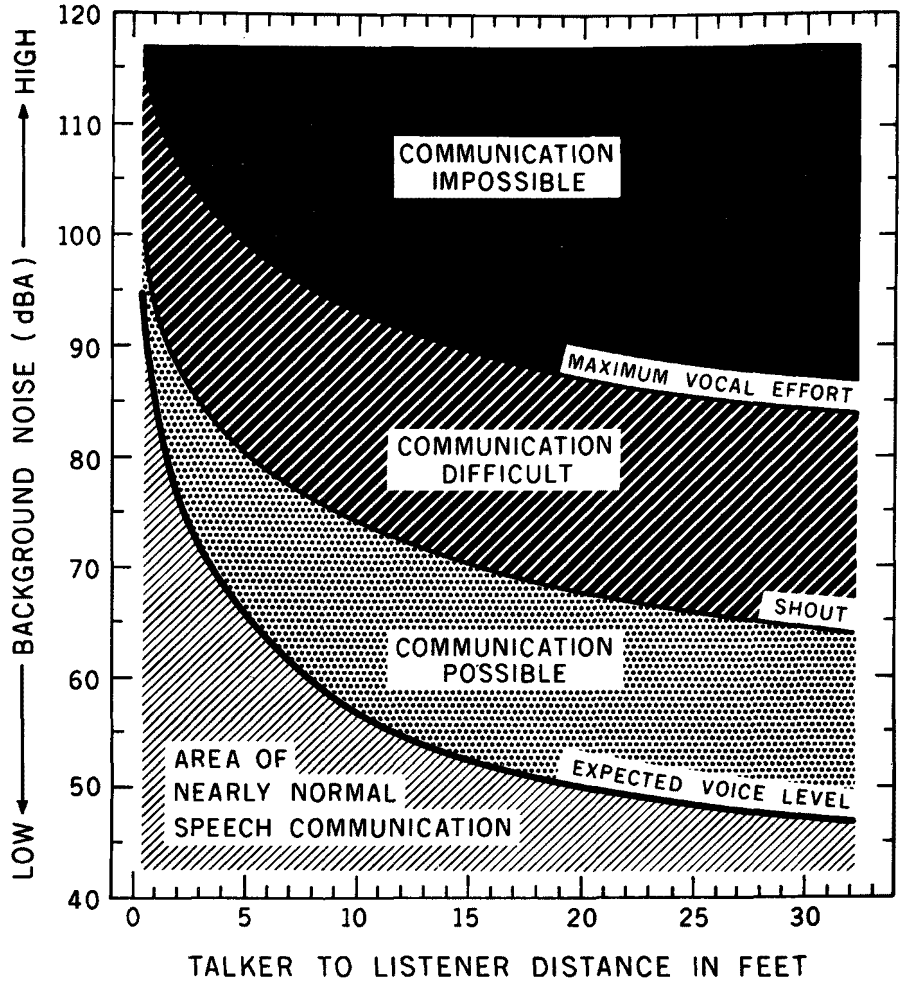

Figure 15. Simplified chart that shows the quality of speech communication in relation to the A-weighted sound level of noise (dBA) and the distance between the talker and the listener.

People vary their voice levels and distances not only in accordance with the level of background noise and physical convenience, but also in accordance with cultural standards (Hall, 1959). Distances less than about 4-1/2 feet are reserved for confidential or personal exchanges usually with a lowered voice. Distances greater than about 5 feet are usually associated with a slightly raised voice and reserved for messages that others are welcome to hear. Thus, levels of background noise that require the talker and listener to move within less than 4 feet will be upsetting to persons who do not normally have an intimate association. Even for close friends there may be some embarrassment if the message would not normally require such nearness. When the content of the message is personal, there will be reluctance to raise the voice level even if the background noise demands it for intelligibility.

In one-to-one personal conversations the distance from talker to listener is usually of the order of 5 feet and nearly normal speech communication can proceed in A-weighted noise levels as high as 66 decibels. Many conversations involve groups and for this situation distances of 5-12 feet are common and the intensity level of the background noise should be less than 50-60 decibels. At public meetings or outdoors in yards, parks, or playgrounds distances between talker and listener are often of the order of 12-30 feet and the A-weighted sound level of the background noise must be kept below 45-55 decibels if nearly normal speech communication is to be possible.

Characteristics of people (speech, age, and hearing) and speech interference by noise. The contours on Figures 14 and 15 represent conditions for young adults who speak the same dialect when they are in a diffuse noise field. The location of these contours would shift in accordance with many variables. Lower noise levels would be required if the talker has imprecise speech (poor articulation) or if the talker and the listener speak different dialects. Children have less precise speech than do adults (Eguchi and Hirsh, 1969) and also their knowledge of language often makes them less able to "hear" speech when some of the cues in the speech stream are lost. Thus, adequate speech communication with children under about 13 years of age probably requires lower noise levels than are required for adults. One's ability to understand partially masked or distorted speech seems to begin to deteriorate at about age 30 and declines steadily thereafter (Palva and Jodinen, 1970). Generally, the older the listener, the lower the background noise must be for nearly normal communication. It is well known that persons with hearing losses require more favorable speech-to-noise ratios than do those with normal hearing. This group again requires lower noise levels for adequate speech communication than do young adults with normal hearing.

Situational factors (message predictability, opportunity for lip reading, spatial arrangements and reverberation, and kinds of noise) and speech interference by noise. Of course, adequate communication in higher noise levels than those indicated on Figures 14 and 15 can occur if the possible messages are predictable. Thus, at ball games, we may be able to discriminate the umpire's "ball" and "strike" at much greater distances and in more intense levels of noise than indicated on the chart. This factor accounts for the success of communication in many industrial situations with high levels of noise. Success may give way to failure, however, when an important but unpredictable message must be communicated. For example, firemen in a high-level noise may have little difficulty with standard communications about the use of equipment, but may encounter grave difficulty communicating about unexpected events that occur at the scene of the fire.

The opportunity to lipread or use facial or bodily gestures in support of hearing will improve the success of communication in background noise. Almost everyone has some small amount of lipreading skill which they often use without awareness of its contribution to intelligibility.

Spatial variables also may facilitate speech communication in noise. If the source of noise is clearly localized in a position different from that of the talker, speech communication may be possible under noise conditions less favorable than those indicated on Figures 14 and 15. On the other hand, spatial factors can sometimes reduce the intelligibility of speech. If a space produces many reflections of sound it is said to be reverberant or lively. Noise interferes with speech communication more in a very reverberant space than in one that is not.

Sometimes unusual acoustic conditions can make our voices clearly audible at great distances. If one raises his voice to talk to a nearby person over the sound of a power lawn mower or outboard motor, he can sometimes be heard more clearly by a distant accidental spectator than by the nearby friend.

The exact characteristics of the noise are also important for predicting speech communication. While the A-weighted noise level is an adequate measure of many noises, some situations and noises demand a more complicated analysis of the noise. A discussion of the use of the various methods of measuring noise to predict speech interference can be found elsewhere (Kryter, 1970, p. 70-91).

B. Implications of Masking and Interference with Speech Communication

Masking of auditory signals. Many auditory signals serve important functions in our lives and these functions may be lost in noise. While the masking of a doorbell because of noise may only be a source of inconvenience and annoyance, the masking of signals can interfere with the performance of tasks. In some cases, the masking of a signal such as that of an approaching vehicle can lead to property damage, personal injury, or even death.

Interference with speech communication. The implications of reduced opportunity for nearly normal speech communication are considerable.

Those who must work in high levels of background noise claim that they "get used to it." There is evidence, however, that they adopt a "non-communicating life style" and increase their use of non-verbal communication through gestures, posture, and facial expression. Even though non-verbal communication is important, it is unlikely that it is nearly as important as verbal communication. Many subtleties of life are lost when verbal communication is restricted.

Among adults, free and easy speech communication is probably essential for full development of social relations and self.

For very young children, there may be an additional problem. They gradually induce their knowledge of language and its subtleties from the speech to which they are exposed. Also, as previously stated, because their knowledge of language is still developing, children probably have more difficulty understanding speech in noise than do adults. Because noise can reduce the amount of speech used at home, in the yard, or on the playground and because noise can make speech difficult to understand, it is possible, though unproven, that the language development of early childhood might be adversely affected. From this, difficulty in learning language and learning to read may ensue. One can only guess at how severe the noise must be to produce such effects; nearly continuous A-weighted sound levels in excess of 70 decibels might be required. Such conditions do exist at some residences in urban areas near freeways. When contemplating possible increases in general levels of community noise, one should give consideration to these possible effects on the linguistic development of children.

Later, school-age children probably encounter more difficulty in noisy classrooms than, for example, do sailors in noisy enginerooms who exchange a limited number of prescribed technical messages. With regard to the impact of noise on formal education, the Jamaica Bay Environmental Study Group of the National Academy of Sciences summarized their findings as follows:

> Within the present impacted area (NEF 30 or greater) there are 220 schools attended by 280,000 pupils. With normal school-room usage, this implies about an hour's interruption of classroom teaching each day and the development by the teachers of the "jet pause" teaching technique to accomodate the impossibility of communicating with the pupils as an aircraft passes overhead. The noise interference goes beyond the periods of enforced non-communication, for it destroys the spontaneity of the educational process and subjects it to the rhythm of the aeronautical control system. Given the advanced age of many of these schools, noise-proofing (where possible) would cost an appreciable fraction of their replacement cost.

Any casual observer of intimate family life is aware of the irritation and confusion that can arise when simple, everyday messages need frequent repetition in order to be understood. Noise does not cause all of these occurrences, but surely it causes some.

The enjoyment of retirement and later life can be hampered by masking noises. It is well known that speech reception abilities deteriorate with age and clinical observations clearly indicate that older persons are more susceptible to the masking of speech by noise than are young adults.

It is likely that one must somehow "work harder" to maintain speech reception in noise than in quiet. Thus, successful speech communication in noise probably has its cost. If the cost is too high, the number of verbal exchanges probably declines.

In a highly intellectual, technical society, speech communication plays an extremely important role. Background noise can influence the accuracy, frequency, and quality of verbal exchange. In excessive background noise, formal education in schools, occupational efficiency, family life styles, and the quality of relaxation can all be adversely affected.

PART II. GENERAL PSYCHOLOGICAL AND SOCIOLOGICAL EFFECTS

Preliminary Statement

Noise not only has direct effects on auditory function as decribed in PART I, but it also produces other behavioral effects of a more general nature. Included among these effects are INTERFERENCE WITH SLEEP, Section 3; the general evaluation of auditory experience included under LOUDNESS, PERCEIVED NOISINESS, AND UNACCEPTABILITY, Section 4; and ANNOYANCE AND COMMUNITY RESPONSE, Section 5. All of these areas have been investigated and certain clearcut patterns have emerged. Plausible, but less thoroughly studied behavioral effects of noise are discussed under OTHER POSSIBLE PSYCHOLOGICAL AND SOCIOLOGICAL EFFECTS, Section 6.

Many of the psychological and sociological effects of noise can be traced to the role of hearing in man's evolutionary development as described in the INTRODUCTION. Others may be linked more specifically to the auditory effects described in PART I or to the general physiological responses to be described in PART III. Because of these interrelations among the effects of noise on people, the organization of topics is necessarily somewhat arbitrary.

Section 3. INTERFERENCE WITH SLEEP[3]

Introduction

From everyday experience it is evident that sound can interfere with

3)The effects of noise on sleep are discussed at greater length in this paper than are other effects of equal or greater importance. This was done because other reviews of the effects of noise on people have given relatively less attention to the subject of sleep disturbance.

sleep. Almost all have been waked or kept from falling to sleep by loud, strange, frightening, or annoying sounds and it is commonplace to be waked by an alarm clock or clock radio. But it also appears that one can "get used to"sounds and sleep through them. Possibly, environmental sounds only disturb sleep when they are unfamiliar. If so, disturbance of sleep would depend only on the frequency of unusual or novel sounds. Everyday experience also suggests that sound can help to induce sleep and, perhaps, to maintain it. The soothing lullaby, the steady hum of a fan, or the rhythmic sound of the surf can serve to induce relaxation. Perhaps certain steady sounds can serve as an acoustical eyeshade and mask possibly disturbing transient sounds.

Common anecdotes about sleep disturbance suggest an even greater complexity. A rural person may have difficulty sleeping in a noisy urban area. An urban person may be disturbed by the quiet, the sounds of animals, and so on when sleeping in a rural area. And how is it that a mother may wake to a slight stirring of her child, yet sleep through a thunderstorm? These observations all suggest that the relations between exposure to sound and the quality of a night's sleep are complicated. They are. Nonetheless, research is beginning to untangle the story and certain trends do appear.

Before these studies are described, it will be necessary to consider the problem of the nature of sleep. There has been significant headway in the description of a night of sleep. Sleep is a complicated series of states rather than a single, uniform state. Experiments verify the common belief that sleep is essential for normal functions while awake. But the "hows" and "whys" are unknown and therefore it is difficult to state flatly that this or that alteration in sleep is harmful. One must rely on every-day wisdom for these judgments.

A. Methods for Studying Sleep Disturbance by Noise

Field studies. One of the most obvious and direct methods is to interview people who live in areas that receive various exposures to noise. People can be asked whether the noise either prevents them from falling asleep or whether it wakes them from sleep. Of course, if such direct questions are embedded in a series of questions concerning noise and sound, the answers may be biased by the person's attitude toward the source of sound. It may be better to ask about the quality of sleep, the number of hours slept, judgments about well-being upon arising, and so on in the context of a survey unrelated to noise.

Laboratory studies. Typically, a subject sleeps in a special laboratory bedroom where his physiological state can be monitored from electrodes attached to his body, and calibrated sounds can be presented by loudspeakers or by other sound-making instruments. By these techniques subtle responses to sounds or subtle changes in the pattern of sleep can be recorded and measured. Furthermore, a variety of instructions and adaptation procedures can be tested. However, such research is very slow, hard work; the required apparatus is expensive; usually only a few subjects can be studied; and the routine is demanding on the experimenter. Furthermore, even though the subjects are adapted to the routine, they are not at home and they are constrained by electrodes and wires. In spite of these difficulties, however, some rather clear trends have emerged.

B. General Properties of Sleep

Sleep stages and a night of sleep. Examination of brain waves, other physiological measures, responsiveness, behavior, and the sequence of events during a night's sleep have led to the concept of sleep stages or states. There are recognizably different patterns that occur during a period of sleep. Since these patterns blend from one to another, there are several schemes for categorizing them into sleep stages or states. A popular set of categories is labelled I, II, III, IV, and I-REM. Another set of stages is defined in a slightly different manner. They are labelled A, B, C, D, and E. Some authors even combine the two sets of definitions.

Perhaps the easiest approach to these stages is to follow an idealized progression as one falls asleep. As one relaxes and enters a stage of drowsiness, the pattern of the electroencephalogram (EEG) changes from a jumble of rapid, irregular waves to the regular 9-12 hertz pattern known as the alpha rhythm. One is relaxed, but not asleep. Later, the alpha rhythm diminishes in amplitude and intermittently disappears. This is sleep stage A. As time progresses, the alpha rhythm is present less and less often until it disappears and is replaced by a low-voltage, fast, irregular pattern in the EEG; this is stage B. In the Roman numeral system, stage I corresponds to the late portions of stage A and all of stage B.

Next, there appear quick bursts of larger amplitude waves known as spindles or the spindles of sleep. Mixed with these spindles there will appear small-amplitude, low-frequency (1.5-3 hertz) waves known as delta waves. This stage is known as stage C or stage II. In the next stage of sleep, the spindles disappear and the delta waves become more regular and grow in amplitude. This is known as stage D. Later, the delta waves become even larger and of lower frequency (0.6-1 hertz). This is stage E. The Roman numeral system III and IV include stages D and E but the criterion for division is different. Stages D and E or III and IV are often referred to as deep or delta sleep.

The purpose is not to confuse the reader with two sets of sleep stages, but rather to communicate the idea that there is a progression of sleep stages. One can reasonably divide this progression by various criteria. Generally, in stage A or early I, man is drowsy, but awake. In stage B, or late I, one drifts or "floats" back and forth between waking and sleeping. When awakened at this stage of sleep, one is not quite sure whether he has been asleep. Stages C, D, and E or II, III, and IV represent definite sleep.

The remaining stage, which has been of great interest, is the so-called Rapid Eye Movement (REM) stage of sleep. In REM sleep, the sleeper exhibits characteristics of stage I (late A and B). There are: fast, low-voltage brain waves; other evidence of variable but definite physiological activation; and rapid eye movements. Consequently, this stage is usually tagged I-REM. While dreaming and mental activity can take place in all sleep stages, it is during I-REM that most dreams occur.

A typical night's sleep initially follows a progression, with occasional reversals, from stages A (I) to stages D and E (IV). This progression usually occurs within the first 80 minutes of sleep. After about 90 minutes of sleep, one has left stage IV and has had a period of I-REM. A 90-minute cycle from I-REM to I-REM tends to recur throughout the period of sleep. There are, however, some irregularities and some systematic changes.

Roughly equal amounts of time are spent in I-REM and in IV. Early in the sleep period more time is spent in IV than in I-REM and later in the sleep period more time is spent in I-REM than in IV. Generally, after the first 80-90 minutes of sleep, more and more time is spent in the "lighter" stages of sleep. These facts are summarized in Figure 16. Overall, sleeping young adults distribute sleep as follows: Stage I—5%; Stage I-REM—20-25%; Stage II—50%; and Stages III and IV—20% (Berger, 1969).

Even after falling asleep, one awakens during the night. Roughly, five per cent of the total period of "sleep" is spent awake from adolescence to about age 40. From ages 40 to 90 the time awake during "sleep" increases to nearly 20 per cent (Feinberg, 1969). The number of awakenings that occur after falling asleep increases from an average of about two at age six to six at age 90 (Feinberg, 1969).

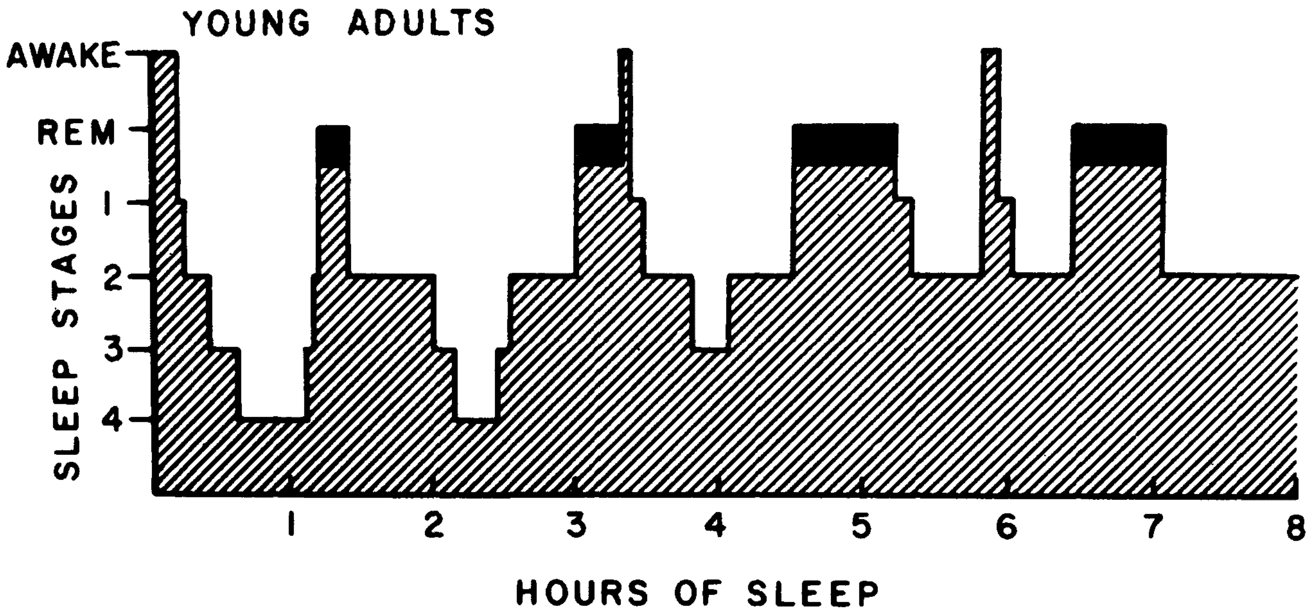

Figure 16. The nocturnal sleep pattern of young adults is shown. During the later part of the sleep period stage IV is absent and more time is spent in stage II and in REM. Notice the two brief periods that the sleeper spontaneously awoke. (From Berger, 1969, in <u>Sleep: Physiology and Pathology</u>, A. Kales, Editor, with the permission of the author, editor, and the J. B. Lippincott Company.)

Sensory responses to stimulation during sleep. The sense organs are just as sensitive to their appropriate physical stimuli during sleep as they are during wakefulness. One may wonder whether mechanisms near the periphery of the nervous system somehow "block" the sensory pathways during sleep. Such mechanisms would prevent the neural messages from the sense organs from reaching the higher centers of the brain. Available research (Koella, 1967) does not support this view. Rather, one can state quite strongly that information from the sense organs does reach the highest centers of the brain even during deepest sleep. This conclusion is based on the fact that electrical responses to stimuli can be recorded in the highest centers of the brains of sleeping or anesthetized men and animals. These responses usually are of brief duration and have latencies of 0.01-0.8 second.

Therefore, the apparent indifference to stimulation during sleep is not a simple "shutting out" of the neural messages at or near the periphery of the nervous system close to the sense organ. Rather, this apparent indifference to external stimulation is due to a complicated reorganization of brain processes during sleeping as opposed to waking states. It is also true that when the eyelids are closed, an ear is on a pillow, or the middle-ear muscles are contracted, responsiveness to the environment can be reduced because the magnitude of the stimulus that reaches the sense organ is not as great. But these physical conditions are no more related to the basic nature of sleep than are reduction of light by eye patches or the attenuation of sound by ear plugs.

Arousal. Sensory messages reach the highest centers of the brain, but whether or not they influence the sleeper will depend on a complicated set of circumstances. Many theorists believe that mechanisms in the brain busily carry out "sleep work" throughout the sleeping period. These mechanisms assess the significance of incoming sensory messages and adjust the state of the brain in accordance with the sensory message and the whole situational complex. This view is supported by everyday experience as well as by scientific investigation.

Arousal from sleep can be recognized by brief changes in physiological function; by shifts from deeper to lighter stages of sleep; or by behavioral evidence of awakening. Some of the properties of arousal mechanisms will become apparent as the effects of noise on sleep are discussed.

C. Noise and Sleep

Effects of brief noises. In the area of sleep disturbance by noise it is the effects of relatively brief noises (about 3 minutes or less) on a person sleeping in a quiet environment that have been studied most thoroughly. Typically, presentations of the sounds are widely spaced throughout a sleep period of 5-7 hours.

A summary of some of these observations is presented on Figure 17. The heavy dashed lines are hypothetical curves which represent the per cent awakenings under conditions in which the subject (1) is a normally rested young adult male who has been adapted for several nights to the procedures of a quiet sleep laboratory, (2) has been instructed to press an easily reached button to indicate that he has awakened, and (3) has been moderately motivated to awake and respond to the noise (such motivation can be established by instructions which imply that somehow the subject's ability is being tested). A datum for sleep stage II is indicated by an Arabic two, 2. A datum for sleep stages III and IV is indicated by a Greek delta, Δ. While in stage II, subjects can awake to sounds that are about 30-40 decibels above the level at which they can be detected when subjects are conscious, alert, and attentive. While in deep sleep, stages III or IV, the stimulus may have to be 50-80 decibels above the level at which they can be detected by conscious, alert, attentive subjects before they will awaken the sleeping subject.

The solid lines are data from questionnaire studies of persons who live near airports. The percentage of respondents who claim that flyovers wake them or keep them from falling asleep is plotted against the A-weighted sound level of a single flyover (Wyle Staff, 1971). These curves are for the case of approximately 30 flyovers spaced over the normal sleep period of 6-8 hours. The filled circles represent the percentage of sleepers that awake to a 3-minute sound at each A-weighted sound level (dBA) or lower. This curve is based on data from 350 persons, each tested in his own bedroom (Steinicke, 1957). These measures were

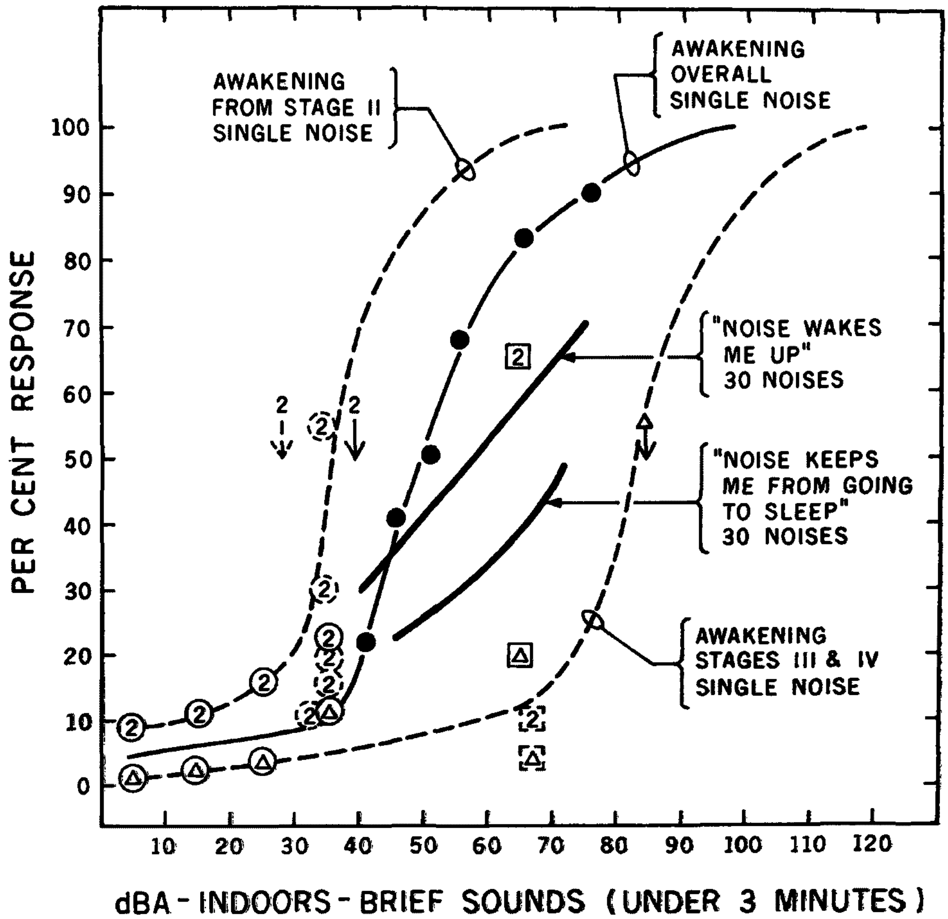

Figure 17. Awakenings to sound from various laboratory and questionnaire studies are shown. The horizontal axis gives the approximate A-weighted sound level (dBA) of the noise. The curves labelled "awakening" are from normally rested young adults who were sleeping in a laboratory and were moderately motivated to awake in response to sound. The percentage of awakening responses will depend not only on the intensity of the sound but also on the definition of "awakening," the motivation of the subject to awake in response to sound, and the sleep stage (I, II, III, IV, or I-REM) when the stimulus is presented. The questionnaire results, "Noise wakes me up" and "Noise keeps me from going to sleep," are derived from the Wilson Report (1963) for the case of 30 brief noises distributed throughout the night. The laboratory results are from various studies. The filled circles were gathered throughout the night without regard to sleep stage (Steinicke, 1957). Data from sleep stage II are represented by 2's; those from sleep stages III and IV by deltas, Δ's. The circles with unbroken borders are from Williams et al. (1964). The circles with broken borders are from Williams et al. (1965). The boxes with solid borders are from Rechtshaffen et al. (1966). The boxes with broken borders are from Lukas and Kryter (1970). The broken arrow is from Watson and Rechtshaffen (1969). The solid arrows are from Kryter and Williams (1970).

made between 2:00 and 7:00 AM, and it is reasonable to assume that most of the subjects were roused from stages II or I-REM.

Motivation to awake and intensity level of the noise. There is clear evidence that motivation to awake can influence the probability of awakening to noise (Williams et al., 1965; Watson and Rechtschaffen, 1969; and Wilson and Zung, 1966). The effects of motivation, however, depend on the stage of sleep and the intensity level of the noise. For weak stimuli, motivation may have a strong influence on arousal only during light sleep (Williams et al., 1965). For moderately strong stimuli, motivation to awake may have a powerful effect on the probability of an upward shift in sleep stage (probably awakening also) from all depths of sleep (Wilson and Zung, 1966). With very intense stimuli it is likely that motivation would have little influence; for example, brief noises with A-weighted sound levels of 100-120 decibels awaken nearly everyone from any stage of sleep.

The effects of motivation are illustrated indirectly on Figure 17. The results of Lukas and Kryter (1970) are the boxes with broken borders that lie towards the lower right of the graph. Here awakening is defined in the experimental setting by instructions that imply "if you happen to wake up, push the button." The button is located on the headboard of the bed and requires that the subject find it (often having to turn over to do so) and press it. This definition of awakening is similar to a typical kind of night awakening.

The ascending series of stage 2 awakenings for stimuli of 30-40 decibels (encircled by broken lines on Figure 17) are from Williams _et al._ (1965). The ascending percentage of awakenings is correlated with the sleeper's motivation as controlled by instructions and punishments for failure to respond by pushing a convenient button. As the motivation to awake was increased, the percentage of awakenings showed a five-fold increase from less than 11% to about 55% of the presentations of the same noise at the same stage of sleep.

Fluctuating noise levels. A very important and extensive study of the effects of noise on sleep was done at the Centre d'Etudes Bioclimatiques du CNRS in Strasbourg, France (Schieber, Mery, and Muzet, 1968). Several measures of the quality of sleep were used. These included: the amount of time in each of the sleep stages; the numbers of brief awakenings as evidenced by the appearance of alpha waves in the electroencephalogram; the number of bodily movements; the degree of muscular tension; the occurrence of perturbations in heart rate; the presence of eye movements; and the occurrence of various components of the electroencephalogram such as K-complexes, sleep spindles, alpha waves, theta waves, and delta waves. Artificial sounds (crescendos of white noise that rose to about 80 decibels in 10 seconds and were terminated abruptly), sounds of aircraft flyovers with peak values of 72 and 89 decibels (either 16 or 33 per night), or traffic noises were used in various experiments. The time required to fall asleep was longer for noise than control conditions. Under control conditions, about 26 minutes elapsed between going to bed and the first occurrence of stage IV. Under traffic noise, the delay between going to bed and the first occurrence of stage IV was 33 or 52 minutes depending on the type of noise. When noises were presented, there was a tendency for sleep to be much lighter than normal for the first half of the night and slightly deeper than normal for the second half of the night. Thus, there was a tendency to compensate for the loss of deep sleep in the early part of the night by an increase in deep sleep in the later part of the night. Nonetheless, almost all measures of sleep disturbance indicated that sleep was disturbed overall and throughout the sleep period.

The results with traffic noise were of particular interest. These sounds were actually recorded in a bedroom near a busy street. One set of recordings was made between 10:00 PM and midnight. Another was made between midnight and 4:00 AM. The 10:00 PM to midnight sample represented about 4.3 vehicles passing per minute, while the midnight to 4:00 AM sample had only about 1.8 vehicles per minute. The peaks in both samples reached A-weighted sound levels of nearly 80 decibels, but the long-term averages were 70 decibels for the high-density traffic and only 61 decibels for the low-density traffic. The control night had steady ventilation noise with a median A-weighted sound level of 48 decibels. The interesting fact was that the low-density traffic pattern was more disruptive of sleep than was the high-density pattern. However, both traffic patterns were more disruptive than the control noise.

These results strongly suggest that fluctuations in the noise levels and degree of fluctuation are important factors in determining sleep disturbance by sound.

Steady and rhythmic sounds. It seems plausible that steady, periodic, or rhythmic sounds might improve the quality of sleep. Certainly, anecdotal evidence suggests that steady sounds can mask out brief disturbing sounds and that some periodic or rhythmic sounds have certain soothing qualities. Investigations along these lines are badly needed. Pertinent questions are: (1) At what levels do steady sounds begin to adversely influence sleep patterns? (2) Can a moderate amount of masking noise reduce the influence of brief sounds on sleep, or are brief sounds that suddenly emerge above a masking noise more disturbing than those that simply join the usual rise and fall of community noise? (3) Can sleep be induced and maintained by particular rhythms of sound?

One investigation of complaints about noises produced by air-conditioning and heating equipment may be relevant to the effects of steady noise on sleep (Blazier, 1959). From complaint files, conversations with dealers and distributers, and field trips to problem sites, the investigator found what types of noises in bedrooms resulted in adverse responses. He also noted that the fewer the complaints, the greater the customer's acceptance of the product.

It was found that people especially objected to noises that included "tones" and "throbbing" or "beats." Blazier summarized the frequency of complaints in relation to A-weighted sound levels of noises in sleeping quarters as follows: below about 33 decibels, no complaints; 33-38 decibels, occasional complaints; 38-48 decibels, frequent complaints; and over about 48 decibels, unlimited complaints. While it is not known whether these complaints are due to sleep disturbance or other factors, these results do appear to be in remarkable agreement with the trends for sleep disturbance by brief noises shown on Figure 17.

Sound quality and sleep disturbance. As yet we have no evidence on the role that pitch, timbre, and temporal structure play in sleep disturbance or enhancement. Until such data are forthcoming, it may be useful to assume that those variables that influence perceived noisiness would similarly influence sleep disturbance.

Sleep deprivation and sleep disturbance. Subjects who have been deprived of sleep require more intense noises for awakening then do normally rested subjects (Williams *et al.*, 1965).

Difference between men and women. One study found that women tended to awaken to noises of lower levels than did men (Steinicke, 1957). Another study (Wilson and Zung, 1966) found a clear difference in arousal as defined by upward shifts in sleep stage. In response to noise, women shifted toward lighter stages of sleep much more frequently than did men. Lukas (1971) finds that sleep disturbance from subsonic-aircraft noise or sonic booms is greater for middle-aged women than for middle-aged men.

Thus, it appears that women's sleep is more easily disturbed by noise than is men's, even when other variables such as motivation and stage of sleep are equated.

Age and sleep disturbance by noise. There is clear evidence that persons over about 60 years of age are much more easily awakened or shifted towards lighter sleep stages than are middle-aged adults or children (Lukas and Kryter, 1970). This effect is large and dramatic. More specifically, simulated sonic booms that awaken middle-aged adults and 7- and 8-year-old children on less than 5% of their occurrences will awaken 69- to 72-year-old adults on nearly 70% of their occurrences. These dramatic differences hold over all stages of sleep. Also, once awakened, an older person has more difficulty in returning to sleep than does a middle-aged adult or a child. There is no evidence that children are especially sensitive to sleep disturbance by noise. On the contrary, Lukas et al. (1971) found that 7- and 8-year-old children are slightly less sensitive to noise during sleep than are middle-aged adults. However, since general sleep disturbance in children (enuresis, somnambulism, night terrors, and nightmares) seems to peak between 4 and 6 years of age (Broughton, 1968; Feinberg, 1969; Jacobson et al., 1969; Kessler, 1966), one suspects that sleep disturbance by noise may have a special impact on children in this age range. It is well known, for instance, that thunderstorms can waken and frighten children of these ages. Children in the age group of 4-6 years seem to be particularly disturbed by sudden arousal from stage IV of sleep (Broughton, 1968).

Sleep stage and accumulated sleep. In terms of either behavioral awakening or an upward shift in sleep stage as indicated by the electroencephalogram, sleep can be influenced most easily in stages I and II and least easily in stages III and IV. Sometimes I-REM seems to be more like III and IV in this regard; other times it is more like stages I and II. A person can be aroused from sleep more easily the longer he has slept no matter what the stage of sleep (Lukas and Kryter, 1970; Rechtschaffen et al., 1966; Williams et al., 1966).

Stimulus meaning and familiarity. The effects of stimulus meaning and familiarity are closely bound to those of motivation and stimulus intensity. There is considerable evidence that sleepers can discriminate among stimuli if the differences were learned and the discrimination was established while they were awake (Williams, et al., 1965; Wilson and Zung, 1966). In a classic experiment Oswald et al. (1960) demonstrated that sleeping subjects will respond when their own names are spoken but show few responses to other names. Generally, when auditory stimuli are faint and similar, discriminations are probably performed better in light sleep (I, II, and I-REM) than during deep sleep (III and IV). The effect of stimulus familiarity on arousal from sleep has not been studied extensively. In one experiment, small but consistent differences were found between familiar and unfamiliar sounds. "Familiar" sounds shifted sleep stages less frequently than "unfamiliar" sounds (Zung and Wilson, 1961).

Adaptation to sleep disturbance by noise. Whether adaptation takes place is the subject of considerable debate. A reasonable guess at this story is as follows. The stronger the stimulus, the less likely it is that total adaptation will take place. Behavioral awakening and duration of awakening will probably show the most adaptation. Upward shifts in sleep stage are likely to show some adaptation, but less than behavioral awakening. Brief responses in the electroencephalogram and autonomic responses such as changes in heart rate, blood flow, skin resistance, and so on appear to show very little adaptation. The most significant and surprising finding has been that adaptation, even in behavioral awakening, has been absent (Theissen, 1970) or slight (Lukas and Kryter, 1970). The adaptation that seems apparent from everyday experience may be the result of (1) changes in the motivation to awake; and (2) amnesia for awakening. The last point is supported by the observation of sleep researchers that subjects in their laboratories often cannot remember and often underestimate the number of times that they awake during a sleep period.

There is clear evidence for adaptation to the total sleeping environment. Sleep researchers talk of the "first night" effect. Normal sleep is rarely if ever observed during the first night in the laboratory. It is likely then that some of the disturbance reported by the rural person trying to sleep in an urban area and the urban person trying to sleep in a rural area is but the "first night" effect. It is commonplace that when we cannot sleep, for whatever reasons, we "hear" many sounds.

Other factors. There are, of course, a host of other factors related to sleep and arousal from sleep (Kales, 1969). These include mental and physical disease states, drug usage, general stress, and so on. Most of these have not been studied in relation to the problem of sleep disturbance by noise. There is however, clear evidence that male patients suffering from depression are more easily shifted from deeper to lighter stages of sleep by sounds than are normal males (Wilson and Zung, 1966). Generally, it seems probable that persons with disorders which result in light, restless sleep or frequent awakenings will be more frequently aroused by sounds than will normal persons or persons with disorders that produce unusually deep and prolonged sleep. Also, it has been demonstrated that sleep deprivation has more adverse effects on "poor" than on "good" sleepers (Williams and Williams, 1966).

D. Noise, Sleep Disturbance, Health, and the Quality of Life

Brief sounds of sufficient intensity and fluctuating noise levels definitely can alter the normal sleep pattern. These changes in sleep pattern are in the direction of lighter sleep. The effects of noises are to produce sleep patterns that are more like those of "poor sleepers" than "good sleepers" (Luce, 1966, p. 105-108; Williams and Williams, 1966).

Whether such sleep disturbance constitutes a health hazard is debatable. While good sleep is necessary for physical and mental health, normal persons who lose sleep compensate by spending more time in deep sleep, by becoming less responsive to external stimuli, and by napping. Thus, it may be very difficult to deprive a normal person of sufficient sleep to produce adverse health effects.

On the other hand, the data presented here amply support the notion that people exposed to sufficient noise will complain of sleep loss. Everyday experience strongly supports the notion that a "good" sleep is important to one's feeling of well-being.

All factors considered, one must tentatively assume that sleep disturbance by excessive noise will reduce one's feelings of well-being. Furthermore, when noise conditions are so severe as to disturb sleep on a regular, unrelenting basis, then such sleep disturbance may constitute a hazard to one's physical and mental health.

Section 4. LOUDNESS, PERCEIVED NOISINESS, AND UNACCEPTABILITY

Introduction

To be annoyed, irritated, distracted, or disturbed by sound is commonplace. Often the annoyance, irritation, distraction, or disturbance can be traced to particular situational factors. If a conversation is interrupted by the noise of a neighbor's power mower, the annoyance may be traced to masking and speech interference. If one interprets a sonic boom as the explosion of a water heater, the annoyance may be attributed to fear. If the noise of a motorcycle awakens one from sleep, perhaps the annoyance can be traced to the disturbance of sleep. A sudden noise, which may produce an unnecessary startle or fear reaction, may be annoying because of the startle and fear reaction. Thus, a great many instances of annoyance produced by sound may be due to the masking effects of sound, to particular responses to the message content of the sound, or to physiological responses to the sound.

If all instances of annoyance from noise were purely idiosyncratic, then the possibility of dealing with the relations between the physical properties of sound and the frequency and intensity of annoyance would be hopeless. <u>This is not the case</u>. In spite of wide variations among members of a community with regard to the intensity of their reactions and the specific noises that they find objectionable, well-defined trends have emerged. <u>On the average</u>, there are relations between the physical characteristics of noises and the amount of annoyance, irritation, distraction, and disturbance.

Annoyance *per se* is not to be the topic of this section. Rather, the dimensions of auditory experience which can be used to predict some of the annoyance produced by sound are discussed.

One of these dimensions is the judged *loudness* of a sound. Loudness is clearly an attribute of auditory experience. Another dimension is called the *perceived noisiness* of a sound. Some argue that perceived noisiness is a basic attribute of auditory experience, while others argue that it is a response to auditory experience. There is no doubt, however, that perceived noisiness is closely tied to the physical characteristics of the sounds themselves. The third dimension is the *unacceptability* of a sound and it is probably the same as *perceived noisiness*, or nearly so. These terms are often used interchangeably.

Knowledge of the loudness and perceived noisiness and their relations to the physical characteristics of sounds provide part of the foundation for the description of annoyance and community response (Section 5).

A. Measurement of Auditory Dimensions

Field studies. One approach to the relations between the physical properties of sounds and judgments of loudness, noisiness, or unacceptability is the field study and questionnaire. By this technique, people are asked either directly or indirectly to what degree they judge various sounds to be loud, noisy, or unacceptable. The characteristics of the sounds are then measured, and one attempts to find the relations between the characteristics of the sounds and the responses to them. These methods and their results will be discussed in the next section, Section 5, because they are most often applied to the annoyance and disturbance of activities produced by noise.

Laboratory methods. Another approach is to bring subjects to the laboratory and ask them to judge a variety of sounds. The sounds are often artificial sounds with well-specified properties. In this way the researcher tries to ferret out the underlying relations between the properties of sounds and their judged loudness, noisiness, or unacceptability.

Three techniques are often used. Category scaling is a very simple procedure. One asks the subject to place a sound into one of several categories that seem to fall along a single dimension. For example, a subject may be asked to categorize each of a series of sounds as not noisy, slightly noisy, moderately noisy, very noisy, or intolerably noisy. Category scaling is the familiar everyday process of judgment that we all use many times in many different situations. It has the advantage of simplicity. Among its disadvantages are the following: people tend to use the middle categories, the way people categorize one stimulus strongly depends on the other stimuli included in the set being judged, and people are often strongly influenced by seemingly irrelevant aspects of the stimuli or the judgmental situations (for example, judgments of the loudness of sounds may be influenced by their esthetic quality).

Another method is that of magnitude scaling. People given a series of stimuli can and will judge the relative magnitude of the stimuli along some dimension. Thus, people can estimate whether a sound seems twice as bad as another, or ten times as noisy as another, or one-half as beautiful as another. Magnitude judgments allow a measure of the apparent "somethingness" of a stimulus in quantitative but subjective terms.

A third method is that of paired comparisons. People can be presented with a pair of stimuli. They are then asked to judge which is louder, more pleasant, noisier, and so on. By many such comparisons the stimuli can be ordered along a so-called "psychological dimension."

"Psychological dimensions" measured by "psychological instruments" seem formidable to the uninitiated. They are not! Psychological dimensions as measured by psychological instruments are simply orderly descriptions of the judgments we all make in our everyday experience.

There are some differences between what the psychologist does and what we all do in our everyday judgments of the events of the day. The psychologist tries to standardize the conditions under which the judgments are made and the methods by which these judgments are summarized. The psychologist may select, control, and measure the events that are to be judged. And in order to be able to communicate accurately the conditions, he may invent terminology which refers to the specific conditions and judgments. Unfortunately, the terminology which is invented for preciseness and clarity sometimes confuses the audience or consumer of the knowledge.

B. Loudness, Perceived Noisiness, and the Physical Characteristics of Sounds

Loudness. Loudness is an attribute of auditory experience. As a rule of thumb, people agree that when a single component sound such as a tone or a band of noise is raised in intensity by about 10 decibels, it sounds twice as loud. While this basic and simple rule is of great importance, the complete story of loudness is much more complicated. Loudness depends on the frequency (pitch) of a sound as well as its intensity level. At moderate levels, low-frequency sounds (those below 900 hertz) are judged to be less loud than high-frenquency sounds (those between about 900 and 5000 hertz) when both sounds are of equal physical intensity (sound pressure level). The sound-level meter is so designed that tones or narrow bands of noise will all sound equally loud if their A-weighted sound levels are about 40 decibels. These relations change with intensity, however.

If a complex sound is made by simultaneous presentation of components that are widely spaced in frequency (pitch) and about equally loud, then the total loudness of the complex sound is the sum of the loudnesses of the individual components. When the components are not widely spaced or are greatly unequal in loudness, then there is mutual inhibition and interference resulting in the total loudness being less than the sum of the loudnesses of the components. Fortunately, methods are available to measure the loudness of combinations of sounds (Stevens, 1961; Zwicker and Scharf, 1965).

The growth of loudness near the threshold of detectability is more rapid than the growth of loudness implied by the general rule that a change of 10 decibels of intensity level equals double the loudness. Indeed, as a sound emerges from inaudibility, a 10 decibel change of intensity level may increase the judged loudness by a factor of ten instead of two. Also, rapid growth of loudness may occur as sounds become audible over a masking noise. Thus, masking sometimes may be an ineffective way of reducing the loudness of unwanted sounds. Once audible, the unwanted sounds may seem nearly as loud as without the masking noise.

Perceived noisiness (unacceptability). If one assumes that people don't like loud noise, it would seem that the goal of acoustical engineers should be to reduce the loudness of noise. If this were the case, design objectives could be specified in terms of loudness and the appropriate measurements of noise would then be measurements of loudness.

It has been proposed that there is yet another dimension of human response to noise that is similar to, but distinct from, loudness. This dimension is called perceived noisiness. The notion is that people can judge their impression of the unwantedness of a sound. These judgments are made of sounds that are expected and that do not provoke pain or fear. Dr. Karl D. Kryter of the Stanford Research Institute, who developed the idea that people can judge the "noisiness" of a sound as opposed to its loudness, explains the concept as follows (Kryter, 1970, p. 270-277).

> Perceived Noisiness. The subjective impression of the unwantedness of a not unexpected, nonpain or fear-provoking sound as part of one's environment is defined as the attribute

of perceived noisiness. The measurement or estimation of this subjective attribute or quantity is of central importance to the evaluation of environmental sounds or noises with regard to its physical content. For this reason, this topic will be discussed in considerable detail.

Confusion sometimes results in the use of the word noise as a name for unwanted sound because there are two general classes of "unwantedness." The first category is that in which the sound signifies or carries information about the source of the sound that the listener has learned to associate with some unpleasantness not due to the sound per se, but due to some other attribute of the source...... In these cases it is not the sound that is unwanted (although for other reasons it may also be unwanted) but the information it conveys to the listener that is unwanted. This information is strongly influenced by the past experiences of each individual; because these effects cannot be quantitatively related to the physical characteristics of the sounds, they are rejected from the concept of perceived noisiness. After all, the engineer, attempting to control the noise from a given source, must shape the characteristics of the noise in as effective a way as possible for the majority of the people and the most typical of circumstances; those legislating or adjudicating the amounts of noise to be considered tolerable must also have a quantitative yardstick that is relatable to groups of people and typical circumstances.

Psychological judgment tests have demonstrated that people will fairly consistently judge among themselves the "unwantedness," "unacceptableness," "objectionableness," or "noisiness" of sounds that vary in their spectral and temporal nature provided that the sounds do not differ significantly in their emotional meaning and are equally expected. Presumably this consistency is present because men learn through normal experience the relations between the characteristics of sounds and their basic perceptual effects; masking, loudness, noisiness, and, for impulses, startle. This is a basic premise of the concept of perceived noisiness and of the word noise as unwanted sound. .....

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Psychological-sociological factors can usually be reconciled with the general attribute of sound called perceived noisiness. ...[Some have]...found that propaganda, stressing the importance of military aviation to the people and the plans of the government to control and lessen the noise, reduce the willingness of citizens near military airports to complain about the aviation noise; the reduction was equivalent to the effect that would have been obtained by lowering the noise levels by 6 dB or so. At the same time, the concept of perceived noisiness would maintain that reduction of the actual noise level should further reduce the willingness of the average person to complain about the noise, regardless of his particular absolute willingness at a given moment, and that this amount of average reduction in complaints would be a function of how cleverly, and compatible, to the attribute of perceived noisiness, the noise spectrum and its duration were tailored. ... It has been ... proposed to obtain the quantitative relations between some of these psychological, sociological, and attitudinal factors and noise exposure. According to this concept, one could apply correlations or adjustments during the calculation or measurement of noise exposures to take these factors into account. Although the evaluation of the relative contribution of the physical aspects of sounds to their perceived noisiness should in no way interfere with or diminish the manipulation of psychological and sociological factors in the control of environmental noise, basic aspects of perceived noisiness probably set certain fundamental limits, as will be discussed later, on the tolerability of noise.

Loudness versus Noisiness. Loudness of sounds is often assumed to be an adequate indicator of the unwantedness, for general noise control purposes, of sounds. Experiments have shown, however, that for many sounds there are differences between some physical aspects of sounds, and judgments of loudness compared to judgments of perceived noisiness. The difference between loudness and perceived noisiness in terms of spectral content per se (the equal loudness vs. equal noisiness contours) is insignificantly small for broadband sounds, ... On the other hand, the differential effects of duration and spectral complexity upon these two attributes, ... are rather large.

The fact that loudness is apparently not influenced by duration and spectral complexity features of a sound would seem to disqualify loudness as an appropriate attribute for the estimation of the unacceptability of environmental noises. Although loudness and perceived noisiness differ in some respects, an assumption of the concept of the perceived noisiness of non-impulsive noises is that, as the intensity of a noise changes, keeping other factors constant, the subjective magnitude of loudness and noisiness change to a like degree; e.g., a 10 dB increase in the physical intensity of nonimpulsive sounds causes a doubling of the subjective magnitude of its loudness and its noisiness. There is some experimental proof of this common relation between this subjective scale of noisiness and loudness, but, as with loudness, the scale found is somewhat dependent on the experimental methods used and sounds judged.

<u>Instructions to Subjects</u>. The words used in the instructions to the subjects for judgment tests of the acceptability of sounds have some influence upon their rating of sounds, ... It is difficult and probably academic to fathom what is the basis for the range of differences [usually small] ....., such as whether the words used really mean different things to different people. In any event, there is no apparent reason why listeners should not be asked to rate directly sounds in terms of their unwantedness, unacceptability, annoyance, or noisiness, as synonyms, rather than to rate their loudness in the expectation that the latter is an indirect clue to the noisiness or unwantedness of the sounds.

Following are parts of the instructions that have been given to subjects who were asked to make subjective judgment tests of the noisiness of sounds. "<u>Instructions, Method of Paired-Comparison, for Judgments of Noisiness</u>. You will hear one sound followed immediately by a second sound. You are to judge which of the two sounds you think would be the most disturbing or unacceptable if heard regularly, as a matter of course 20 to 30 times per day in your home. Remember, your job is to judge the second of each pair of sounds with respect to the first sound of that pair. You may think that neither of the two sounds is objectionable or that both are objectionable; what we would like you to do is judge whether the second sound would be more disturbing or less disturbing than the first sound if heard in your home periodically 20 to 30 times during the day and night." The purpose of including in the instructions to the listeners a number of terms in rating the noisiness or unwantedness of expected sounds is to try to reduce possible differences in how different subjects might interpret the purpose or intent of the judgments when only one term such as "disturbing" or "annoyance" is used.

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<u>Five Physical Aspects</u>. So much for the general concept of the perceived noisiness of individual sounds. For practical purposes the measurable physical aspects of a sound that are most likely to control its perceived noisiness must be determined. To date, five significant features have been identified or suggested --(1) spectrum content and level; (2) spectrum complexity (concentration of energy in pure-tone or narrow frequency bands within a broadband spectrum); (3) duration of the total

sound; (4) duration of the increase in level prior to the maximum level of nonimpulsive sounds; and (5) the increase in level, within an interval of 0.5 sec, of impulsive sounds. Some physical aspects that might seem important—for example Doppler shift (the change in the frequency and sometimes noted pitch of a sound as a sound source moves towards and away from the listener) and modulation of pure tones—appear to be very secondary in their effects on people compared to the five physical characteristics mentioned above.

The five physical factors mentioned by Kryter operate approximately as follows: (1) Intensity and frequency content—noisiness increases with sound level approximately as does loudness, that is a ten-decibel increase results in a doubling of judged noisiness. Sounds with energy concentrations between 2000 hertz and 8000 hertz are judged to be more noisy than sounds of equal sound pressure level outside this range. This effect can be equivalent to 10-20 decibels or a factor of 2-4 in judged noisiness. (2) A concentration of energy or spectrum complexity—this may have an effect which increases the noisiness by 2-3 times or 10-15 decibels over that noisiness that would be predicted by the sound pressure level. (3) Duration—the noisiness of a sound increases with its duration. The relation is logarithmic, and over a range from a few seconds to a few minutes, an increase in duration by a factor of ten results in a change that is roughly equivalent to ten decibels. In other words, this means an increase in noisiness by a factor of two. Detailed study indicates that the relation between noisiness and duration is more pronounced in the range from 1-4 seconds and less pronounced beyond 15 seconds than indicated by the general rule just stated. (4) Duration of the period of rising sound pressure level--sounds that are increasing in level are judged to be of greater noisiness than those decreasing in level. A sound that takes ten seconds to reach a maximum level may be judged more noisy than one that reaches its maximum level in three seconds. This difference can be the equivalent of about three decibels or a factor of 1.5 in noisiness. (5) Sudden increases in level--in contrast, impulsive sounds that reach a high peak very abruptly, say in less than 0.5-1.0 second, may be judged to be very noisy. While this effect depends on the magnitude of the impulse, it can be very large. People judge impulsive sounds to be very noisy even when these sounds are familiar and expected.

Physical measurements of sounds can be weighted in such a manner as to enable one to predict judgments of noisiness. The resulting decibel values are said to be perceived noisiness levels (PNLs) and they are expressed as PNdB.

There has been great debate among students of loudness and noisiness concerning (1) whether these two attributes are the same or different; (2) the relative importance of the various temporal and spectral attributes of sound for loudness and noisiness; and (3) the relative merits of various schemes for predicting loudness and noisiness from physical measurements of sound. These debates are of some importance to the practical problems of noise control. Mainly it is important to be able to predict the loudness or perceived noisiness of a potential source of sound, such as a new machine, while it is being designed.

No doubt these debates will continue and as a result our knowledge will become more refined. In spite of the apparent conflict and confusion, numerous reports indicate that many of the major variables have been identified and their effects are known, at least qualitatively.

C. Verbal Descriptions of Sound and Auditory Experience

Auditory experience has a richness and variety that far exceeds those aspects represented by loudness or noisiness. Even sustained pure tones have the attributes of loudness, pitch, and volume. Tones appear to be of low or high loudness, low or high pitch, and of small or large volume (Stevens and Davis, 1938). Volume refers to the fact that some tones seem to be large and diffuse, while other tones seem to be thin and compact. Complex tones, being mixtures of pure tones, vary in quality or timbre and seem to have at least three qualities in addition to loudness, pitch, and volume. These are brightness, roughness, and fullness (Lichte, 1940). Everyday sounds and music grow in dimensionality and variety as they are extended in time. The full richness of sound only emerges when sounds form a sequence spread over time. While an extremely rich visual scene can be "taken in" at a glance, the auditory scene must be "taken in" over a period of time. Psychologists have only begun to study the richness and variety of auditory experience. A few studies (Solomon, 1958, 1959a, 1959b) have been done. Even though only limited sets of sounds have been used, the results suggest that people can meaningfully evaluate sounds on a magnitude dimension (heavy-light); on an esthetic-evaluative dimension (good-bad, beautiful-ugly); a clarity dimension (clear-hazy); a security dimension (gentle-violent, safe-dangerous); a relaxation dimension (relaxed-tense);

a familiarity dimension (familiar-strange); and a mood dimension (colorful-colorless). These dimensions relate to the overall spectral patterns of the sounds, their temporal pattern of spectral changes, and their rhythmic structure. These examples of possible dimensions are not meant to be taken as <u>the</u> dimensions of auditory experience. Rather, these results are mentioned only to suggest the diversity of auditory experience and its description.

An approach to the verbal description of objects, events, and perception has been developed by Charles E. Osgood of the University of Illinois (Osgood, 1952). Subjects are allowed to rate objects, events, or stimuli along many dimensions as defined by pairs of adjectives in opposition. After statistical treatment, it is found that many of these dimensions are highly correlated. In general, an intensity dimension (weak-strong), an activity dimension (active-inactive), and an evaluative dimension (good-bad) emerge whether people are judging pictures, sounds, political ideals, or whatever. In addition, several special dimensions are usually isolated that are specific to the situation and the set of stimuli being judged.

Loudness and perceived noisiness are similar, but probably distinct, attributes of auditory experience. These dimensions in turn are correlated with many adverse effects of excess and unwanted sound. Indeed, loudness and noisiness are probably the most important dimensions of auditory experience in this regard. Other variables will undoubtedly be uncovered that are also of importance—the apparent extent in space may be an example.

But if we are to reach a stage where we wish to speak of an optimal acoustical environment, as opposed to a damaging or intolerable environment, we shall have to learn much more about the dimensions of auditory experience. Perhaps the techniques of Osgood and Solomon will lead to a better understanding of auditory experience and allow improved acoustical design. For example, it may be possible to design a vacuum cleaner that sounds "busy" and "active" without excessive loudness.

Section 5. ANNOYANCE AND COMMUNITY RESPONSE

Introduction

Annoyance by noise is a response to auditory experience. Annoyance has its base in the unpleasant nature of some sounds, in the activities that are disturbed or disrupted by noise, in the physiological reactions to noise, and in the responses to the meaning or "messages" carried by the noise.

The degree of annoyance and whether that annoyance leads to complaints, product rejection, or action against an existing or anticipated noise source are dependent upon many factors. Some of these factors have been identified and their relative importance has been assessed. Responses to aircraft noise have received the greatest attention. There is less information available concerning responses to other noises such as those of surface transportation and industry and those from recreational activities. Nonetheless, the principal factors controlling annoyance appear to be understood. Action by individuals or communities against noise sources or those responsible for the regulation of noise is not as well understood; but even in this difficult area there seem to be sufficient data to allow prediction of major trends.

A. How Annoyance and Community Response to Noise Are Studied

Case histories. Case history data are usually collected when there are complaints about particular noise sources. Often an acoustical consultant analyzes the problem. The consultant usually obtains the following kinds of information: (1) He measures the sound and tries to analyze how it is being generated by the source. (2) He interviews the involved people. (3) He establishes hypotheses concerning the "noise problem." (4) He suggests corrective action. If the corrective action is taken and the "problem" is eliminated or significantly reduced, he feels that the hypotheses were probably correct. Such case history data have contributed greatly to our understanding of the problem of noise.

Social surveys. The social survey is a more elaborate version of the case history. There are two kinds of social surveys. One can either study areas that are experiencing high levels of noise, or one can deliberately introduce a new source of noise, such as a sonic boom, and evaluate its effects on the community.

The tools of the field study are: (1) instruments for the measurement of the noise; (2) interviews and questionnaires; (3) records of complaints; and (4) statistical description of the measurements, whether they be of the noise or of the responses to it.

The appropriateness of social surveys have been discussed elsewhere (Borsky, 1970), and there are many difficulties. The mere presence of observers in a community as well as the way in which they present themselves can influence the response. The exact method of an interview and the construction of a questionnaire are also important. The measurement of the irregularly fluctuating noise levels within a community is also difficult. The measurement of both the noise and the responses to it require careful sampling methods and adequate statistical treatment of the resulting data.

In spite of all of these difficulties, the results of case histories and more formal social surveys appear to be in overall agreement concerning the major facts of annoyance and community response to noise.

B. Acoustical and Situational Factors

Acoustical factors. Annoyance from sound depends, in part, on the properties of the acoustical environment, and some of these properties were discussed in the previous section on Loudness, Perceived Noisiness, and Unacceptability. Included among these are: the intensity level and frequency content of the noise, the concentrations of energy in narrow regions of frequency (pitch), the duration of a noise, the period of initial rising intensity level, and the presence of impulses (such as those associated with gunfire, automobile backfires, hammering, and so on). These variables have been isolated in laboratory studies of judgments of single noise events in relatively controlled and quiet environments.

Other variables become obvious in social surveys or case histories where attention is usually focused on one kind of noise such as aircraft noise, and other noises are considered as part of the background noise. The definitions of the terms "noise" and "background noise" shift with the intent of the discussion. For example, if interest is focused on aircraft noise, then the noises of flyovers will be called "intruding noise" or "the noise" while other noises, such as those of surface transportation, household devices, and so on, would be grouped together as "background noise." It is interesting that when the "background noise" is great, then the annoyance attributed to a particular "intruding noise" may be less than when the same intruding noise appears against a lesser background noise. Field studies of annoyance and community responses to particular types of noises must include, therefore, direct or indirect measures of the number of repetitions of the "intruding noise," the level of the "background noise" from all other sources, and in one way or another the variability in the noise exposure from the combination of "intruding noises" and "background noises."

Further complications arise in field studies because the exposure that each individual receives is not measured. Rather, the noise is usually measured at some rationally selected monitoring point. For this reason, there are two other sets of acoustical variables that are crucial for an individual's response to sound. One set concerns the transmission path between the point where the sound is measured and the location of the exposed person. The other set of acoustical variables has to do with the acoustical characteristics of the exposed person's immediate environment.

Propagation of sound along a transmission path depends on many factors. The nature of the terrain, such as the sound-absorbing properties of its surface and whether it includes barriers which produce "sound shadows," are important. Weather conditions such as wind and thermal layering also influence the transmission of sound. Thus, an individual's exposure can only be predicted on a statistical basis from noise monitoring stations. An individual's exposure will depend on whether there is a building between him and the sound source, whether he is outside or inside, in which part of his dwelling he spends most of his time, whether windows are open or closed, the construction of his dwelling, and so on.

The acoustical properties of an individual's immediate environment are also important. In the exposed person's immediate environment, it is the intensity level of the background noise and the reverberant characteristics of the space that are crucial. For example, background noise can mask an intruding noise. The reverberant characteristics of the space have to do with its acoustical liveliness. For example, a room with heavy carpeting on the floor, cloth drapes, furniture covered with fabric, and walls and ceiling that absorb sound (either because of their construction or treatment with acoustical materials) is acoustically dead. Such a room is not reverberant. If the interior surface of a room is hard and acoustically reflective, sound within the room will "bounce around" for a long time. This is a reverberant room. Notice that the transmission loss from the point of measurement of the sound, the background noise, and the acoustical liveliness of the exposed person's immediate environment can operate separately and in different "directions." A "dead" room with many open windows provides little loss in the transmission path. A "live" room with thick concrete walls and no windows may provide a large attenuation in the transmission path, but sound that does penetrate the space will be frequently reflected within the room. Internally generated sound can vary the level of background noise, and so on.

It is not surprising, therefore, that measures of acoustical variables at the monitoring points are not successful in predicting each exposed individual's degree of annoyance or disturbance. However, as will be shown, measurements from monitoring points have been successful in predicting <u>average</u> levels of annoyance and disturbance among persons located near the point where the measurements are made.

<u>Relations between situational and acoustical variables</u>. It has been found that evaluation of intruding noises should include situational variables if annoyance, disturbance, and community responses are to be predicted. For example, the type of neighborhood makes a difference. For a fixed exposure, instances of annoyance, disturbance, and complaint will be greatest in number for rural areas, followed by suburban, urban, residential, commercial, and industrial areas, in decreasing order. Similarly, a given noise usually will be more disturbing at night than during the day. Seasonal variations have also been noted; noise is more disturbing in summer than in winter.

Some of the situational factors that are correlated with annoyance by noise may be related to the attitudes and activities of people in these various locations and at different times of the day or year. But it is also plausible that these situational variables directly influence the noise exposures that people actually receive. Background noise levels vary in an appropriate manner with type of neighborhood and with the time of day; that is, it is generally quieter in a rural than in an industrial area, and it is often quieter at night than during the day. Also, there are fewer acoustical barriers in rural than urban areas. There are fewer acoustical barriers between the people and the point of mearsurement in summer than in winter. This is true because in summer more often than in winter people are likely to be outdoors or, when indoors, to have their windows open.

Physical measurements of noise exposure. From the previous discussion, it should be obvious that annoyance, disturbance, and complaints cannot be predicted simply by measurement of the sound emitted by a single source. Furthermore, it should be obvious that measurements from noise monitoring stations cannot be expected to predict the responses of particular individuals.

A variety of methods have been proposed for the measurement of community noise or noise due to particular sources, such as aircraft, traffic, and so on. The array of methods and their names, usually given by initials, is bewildering to the uninitiated and the experienced specialist alike. There are CNR, NNI, NEF, TNI, NPL, CNEL, and even more. However, in general, these measurement schemes are more alike than they are different. Each includes several of the following factors: (1) a scheme for the identification of single noise "events;" (2) allowance for the intensity levels and durations of the noise events; (3) allowance for the number of noise events; (4) allowance, either direct or indirect, for the intensity levels of the background noise; (5) allowance for the variability of the intensity levels of the noises; and (6) allowance for one or more special factors related to the loudness or perceived noisiness of the noises. As previously discussed, situational factors such as season, time of day, and type of area often are included as corrections on the acoustical measurements.

The measure of community noise exposure suggested by Dr. D. W. Robinson of England (Robinson, 1971) may have special merit. This measure, called the noise pollution level (NPL), is conceptually simple. Furthermore, it seems to incorporate some of the same basic features as does the adaptation-level theory developed by Helson (1964). Adaptation-level theory deals with human reactions to and judgments of stimuli. Helson supposes that responses to stimuli are controlled by the focal properties of the stimuli and their variation from an adaptation level. The adaptation level is determined by the background levels of stimulation and the residual effects of previous and other incidental stimulation. When a variable such as perceived noise level is used in conjunction with Robinson's noise pollution level this measure seems to take into account the focal properties of the stimulus as well as the difference between the stimulus and the adaptation level as established by the background stimuli.

Since Robinson's noise pollution level was so recently proposed, there has not been sufficient time to evaluate its effectiveness as a predictor of human responses to noise.

C. Annoyance, Attitudes, and Disruption of Activities

Annoyance and noise. Annoyance as measured in field studies is distinct from judgments of loudness, perceived noisiness, and unacceptability. Annoyance, as described at the beginning of this section (Section 6), is a response to noise rather than a dimension of auditory experience. A variety of techniques have been used to measure the annoyance that results from noise. The most direct is simply to ask a person to categorize his degree of annoyance. "Rate your annoyance from one to seven where one is 'no annoyance' and seven is 'extremely annoyed'." In general, direct ratings have been found to be subject to a great many biasing influences especially in studies of attitudes. In the case of annoyance by noise, however, such direct ratings correlate very highly with more subtle and indirect measures, and the complicated procedures developed for the study of general attitudes may not be necessary for investigations of annoyance by noise (McKennel, 1970).

Indirect measures are obtained by asking a person about the kinds of activities that are disturbed by noise and about the degree of the disturbance. Total annoyance is calculated from a combination of the number of activities disturbed and the degree to which they are disturbed (Tracor Staff, 1971). For example, persons may be asked to rate the degree of disturbance by noise for: TV/radio reception, conversation, telephone use, relaxing outside, relaxing inside, listening to records or tapes, sleeping, reading, and eating. The degree of annoyance might then be taken as the sum of the ratings of the degree of disturbance (Tracor Staff, 1971).

Annoyance by noise depends in part on the characteristics of the noise itself, and typical results are illustrated in Figures 18 and 19. These graphs support the contention that the average degree of annoyance among people in an area can be predicted from the characteristics of the noise measured at an appropriately selected monitoring point. Nonetheless, reported annoyance also depends on other attitudinal-psychological factors.

Annoyance and attitudes. There are several attitudinal-psychological factors which correlate with the degree of scaled annoyance. These can be classified under: (1) general attitudes toward noise including differences among individuals in their sensitivity to noise; (2) attitudes of the exposed person toward the source of noise, such as whether they consider the noise-producing activity to be important for their social and economic well-being and whether they believe that the noise is a necessary by-product of the activity that produces it; (3) whether they believe that those persons responsible for the operation and regulation of the noise-producing activity are concerned about their (the exposed population's) welfare; and (4) factors specific to particular noise sources, such as fear of aircraft crashes or the belief that sonic booms cause property damage.

For example, highly annoyed persons are likely to believe that those responsible for the noise are not concerned about those being exposed to the noise, and they are also likely to believe that the source of noise is not of great importance to the economic and social success of the com-

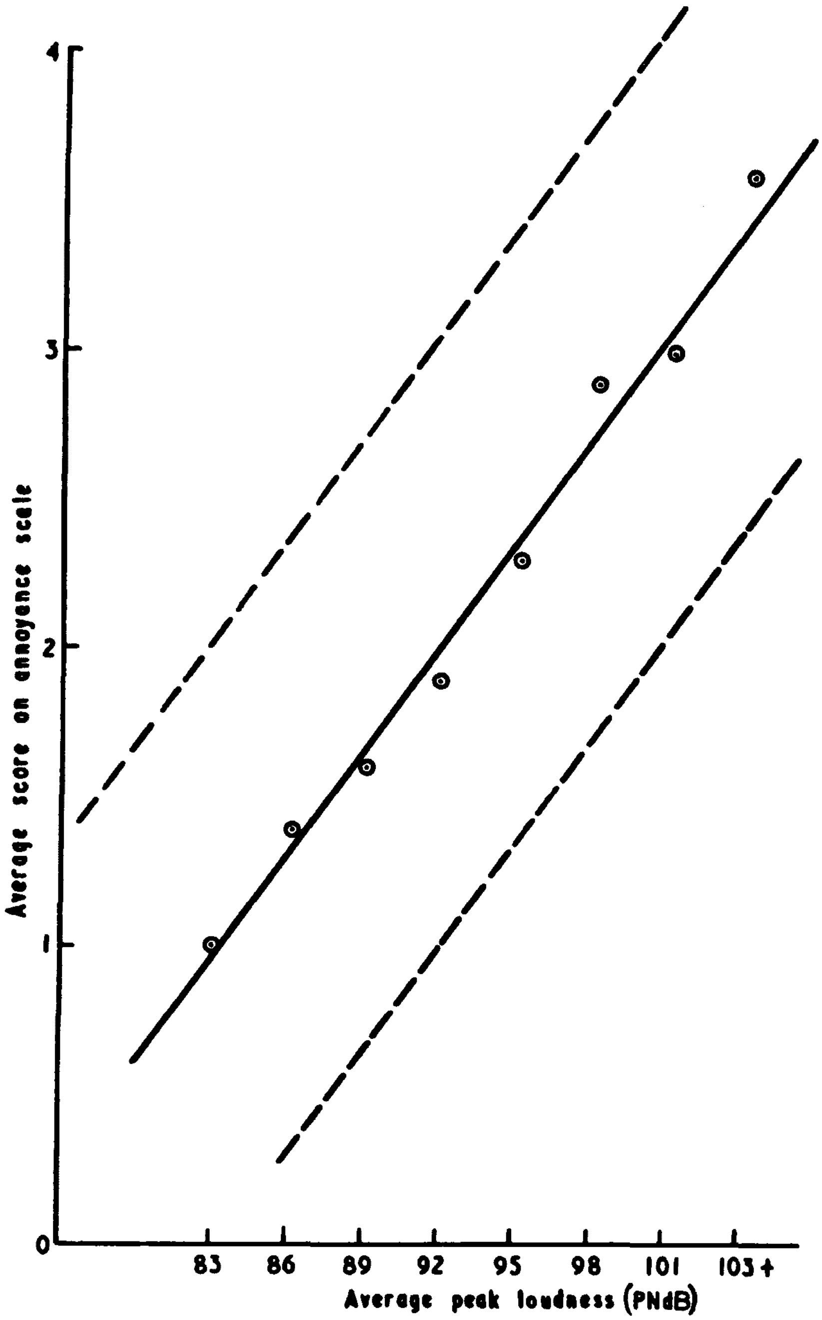

Figure 18. Average scores on an annoyance scale for persons exposed to various levels of aircraft noise are shown. The dashed lines include two-thirds of the persons interviewed. (From McKennel, 1970, with the permission of the author, editor, and the University of Washington Press.)

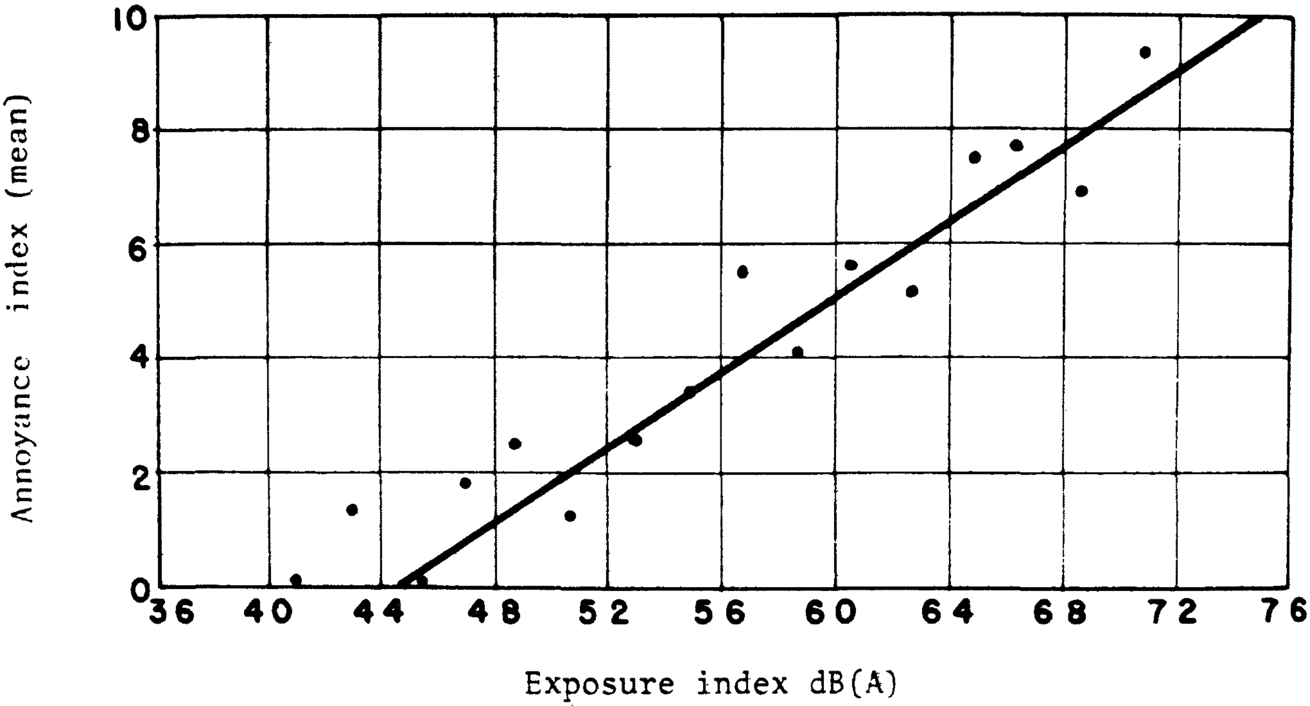

Figure 19. Average annoyance scores for persons exposed to various levels of traffic noise are shown. Notice that the scales on Figures 18 and 19 cannot be compared for absolute magnitudes. (From Kajland, 1970, with the permission of the author, editor, and the University of Washington Press.)

munity. In addition, highly annoyed persons are: likely to have negative attitudes toward many kinds of noise; likely to be generally sensitive to irritation produced by noise; likely to believe that their neighbors share their annoyance; likely to say that they would be unwilling to accept further increases in noise levels; and likely to believe that noise is a health hazard. People highly annoyed by the noise of sub-sonic aircraft are likely to express a fear of a crash in their neighborhood, whereas people highly annoyed by sonic booms are likely to believe that these booms cause property damage. Such statements are based on statistical relations and many highly annoyed people do not conform to the profile given above.

The examples of characteristics of highly annoyed persons were abstracted from several sources (Borsky, 1970; Kryter, 1970; McKennel, 1970; Tracor Staff, 1971; and references cited therein). Unfortunately, when one tries to compare social surveys, he finds that the exact attitudinal-psychological variables that emerge as most prominent vary from study to study. Such variation is to be expected because of differences in the methods, the sampled populations, and the noises.

A recently published survey of responses to the noise of sub-sonic aircraft (Tracor Staff, 1971) reports that an individual's level of annoyance as measured by interview-questionnaire techniques can be fairly accurately predicted if one knows the noise exposure (measured at a community monitoring point) and the weights to assign to seven attitudinal-psychological factors. These factors, ranked in order of predictive power, are: (1) the fear of aircraft crashes; (2) the susceptibility of the individuals to other noises, such as banging doors, dripping water, and so on; (3) the distance from the airport; (4) the willingness of the individual to accept additional increases in noise exposure from aircraft; (5) city of residence; (6) the extent to which residents of the community believe that they are being treated unfairly; and (7) the attitudes of the residents with respect to the importance of the airport and air transportation. Most of these factors can be placed into the four general classes described at the beginning of this subsection. However, exactly why "distance from the airport" and "city of residence" should be important is unexplained.

It is also interesting to contrast responses to sonic booms with responses to the noise of sub-sonic aircraft. There is some indication that annoyance from sonic booms may be most related to the physiological and psychological responses to the suddenness of the booms, whereas annoyance from the noise of sub-sonic aircraft may be more strongly related to the activities disturbed by the noise (Tracor Staff, 1971). The major attitudinal factor that contributes to annoyance by sonic booms is the belief held by many people that booms cause property damage, while the major attitudinal factor that contributes to annoyance by the noise of sub-sonic aircraft is the fear of aircraft crashes.

All of the above is convincing evidence that people's responses to noise depend on their values, beliefs, and attitudes. This is not surprising, for the definition of noise as an unwanted sound is a statement of an attitude and a value judgment. Some researchers have gone so far as to state that the attitudinal-psychological factors are more important for predicting annoyance (by noise) than are the properties of the noise itself. But individuals' exposures to noise, as opposed to community exposure measured at a monitoring point, have never been measured in these social surveys. Also, if the noise were not present, then the attitudinal-psychological factors could not operate. Thus, one must return to the sound itself as the fundamental stimulus for the annoyance from noise.

Examples of activities disturbed by aircraft and traffic noises as measured in social surveys. Two recent studies (Tracor Staff, 1971; Griffiths and Langdon, 1968) report activities disturbed by sub-sonic-aircraft and traffic noise. In the Tracor study (Phase I) people were interviewed in an area with a radius of 12 miles and within an angle of 40° to the right and left of the end of a runway. These runways were in the major airports near Chicago, Dallas, Denver, and Los Angeles. Of 4,153 persons interviewed, 98.6% reported one or more disturbances of daily activities by aircraft noise, and, correspondingly, at least some degree of bother. The percentage who rated an activity as extremely disturbed were as follows: TV/radio reception, 21%; conversation, 15%; telephone use, 14%; relaxing outside, 13%; relaxing inside, 11%; listening to records or tapes, 9%; sleep, 8%; reading, 6%; and eating, 4%. In the study of Griffiths and Langdon, people indicated that traffic noise disturbed sleep, conversation with visitors, conversation at mealtimes, TV and radio reception, and increased the time for children to fall asleep.

Of course, these examples of disturbed activities are based on responses to interviews and questionnaires. These lists are neither complete nor do they necessarily reflect the true ranking of activities disturbed by noise. For example, the interference with formal education in schools, mentioned in Section 2, does not appear on these lists probably because only adult residents of an area were interviewed. Also, the person being interviewed is not necessarily aware of all the ways in which noise may disturb his activities.

Adaptation to noise. There is little evidence that annoyance due to community noise decreases with continued exposure. Rather, under some circumstances annoyance may increase the longer one is exposed to it (Borsky, 1970).

D. Community Response

There are ample data to show that community responses to aircraft noise are related to measures of the exposures. Typical results are shown on Figures 20 and 21. These graphs speak for themselves and clearly show that community response can vary from indifference and mild annoyance to highly organized community action. Complaints such as letters or telephone

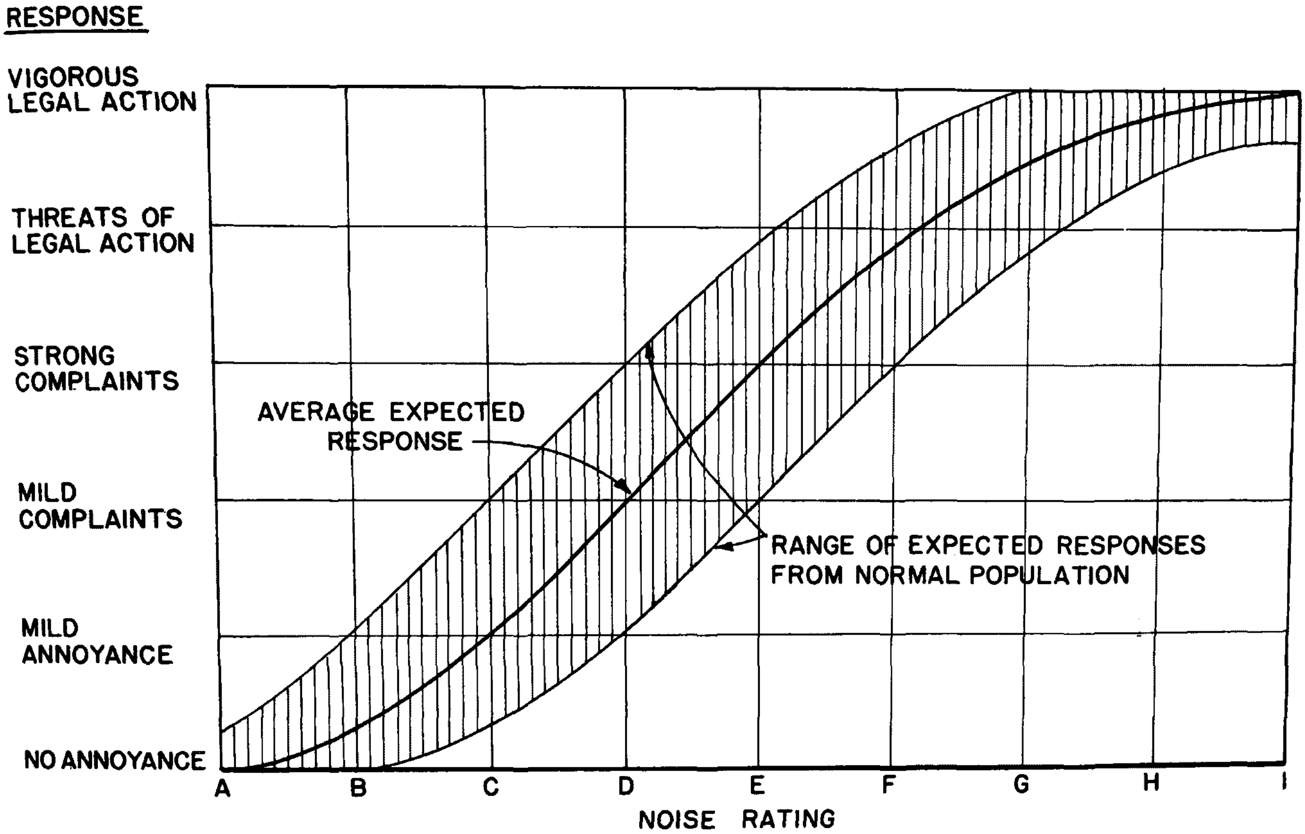

Figure 20. The relation between community response and noise exposure is shown. The noise exposure increases from A to I. (From Rosenblith et al., 1953.)

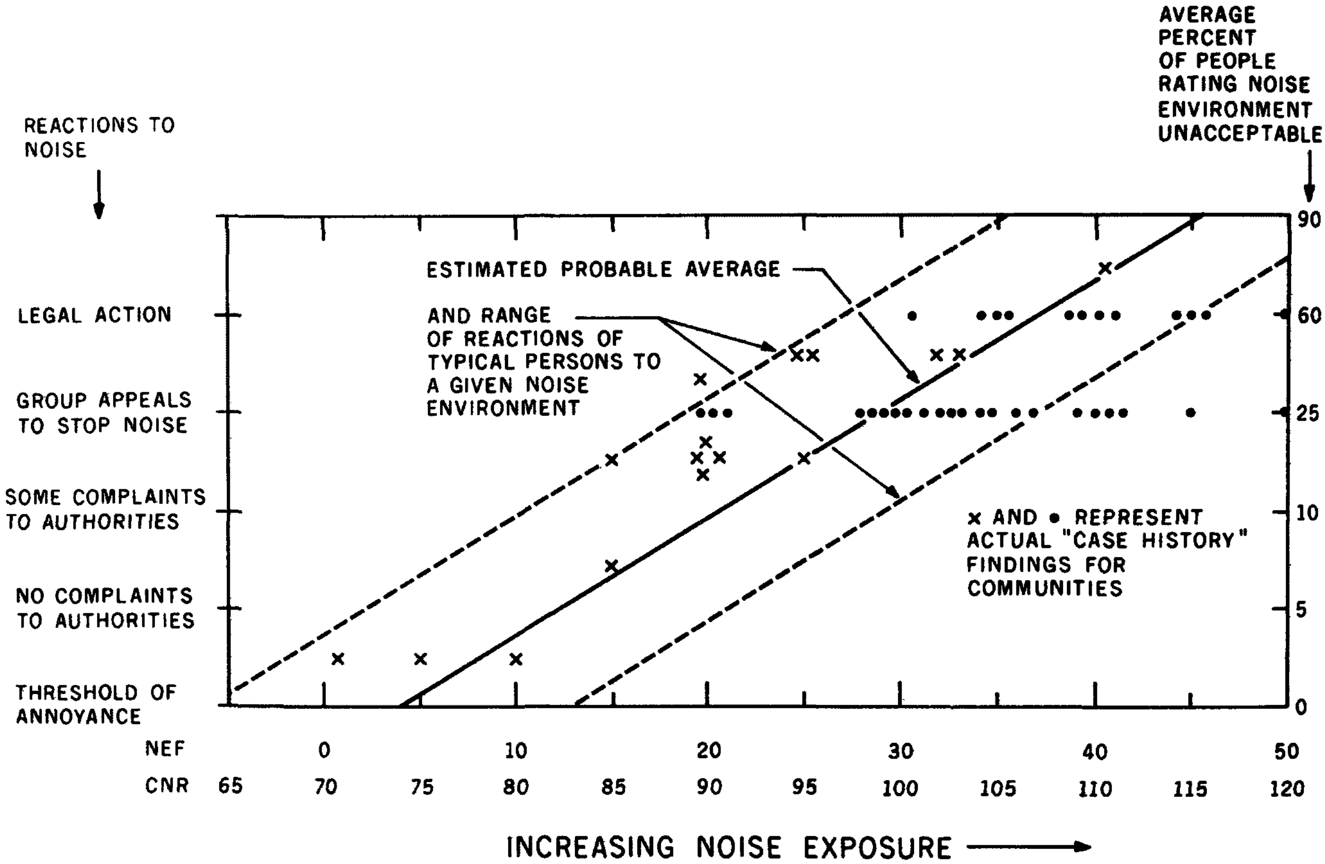

Figure 21. Relations between community noise levels (measured in CNR or NEF), judgments of unacceptability, and community responses are shown. (After Kryter et al., 1971.)

calls to relevant officials and community action are determined by much more complicated sets of circumstances than are annoyance and disturbance of activities. It has been shown, however, that those who complain are not necessarily highly annoyed by noise. In spite of intensive efforts (one study included as many as 17 sociological variables such as age, socio-economic status, and so on), there has been little success in identifying and characterizing those who complain as opposed to those who do not.

It is clear, however, that only a small percentage of those who are highly annoyed or disturbed actually register a formal complaint to some authority in the form of a letter or a telephone call. For example, it was found (Tracor Staff, 1971) that in an area with high noise levels, the number of highly annoyed households per thousand (h) can be predicted from the number of complaints per thousand (c) in the area by the simple equation,

$$h = 196 + 2c.$$

By simple calculation, if there are 200 persons who complain in a tract of 1,000 households, there will be nearly 600 highly annoyed households! This equation, however, probably holds only for a given set of sociological and political circumstances. Annoyance is probably a good measure of the potential for complaint and action. Whether complaints or anti-noise actions actually develop will depend on social and political factors such as the presence of anti-noise leadership, attitudes toward the source of noise or regulatory agents, and so on. These last-mentioned factors are only a few of the factors which make up the whole of community dynamics. These community dynamics, which are poorly understood, very strongly control anti-noise actions.

Examples of the complexities of community response are given by the following two case histories.

Case History A. The noise source was a positive displacement blower within three hundred feet of an apartment house. The sound levels were sufficiently high to cause the pure tone generated by the blower to be heard clearly along the face of the three-story apartment house during the day, and to be well above the ambient sound level at night. The industrial plant and the apartment house were over one thousand feet from a main truck route through the suburb of a major eastern city. The noise produced by the blower was inaudible halfway to the highway because of the shielding of buildings and distance. However, the neighbors of the plant and those living along the highway had joined together as a neighborhood association to fight the industrial plant on the noise issue. The residents within five hundred feet of the highway, all owners of private dwellings, were unable to hear the plant noise, but appeared to have joined with the other members of the community, the apartment dwellers, to fight the "noise problem" even though they could not hear the noise at their homes. Investigation of the situation showed that a traffic hazard problem existed for the community along the highway and that a death had occurred because of the hazardous conditions. The investigation further showed that the identifiability of the owner of the noise source and the focus of the community effort on the noise problem served as an outlet for their frustrations. This in turn caused a community response out of proportion to the actual number of people exposed.

Case History B. The community was complaining to local officials and to the industrial plant of mechanical vibrations shaking their homes. The vibrations ostensibly originated in a new railroad-car-shaker building in which heavy duty vibrators were attached to railroad cars in order to shake the contents loose during their transfer from the hopper car to a plant conveyor. The neighbors were located 300 to 500 feet from the car shaker. Measurement of the vibrations in the earth at various distances from the car-shaker facility indicated that at distances beyond 50 feet, no vibrations were detectable, indicating levels well below 0.01g. Measurement of the airborne sound levels at the neighboring residences showed levels of 64 dB(A), and in the octave band centered at 31.5 Hz of 80 decibels. This results in mechanical forces at the face of the residences sufficiently large to cause the walls of the houses to vibrate with amplitudes of 0.1 inch. The low-frequency noise in the air is inaudible to all but a well-trained listener. However, the result of the shaking wall is a rattling sound, and this higher frequency sound is readily associated by the residences with the plant operation. It should be pointed out that the neighbors are exposed to broad-band noise levels from the plant in the neighborhood of 58 dB, which have in the past produced no complaints. Elimination of the low-frequency radiation from the shaker building eliminated complaints.

(These case histories were provided by Goodfriend-Ostergaard Associates of Cedar Knolls, New Jersey.)

E. Concluding Statement

Community noise exposure can be measured and summarized. There are a variety of competing methods that take into account at least some of the following, not necessarily independent, factors: (1) a scheme for identification of noises; (2) the intensity levels and durations of identifiable noise events; (3) number of occurrences of the noise events; (4) the background noise level; (5) the variability of the noise levels; (6) one or more special factors related to the perceived noisiness or loudness of the sounds; and (7) the time of day and type of area, whether urban, suburban, rural, and so on. While efforts to standardize and refine these measurements will and should continue, many of the important variables have been identified and methods for the measurement have been developed. Of course, these methods cannot accurately measure any single person's exposure to noise.

The degree of annoyance averaged over a large number of individuals near a noise monitoring station can be predicted, in a statistical sense, from the physical characteristics of the noise. Each individual's degree of annoyance cannot be as accurately predicted as can the average annoyance. This is true because individuals differ considerably in the exact noise exposure they receive (due to variations in environmental acoustics), because individuals differ in their sensitivity to disturbance by noise, and because individuals differ in other relevant psychological and social attitudes.

Community responses to noise can range from indifference and mild annoyance to highly-organized group action. Those who complain about aircraft noise cannot be identified as having a special set of psychological and sociological characteristics. Those who complain about aircraft noise, contrary to the beliefs of some, are not highly sensitive to noise they do not seem to be, in general, unusual citizens. Nevertheless, total numbers of complaints and community anti-noise action are correlated with measures of the severity of the noise exposure.

While community responses to aircraft noises have been more thoroughly studied than the responses to other noises, such as those of traffic and construction, case histories reveal that people become annoyed and they complain about a wide variety of noises. In addition to noise exposure, psychological and sociological considerations modify the extent of the annoyance and the inclination to complain. Case histories also reveal that, regardless of whether the noise is produced by traffic, aircraft, construction and so on, the probability of overt action against the noise producers or regulators can be estimated from knowledge of the noise exposure. However, these estimates are fallible and numerous exceptions can be cited.

Two speculations about possible future community actions may be worthy of note. Right or wrong, these speculations serve to illustrate how attitudes and beliefs might combine with actual exposure to noise to influence anti-noise actions.

In a recent survey, members of a sample of about 8,200 people who live within 12 miles of airports in seven major cities of the United States were asked whether they would be able to accept increases in noise exposure from aircraft operations. Fifty-four percent replied that they could <u>not</u> (Tracor Staff, 1971). This, coupled with the fact that fear of aircraft crashes strongly enhances the annoyance produced by aircraft noise, leads to the speculation that substantial increases in aircraft traffic along with a few crashes in populated areas could result in vigorous community action against aircraft operation and those responsible for its regulation.

A second speculation is this. If members of a community believe that noise is necessary to an approved activity and if they believe that people are free to move away from the noise, then they will be less likely to institute or support action against the source of noise than if they disapprove of the activity or believe that there is no freedom to move so as to escape the noise. If this speculation is correct, then perhaps an increase in the total area or number of persons exposed to annoying levels of noise would result in an increase in support for anti-noise actions.

One fact about the relations among perceived noisiness, annoyance from noise, disturbance of activities by noise, complaints about noise, and community actions against noise is especially significant. It is that noisiness, annoyance, and disturbance of activities are more closely tied to the physical characteristics of the noises than are the rates of formally placed complaints or the probabilities of group anti-noise action. Thus, whether or not one files a formal complaint or participates in group anti-noise action, the quality of one's life is influenced by unwanted sound.

Section 6. OTHER POSSIBLE PSYCHOLOGICAL AND SOCIOLOGICAL EFFECTS

An Old Story

Scene. It is a courtroom in a rural area. There is a judge on the bench and a defendant before him. The defendant is about 50 years old, poor, and uneducated, but well-known and well-liked in the community.

Judge. "You are charged with stealing chickens from Brown's coop. There is a strong case against you. I advise you to plead guilty, and we'll try to make it as easy for you as possible. How do you plead?"

Defendant. "Not guilty, Judge."

Judge. "Aw, don't do that. It'll just cause us all a lot of trouble. The prosecutor has ten witnesses who saw you stealing those chickens."

Defendant. "That's nuthin' Judge, I have twenty witnesses who didn't."

Introduction

There have been numerous claims about many deleterious psychological and sociological effects of noise on man. Many of these are difficult to evaluate because of conflicting information (ten people saw them and twenty didn't)—or because of lack of information (nobody looked). In many cases, firm conclusions cannot be drawn and one must rely on one's experience, intuition, and judgment, as well as upon published data in order to reach a tentative conclusion.

Even the selection of the claims to be discussed requires a considerable degree of arbitrary judgment. The areas discussed in this section were selected on the basis of the amount of available information and on the basis of judgments concerning plausibility, importance, and interest. No more could be done.

A. Noise and Performance

The action of noise on the performance of tasks has been studied extensively in the laboratory and in actual work situations. Excellent summaries and reviews of these studies are available (Broadbent, 1957; Burns, 1968; Cohen, 1969; Kryter, 1970; Kryter *et al.*, 1971).

When a task requires the use of auditory signals, speech or nonspeech, then noise at any intensity level sufficient to mask or interfere with the perception of these signals will interfere with the performance of the task.

When mental or motor tasks do *not* involve auditory signals, the effects of noise on their performance have been difficult to assess. Human behavior is complicated and it has been difficult to discover exactly how different kinds of noises might influence different kinds of people doing different kinds of tasks. Nonetheless, certain general conclusions have emerged. (1) Steady noises without special meaning do not seem to interfere with human performance unless the A-weighted noise level exceeds about 90 decibels. (2) Irregular bursts of noise are more disruptive than steady noises. Even when the A-weighted sound levels of irregular bursts are below 90 decibels, they may sometimes interfere with performance of a task. (3) High-frequency components of noise, above about 1000-2000 hertz, may produce more interference with performance than low-frequency components of noise. (4) Noise does not seem to influence the overall rate of work, but high levels of noise may increase the variability of the rate of work. There may be "noise pauses" followed by compensating increases in work rate. (5) Noise is more likely to reduce the accuracy of work than to reduce the total quantity of work. (6) Complex tasks are more likely to be adversely influenced by noise than are simple tasks.

It has been and will continue to be difficult to assess the effects of noise on human performance. Laboratory studies are usually of short duration and the subjects are usually well-motivated young adults. These subjects may be able to perform without decrement in noises that might influence performance under more "everyday" conditions. Studies of the effects of noise in actual work conditions are difficult because factors other than the noise itself are difficult to control.

Even when a person maintains high performance in noise as opposed to quiet, there may be a cost. This cost might include reduced psychological or physiological capacity to react to additional demands and increased fatigue after completion of the task (Finkelman and Glass, 1970; Glass _et al_., 1969; Glass _et al_., In press).

The effects of noise on human performance are often conceptualized in terms of three classes of effects: (1) arousal; (2) distraction; and

(3) specific effects. Arousal of bodily systems including the musculature can result in either detrimental or beneficial effects on human performance. The direction of the effect will depend on the nature of the task and on the person's state prior to exposure. For example, noise might induce muscular tension that could interfere with delicate movements. On the other hand, a sleepy person might be aroused by noise and, therefore, may perform more effectively in noise than in quiet. Distraction can be thought of as a lapse in attention or a diversion of attention from the task at hand. Often distraction is due to the aversive or annoying characteristics of the noise. Distraction can sometimes be related to the physiological responses to noise or to the responses to messages carried by the noise. Also, if the noise is sufficiently intense, it may somehow "overload" the mental capacities and result in a momentary lapse in attention or "mental blink." Specific effects include auditory masking, muscular activation such as startle responses to brief intense noises (sonic booms, backfires, etc.) and the like.

Many physiological and psychological responses to sound diminish or disappear when noises are regular or predictable. Sometimes strategies can be learned so that the detrimental effects of noise on performance can be avoided. Under certain conditions noise may even result in better concentration due to auditory isolation provided by the noise's masking of other sounds, greater activation and alertness of the worker, or pace performance when the noise is regular or rhythmic. For these reasons, people sometimes achieve excellent performance or even exceed their normal performance in spite of noise.

Noises, however, often are not regular and predictable, adaptation of responses to noise is not always complete, and strategies to eliminate the effects of noise are not always learned. Furthermore, the fact that distraction or disturbance can be the result of the "message" carried by the noise rather than a result of the noise, per se, may not seem important to the average person. An ideal acoustical environment is one that does not disturb human performance either because of the properties of the noise itself or because of irrelevant messages carried by the noise. The trick, of course, is to eliminate disturbing noises while maximizing the chances that important, relevant messages carried by sound will reach the appropriate party.

B. Acoustical Privacy

Without opportunity for privacy, either everyone must conform strictly to an elaborate social code, or everyone must adopt highly permissive attitudes. Opportunity for privacy avoids the necessity for either extreme. In particular, without opportunity for acoustical privacy one may experience all of the effects of noise previously described and, in addition, one is constrained because his own activities may disturb others (Cohen, 1969). Without acoustical privacy, sound, like a faulty telephone exchange, often reaches the "wrong number."

It would be helpful for owner and renter and for seller and buyer if standardized acoustical ratings were developed for dwellings. These ratings might include measures of acoustical privacy as well as other measures of acoustical quality. Such ratings would be particularly useful because the acoustical properties of a dwelling are not immediately obvious to the nonspecialist. If such ratings were available, the parties involved could balance the acoustical value of a dwelling in relation to those of appearance, size, convenience, cost, and so on.

C. Time Judgments

Steady noise with an A-weighted sound level up to about 90 decibels seems to expand the subjective time scales; that is, less time has been judged to pass than actually has (Hirsh *et al*., 1956).

Steady noise more intense than about 90 decibels seems to contract subjective time; that is, more time is judged to pass than actually has (Jerison and Arginteanu, 1958).

D. Effects on Other Senses

A variety of effects of auditory stimulation on the other senses have been reported. These are called intersensory effects. Subtle intersensory effects may occur as part of normal psychological and physiological function. At very high noise levels, more dramatic intersensory effects have been reported. For example, there can be disturbances of equilibrium at levels of about 130-150 decibels (Anticaglia, 1970; Kryter, 1970; and von Gierke, 1965). Dramatic intersensory effects would not occur in response to current levels of community noise.

E. Mental Disorders

There is no definitive evidence that noise can induce either neurotic or psychotic illness. There is evidence that the rate of admissions to mental hospitals is higher from areas experiencing high levels of noise from aircraft operations than in similar areas with lower levels of noise. The type of person most affected appears to be the older woman who is not living with her husband and who suffers from neurotic or organic mental illness (Abey-Wickrama *et al.*, 1969). These authors did not believe that aircraft noise *caused* mental illness, but their tentative conclusion is that such noise could be a factor that increases admissions to psychiatric hospitals.

F. Anxiety and Distress

Nausea, headaches, instability, argumentativeness, sexual impotency, changes in general mood, general anxiety, and other effects have all been associated with exposure to noise (Andriukin, 1961; Cohen, 1969; Davis, 1958; Jansen, 1959; and Shatalov *et al.*, 1962).

These effects are difficult to assess because intense noises are often associated with situations that in and of themselves, even without noise, might involve fear and stress. Whether the noise, purely as noise, contributes significantly to the stress of life (see PART III) is difficult to assess at this time. But all of the facts of speech interference, hearing loss, noisiness, annoyance, and arousal and distraction previously recited clearly support the contention that noises can act as a source of psychological distress, either because of responses directly to the noise itself or because of responses to irrelevant "messages" carried by the sound. Psychological distress in turn can contribute to the unpleasant symptoms listed above.

PART III. GENERAL PHYSIOLOGICAL EFFECTS

Preliminary Statement

There are three classes of <u>transient</u> general physiological responses to sound: (1) the fast responses of the voluntary musculature mediated by the somatic nervous system; (2) the slightly slower responses of the smooth muscles and glands mediated by the visceral nervous system; and (3) the even slower responses of the neuro-endocrine system.

It has been proposed that frequent repetition of these responses might lead to <u>persistent</u> pathological changes in non-auditory bodily functions (Jansen, 1959, 1969). Also, it has been proposed that frequent repetition of these transient physiological responses might aggravate known disease conditions. These proposals have not been verified, but evidence consistent with them has been gathered (Kryter *et al.*, 1971; von Gierke, 1965). While these claims of noise-induced pathology of non-auditory bodily function merit further research and investigation, they are as of now unproven.

The transient physiological responses to sound, the possible persistent physiological responses to sound, and the possible relation of noise to stress theory are each discussed in the sections that follow.

Section 7. TRANSIENT AND POSSIBLE PERSISTENT PHYSIOLOGICAL RESPONSES TO NOISE

A. Transient Physiological Responses to Noise

<u>Responses of the voluntary musculature</u>. Man is equipped with an elaborate set of auditory-muscular reflexes. These serve the basic

functions of orienting the head and eyes toward a sound source and of preparing for action appropriate to an object whose presence is signalled by a sound. These reflexes operate even at low levels of sound (Bickford _et al._, 1964; Davis, 1950; Mast, 1965), and they can often be detected by suitable electrical recording and averaging even after bodily movements have habituated and are no longer detectable. Auditory-muscular reflexes undoubtedly play a part in all muscular responses to sound. These may range from rhythmic movement and dance to the body's startle response to impulsive sounds such as those produced by gunshots or sonic booms.

These muscular responses to sound can be measured by direct observation of bodily movements (sometimes with the aid of amplifying levers or high-speed motion pictures) or by measurements of the electrical activity of the musculature.

The startle response has been studied in detail (Landis and Hunt, 1939). It includes an eyeblink, a typical facial grimace, bending of the knees, and, in general, flexion (inward and forward) as opposed to extension of the bodily parts. The startle response to the sound of a nearby gunshot, even when expected, may undergo various degrees of diminution with repetition of the sound. The amount of diminution of the response depends on the individual, the rate of repetition, and the predictability of the impulse sound. Some individuals show little diminution of the startle response with repetition while others show a marked reduction of this response. The eyeblink and head movement aspects of the startle response may never habituate completely. Even experienced marksmen exhibit these responses each time they fire a gun.

All of the observations described in the preceding paragraph were made with the aid of high-speed motion pictures. Using the electrical devices available to them, Davis and Van Liere (1949) found that muscular responses to the sound of a gunshot did not disappear with repetition. An early response (the a-response with a latency of about 0.1 second) showed little reduction with repetition of the sound. A later response (the b-response with a latency of about 0.8 second) showed more reduction with repetition.

A series of experiments, done by R. C. Davis and his colleagues at Indiana University, demonstrated that the particular muscular responses to sound and the way in which these responses will influence the performance of a motor task depend in detail on (1) the pattern of muscular tension, or posture, prior to the sound, (2) the movements required by the task, and (3) the auditory-muscular reflexes (Davis, 1935, 1942, 1948a, 1948b, 1956a, 1956b, 1956c, 1956d, 1956e; and Patton, 1953).

Among the important findings was that the magnitude of the muscle-tension reflex in response to sound increased with increasing resting tension in the muscle. (This generalization, of course, would not hold as a muscle approaches its maximum level of tension.) Thus, if the subject was required to make a movement that required flexion and if the subject's posture heightened tension in the appropriate flexor muscle, then a burst of sound, which ordinarily produces the reflex action of flexion, would speed the performance of the movement. Under other conditions, however, the burst of sound could greatly interfere with the required movement. For example, suppose that as before, the required movement was that of flexion but that the subject's posture heightened the resting tension in the opposing extensor. In this case, the burst of sound would result in a greater response in the extensor (because of the higher resting tension) than in the flexor, and consequently, the required flexion response would be interfered with and delayed.

R. C. Davis (1956b, 1956d) also found that steady noise of 90 decibels increased tension in all muscles and influenced the response time in a simple choice task.

In summary, the ebb and flow of muscular activity is closely linked to and influenced by the rise and fall of sound. The relations are complicated. Gross bodily orientation toward an unexpected source of sound will diminish as the sound becomes familiar and predictable. Some components of the startle response to impulse sounds, for instance, will diminish with the repetition of the stimulus. The exact amount of reduction, however, depends on the individual person, his state of muscular tension as defined by posture or activity, and the characteristics of the impulse sound. Subtle changes in the musculature in response to sound may persist and their effects will depend in a complicated way on posture, activity, and the characteristics of the sound.

Responses of the smooth muscles and glands. In response to brief sounds there is general constriction in the peripheral blood vessels with a reduction in peripheral blood flow. There may be acceleration or deceleration of heart rate, reduction in the resistance of the skin to electrical current (an indication of activation of the peripheral visceral nervous system), changes in breathing pattern, changes in the motility of the gastro-intestinal tract, changes in the size of the pupils of the eyes, and changes in the secretion of saliva and gastric secretions (Davis et al., 1955; Jansen, 1969). These responses to brief sounds are obvious for A-weighted sound levels over about 70 decibels. For sound levels below 70 decibels, it is doubtful whether the recording techniques have been sufficiently sensitive to detect whether these responses occur. In any case, they are either small or nonexistent.

Some aspects of these responses diminish and seem to disappear with predictable repetition of the sounds. Others may not disappear (Davis et al., 1955). Jansen (cited by von Gierke, 1965), for example, found these responses persisted in industrial workers when they were exposed to the same noises in which they had worked for many years.

Orienting and defense reflexes. Some of the responses of the smooth muscles and glands to sound are part of a pattern of response known as the orienting reflex. The orienting reflex is a "what is it" response, and this reflex diminishes rapidly as a stimulus becomes familiar and predictable.

Some of the responses of the smooth muscles and glands in response to sound are part of a pattern of response known as the defense reflex. A defense reflex prepares the organism to escape or accept injury and discomfort. Responses that are part of a defense reflex disappear more slowly with stimulus repetition than do those that are part of the orienting reflex. Sometimes they may never completely disappear. Defense reflexes occur in response to warnings of painful stimuli, to painful stimuli themselves, or in response to very intense stimuli to any sense organ. Informative discussions of the orienting and defense reflexes can be found elsewhere (Sokolov, 1963a, 1963b; Voronin et al., 1965).

Neuro-endocrine responses. Loud sounds as well as other intense stimuli such as cold, forced immobilization, forced exercise, pain, injuries, and so on can activate a complicated series of changes in the endocrine system with resulting changes in hormone levels, blood composition, and a whole complex of other biochemical and functional physiological changes (Lockett, 1970; Welch and Welch, 1970). Some of these changes and their implications will be mentioned in the sections to follow.

B. Possible Persistent Physiological Responses to Noise

It has been claimed that steady noise of approximately 110 decibels can cause some changes in the size of the visual field after years of chronic exposure, but there is very little evidence to support this contention. Noise of about 130 decibels can cause nystagmus and vertigo. However, these noise conditions are rarely encountered in the present environment (Kryter et al., 1971).

Evidence from animals exposed to very high noise levels suggests that exposure to these noises can interfere with sexual-reproductive functions, can interfere with resistance to viral disease, and can also produce other pathological effects (Kryter et al., 1971; Welch and Welch, 1970). Among these other effects are hypertrophy of the adrenal glands, developmental abnormalities of the fetus, and brain injury (Welch and Welch, 1970). These experiments often have not been well controlled; e.g., fear, handling, and so on have not always been equated for noise-exposed animals and non-noise exposed animals. Also, rodents have often been used as subjects, and these animals are known to have special susceptibility to the effects of certain sounds. Furthermore, the sound levels used in these experiments have usually been well above those normally encountered in our present environment.

There is evidence that workers exposed to high levels of noise have a higher incidence of cardiovascular disorders; ear, nose, and throat problems; and equilibrium disorders than do workers exposed to lower levels of noise (Andriukin, 1961; Jansen, 1959, 1969; Kryter et al., 1971). The results of one of these studies are summarized on Figure 22.

The fact that those who work in high noise levels show greater evidence of medical problems than those who work in lower noise levels is not conclusive evidence that noise is the crucial factor. In each case it is possible that the observed effects can be explained by other factors such as

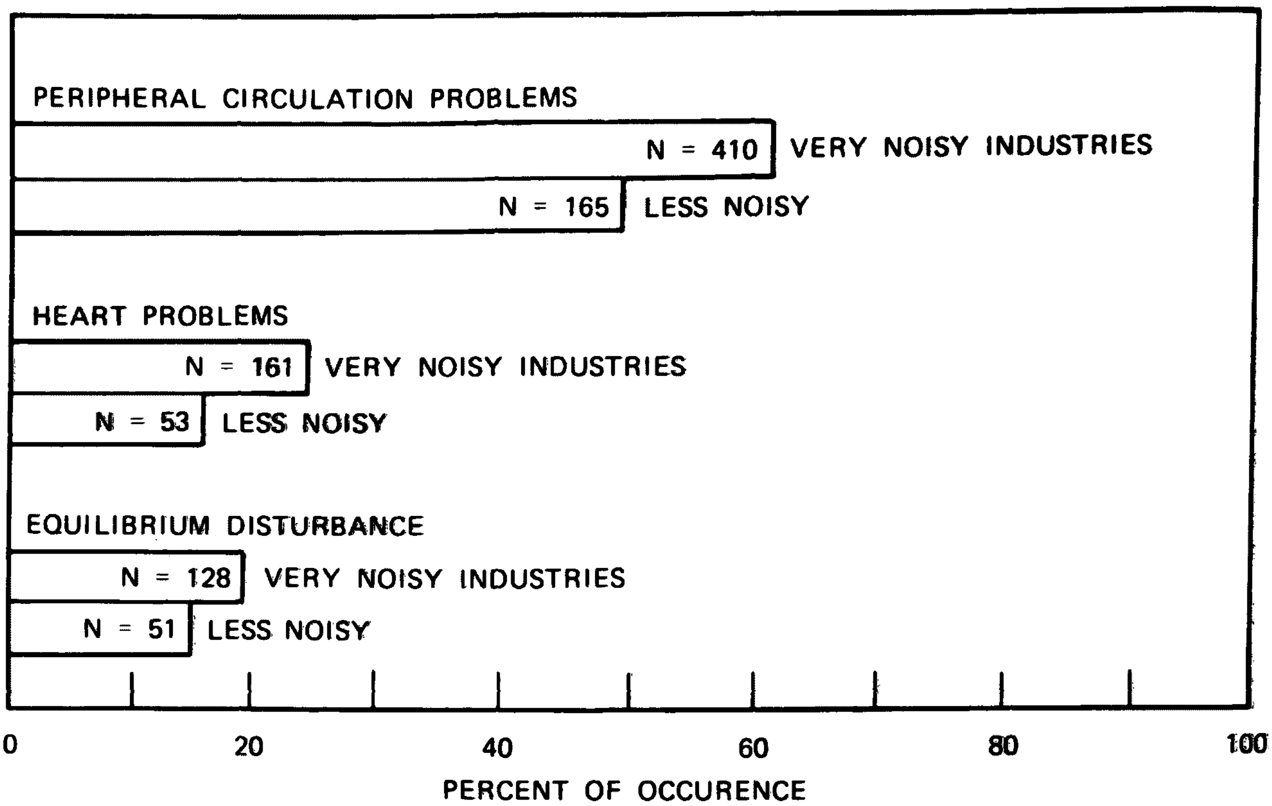

Figure 22. Differences between the percentages of physiological problems of those who work in two different levels of noise. These data are from 1005 German industrial workers. Peripheral circulation problems include pale and taut skin, mouth and pharynx symptoms, abnormal sensations in the extremities, paleness of the mucous membranes, and other vascular disturbances. (From Kryter et al., 1971.)

age, dust levels, occupational danger, life habits, and other non-noise hazards. However, much more research of this type should be undertaken with attempts to rule out the effects of non-noise factors.

From the facts presented about transient physiological responses to noise, one can argue that chronic arousal by sound might lead to some of the medical problems just described. These transient responses ordinarily are useful to man because they help protect him from potentially harmful events. It is also appropriate that these responses diminish when repetition of the stimulus signifies that particular noises do not represent a threatening or harmful condition. The crux of the problem is whether man is so designed to adapt to sufficiently loud or abrupt sounds or whether the modern environment presents such ever-changing auditory stimulation that arousal responses are chronically maintained.

Section 8. STRESS THEORY, HEALTH, AND NOISE

A. Stress Theory

The neuro-endocrine responses mentioned in Section 7 are similar to the responses to stress. The response to stress is called the general adaptation syndrome (Selye, 1956). It consists of three stages: an alarm reaction, a stage of resistance, and a stage of exhaustion. If a stressor is very severe and is maintained for prolonged periods of time, an organism passes in succession through the stages of the alarm reaction, resistance, and exhaustion. In the extreme case, the end result is a breakdown of bodily function and death. In a less severe case, there may be a price to be paid in the stage of resistance. This price may include lowered resistance to infection, and perhaps, specific diseases known as the diseases of adaptation. These <u>may</u> include, among others, some types of gastrointestinal ulcers, some types of high blood pressure, and some types of arthritis. Many medical authorities do not accept the theory that there are diseases of adaptation. Rather, they theorize that each disease has its own special set of causes.

Stress theory, even as presented by its strongest advocates, is complicated. These advocates speak of complicated interactions between conditioning factors that set the scene for disease, specific reactions to particular stressors, and general reactions to non-specific stressors.

It is nearly certain that noise of extremely high level can act as a stressor and, at least for some animals, can lead to some of the physiological changes associated with the general adaptation syndrome. Also, it is plausible that some of the more intense noises encountered in our present environment can act as stressors for people. However, the details of how such noises might act as stressors for people are unknown. The intensity level of the noise, the amount of fear and annoyance produced by the noise, and the susceptibility of the individual are probably examples of important factors. While certain pathways in the central nervous system and the hormonal system are probably important, these have not yet been established for the case of noise. For example, it could be necessary for the noise to produce ear damage, evoke annoyance and negative emotional reactions, or disturb sleep before elements of the general adaptation syndrome would appear. The picture is further complicated by the fact that a mild amount of stress at the right time of life may be beneficial. Therefore, while it is plausible that noise can be a detrimental stressor for people, it appears to be impossible to make firm statements about noise stress at this time.

B. Noise and General Health

While physiological arousal in response to sound can be of great benefit in the maintenance of response to possibly dangerous events, unnecessary arousal to irrelevant sounds can provide a basis for annoyance and for interference with performance of tasks. Chronic arousal from noises of sufficiently high levels or from noises that are sufficiently varied may, although it is unproven, contribute to the incidence of non-auditory disease. However, the evidence does suggest that, if noise control sufficient to protect persons from ear damage and hearing loss were instituted, then it is unlikely that the noise of lower level and duration resulting from this effort could directly induce non-auditory disease. Nevertheless, it is conceivable, though unlikely, that certain patterns of exposures to irregular, brief sounds could produce non-auditory pathology of greater significance than the noise-induced pathology of the inner ear.

As mentioned earlier (see end of Section 6), general psychological distress produced by noise can add to the overall stress of life and in this way may contribute to the incidence of non-auditory disease. At this time, however, one cannot evaluate the contribution of noise-induced distress in relation to those other sources of stress we all encounter in our daily activities.

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