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NOISE AND HUMAN PERFORMANCE

WALTER F. GRETHER, Ph.D.

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13. ABSTRACT

The possible effects of noise on human performance have been the subject of considerable research dating back to 1916. This interest has been stimulated by concern about noise in factories, offices, schools, aircraft and other military vehicles. Two very direct and harmful effects of noise, permanent hearing loss and auditory masking, are treated only briefly in this review. Special attention is given to the so-called non-auditory effects on such performance measures as reaction time, vigilance, time estimation, tracking, manual manipulation, intellectual capacities, and industrial work tasks. Overall, the research data on noise and human performance appear rather contradictory and inconsistent. While many studies have found no performance impairment, and even improvement, there are some types of measures that rather consistently show decrements from exposure to noise. Some theoretical explanatory mechanisms to account for effects of noise on performance are included in the review.

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Internal-Blinks Analogy						
Short-Term Memory						
Arousal						
Sonic Boom						
Masking						
Hearing Loss						

FOREWORD

This report presents a review of the literature on the effects of noise on human performance. It was carried out to obtain information about the effects of noise as a single stress, in preparation for a series of experiments on the effects of noise in combination with other aerospace stresses. This work was carried out under project 7222, Combined Stress Environments in Aerospace Operations.

This technical report has been reviewed and is approved.

CLINTON L. HOLT, Colonel, USAF, MC
Commander
Aerospace Medical Research Laboratory

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INTRODUCTION

The effects of noise on human behavior and performance have for a long time been of considerable practical and scientific interest. Most of the early research, in the period before World War II, was stimulated by a concern about noise in factories and offices, and the possible effects on the productivity of workers. There was also some interest in the effects of noise in schools. During and after World War II much more of the research interest seems to have been oriented to problems of aircraft noise, first for reciprocating and later for jet engine aircraft. More recently the noise of rocket engines and the boom from supersonic aircraft have been of special concern.

This review devotes primary attention to research on the effects of noise on human performance. Although particular attention is focussed on the kinds of tasks required of aircrew in performing their flight duties, the research findings are equally applicable to performance in factories, on the highways, and in people's daily lives. Of necessity, most research on noise and human performance has used psychological tests of performance rather than real-life tasks.

For the purpose of this review, noise is unwanted sound. Thus it is distinguished from speech sounds used in communication, other uses of sound for signalling and communication, and music. By this definition what is a wanted use of sound for one person may be unwanted, and therefore noise, to another.

Noise may also be defined in other ways, such as by the randomness or noncyclic nature of the sound pressure wave. We commonly speak of white noise, for example, which is a random mixture of all frequencies of the audible spectrum. Other definitions of noise are in terms of the source of the sound. Thus we may speak of factory noise, jet engine noise, or street noise. In this review, however, noise may be a pure tone, a sonic boom, or music, as well as broadband mixtures from all or most of the audible spectrum.

There are several ways in which noise can affect human performance, and for two of these there is no doubt concerning the effects of noise on performance and the harmful nature of these effects. These are hearing loss, both temporary and permanent, and the masking of speech and other desired sounds. Noise can also produce distraction and annoyance, but these are subjective effects that are difficult to evaluate. Individuals differ widely in their sensitivity to distraction and annoyance. For a given individual a noise that is distracting and annoying at one time and place may not be under other circumstances.

Of particular interest in this review are the possible effects of noise on general human performance, aside from those caused by hearing loss and masking. These are sometimes referred to as the nonauditory effects. As will be apparent later the effects of noise on performance are subtle and elusive. Many studies have shown little or no effect. In some instances noise seems to facilitate performance. There is, furthermore, no clear mechanism of action for noise to cause nonauditory effects, other than through distraction or annoyance. A common finding is for noise to cause a performance decrement during the initial period of exposure, but not after the subjects have become accustomed to the noise. Thus it seems likely that distraction is a major factor in those studies showing a performance decrement.

Since the effects of noise have been a subject of considerable research interest, dating back to at least Morgan's paper in 1916, a considerable body of research literature has been built up. Among this literature are reviews by Berrian (1946), Kryter (1950), Broadbent (1957a), and Plutchik (1959). Of these the reviews by Kryter and Broadbent are particularly thorough and highly recommended to the reader. In the current review somewhat greater stress is placed on the research conducted since the previous reviews.

Production, Measurement and Description of Noise

For research on the effects of noise several types of sound generators have been employed. Many experimenters have used a tape or phonograph recording of some common noise, which was then electronically amplified to the desired loudness. The recorded noise may be that of a factory, street traffic, music, or a jet engine, depending on the particular focus of the research. In this method of sound generation there is no direct control over the composition of the noise. Other experimenters have used electronic noise generators to produce either tones or so-called white noise, which is a random combination of frequencies from all or most of the audible spectrum. A few experimenters have used mechanical sirens as noise sources.

The standard unit of measurement for specifying the loudness of noise is the decibel (dB). This is a measure of the sound pressure level as expressed by the following equation:

$$L_P = 10 \log \frac{P^2}{P_0^2} = 20 \log \frac{P}{P_0}$$

L_P - Loudness in decibels

P = Sound pressure in microbars

P_0 = Reference sound pressure, normally 0.0002 microbar

The reference sound pressure of 0.0002 microbar is approximately the absolute threshold for hearing at 1,000 Hz, the part of the audible sound spectrum (roughly 20 - 10,000 Hz) to which the ear is most sensitive. Also, up to the upper limit of tolerable noise exposures (about 130 decibels) one decibel unit represents approximately the human difference threshold for sound. Some decibel levels for common sounds are given in Table 1.

Occasionally used is another decibel unit, dBA, to measure noise level. In this measurement some bands of the frequency spectrum have been weighted to equalize loudness, based upon normative audiometric data. Some data reported in this review use the dBA rather than the more common dB unit of measurement.

TABLE 1

Wideband Sound Pressure Levels for a Variety of Sounds (Young, 1957)

Sound Pressure Level L_p, dB	Source
130 - 140	Hydraulic press, distance 3 feet.
120 - 130	Bass drum at 3 feet, peak.
110 - 120	Automobile horn, distance 3 feet.
100 - 110	DC-6 airliner, inside.
90 - 100	Automatic lathe, distance 3 feet.
80 - 90	Automobile at 40 mph, inside.
70 - 80	Office with tabulating machines, ambient noise.
60 - 70	Conversational speech, distance 3 feet.
50 - 60	Residential kitchen, ambient noise.

Most experiments on the effects of noise on performance have used maximum loudness levels of 90 to 110 decibels. Many of the older experiments dating back to 1916 (Morgan), 1918 (Cassel and Dallenback), and 1925 (Tinker) did not describe the sound exposures in terms of physical energy measurements. They merely described the sound sources, such as buzzers, bells, or fire gongs. Most of the experiments have compared a quiet condition with one or more noise conditions. But quiet is a relative condition and not one with zero ambient noise. Many experimenters have provided a reference noise, commonly about 70 dB, to represent the quiet condition.

Most experimenters have also given some description of the frequency characteristics of the noise used. Usually this has been a broadband white noise, or an approximation to this condition, such as machinery, aircraft, or office noise. A few experimenters have used pure tones, or random frequencies from a selected portion of the spectrum.

Hearing Loss

Among the harmful effects of exposure to noise is physiological damage to the auditory system and resultant hearing loss. This loss may be temporary and several hours may be required for recovery. Far more serious is the permanent hearing loss that results from long duration and repeated exposures. Either type of loss reduces human performance capability for voice communication. But only the permanent loss is of major concern and is the basis for setting physiological limits for noise exposure. Setting tolerance limits based on hearing loss is a complex problem and is not covered in detail here. For comprehensive treatments of this subject the reader is referred to reviews by Kryter (1950; 1960).

Quantification of hearing loss is normally in terms of the elevation of the absolute threshold for hear[illegible] For reasons not yet well understood the threshold increases are grea[illegible]st at the higher frequencies of the auditory spectrum, particularly at frequencies of 4,000 Hz and higher. This is true even when the exposure amplitudes are greater for lower frequencies. In causing hearing loss, the higher frequency sounds are more harmful than those at the lower end of the auditory spectrum. Pure tones are more harmful than broadband noises of equal decibel level.

As might be expected there are wide individual differences among people in their susceptibility to hearing loss from noise exposures. Also some hearing loss occurs normally as a function of age and disease processes. Because of these complicating factors and the accumulative effect of repeated exposures over a long period of time, it is difficult to distinguish between hearing loss caused by noise and that caused by age or other factors. In actual practice the identification of effects from noise involves analysis of statistical data on rather large populations of people whose noise exposure history can be rather accurately quantified.

Because of its importance to public welfare considerable effort has been devoted to the setting of noise exposure criteria for avoidance of hearing loss or damage. Such data are normally referred to as damage-risk criteria. Damage-risk criteria prepared by the American Standards Association (Rosenblith, 1954), as reproduced by Kryter (1960), are shown in Figure 1. This figure shows that the tolerable exposures for pure tones are about 10 dB lower than for wideband noise. It also shows the variations of tolerable exposure with frequency and with age of the subject. Data such as these have been used as guides for control of human exposures to noise; one implementing document for control is Air Force Regulation No. 160-3 (1956), Hazardous Noise Exposures. More recently a Federal Standard has been implemented by the Department of Labor (1969). The exposure values specified by this standard are given in Table 2. The tolerance limits or damage-risk criteria, shown in Figure 1 and Table 2 will be useful in evaluating the nonauditory effects of noise reviewed in ensuing sections.

interferes with hearing of tones and other nonspeech sound signals. A relatively large amount of research effort has been devoted to the study of masking and speech interference, and as a result the physical and auditory relationships are fairly well quantified. Considerable use is made of masking data in the design and evaluation of communication systems. In this review only some of the more general phenomena of masking will be discussed. For more detailed information the reader is referred to reports by Hawkins and Stevens (1950), Kryter (1950), Hirsch (1952), Hawley and Kryter (1957), Webster and Klumpp(1965), and Webster (1969).

In simple terms masking can be considered as an elevation of the absolute threshold for a wanted sound by a simultaneous unwanted sound. Generally, the masking sound is a broadband noise including a wide range of frequencies. But the masking effect is greatest from those sound frequencies closest to the tone or other sound for which the threshold is being measured. The greater the difference in frequency between the two sounds the less the masking effect. For pure tone thresholds, the elevation of absolute thresholds as the level of the masking sound is increased is shown in Figure 2 taken from Hawkins and Stevens (1950). Although the masking illustrated in this figure is produced by broadband noise the loudness of the masking sound is indicated in terms of noise level per cycle. The overall noise level for a 7,000 cycle band of noise would be about 40 dB higher.

It can be seen in Figure 2 that except at the lowest levels, the threshold increases seem to be a linear function of the masking noise level. This is better shown in Figure 3, also from Hawkins and Stevens

(1950). As can be seen in this figure not all frequencies are equally sensitive to masking. The masking effect is greatest for frequencies around 3,000 Hz.

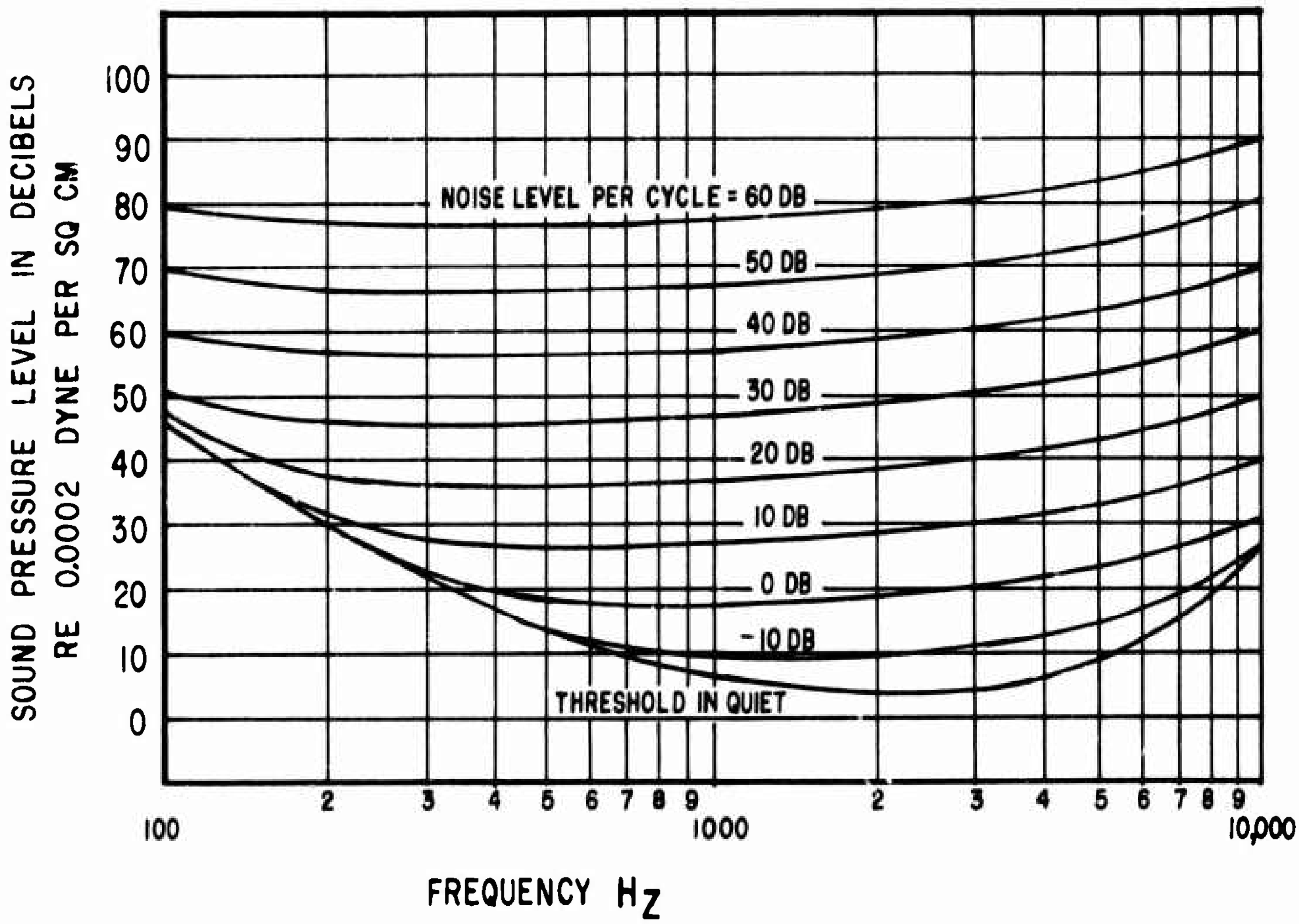


Figure 2. Absolute and masked thresholds for pure tones as a function of frequency measured in the presence of different background noises (Hawkins and Stevens, 1950, from Hirsch, 1952).

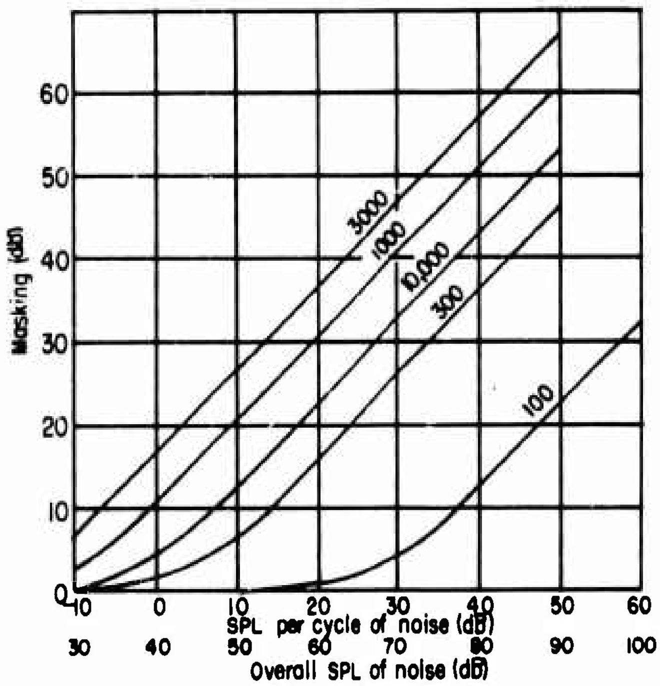


Figure 3. Relation between masking for pure tones of different frequency and the level of the masking noise (Hawkins and Stevens, 1950, from Hirsch, 1952).

Various techniques have been devised and used for evaluating noise environments in terms of their interference with voice communication. One of these is the articulation index. For this, the audible spectrum is divided into 20 frequency bands, and an average is computed from the sound pressure levels of these 20 bands. This average is then converted into an articulation index, derived from intelligibility studies, ranging between 0 (no intelligibility) and 10 (100% intelligibility). The computed index, then, quantifies the noise environment as to human speech intelligibility. A somewhat simpler method, the Sound Interference Level (SIL) uses the average sound level for three octave bands (600-1200, 1200-2400, and 2400-4800 Hz) in the speech range. Still another method called Perceived Speech Interference Level (PSIL) uses octave bands centered at 500, 1000, and 2000 Hz. The relation between speech intelligibility and PSIL, and also overall noise level, is shown in Figure 4, taken from Webster (1969).

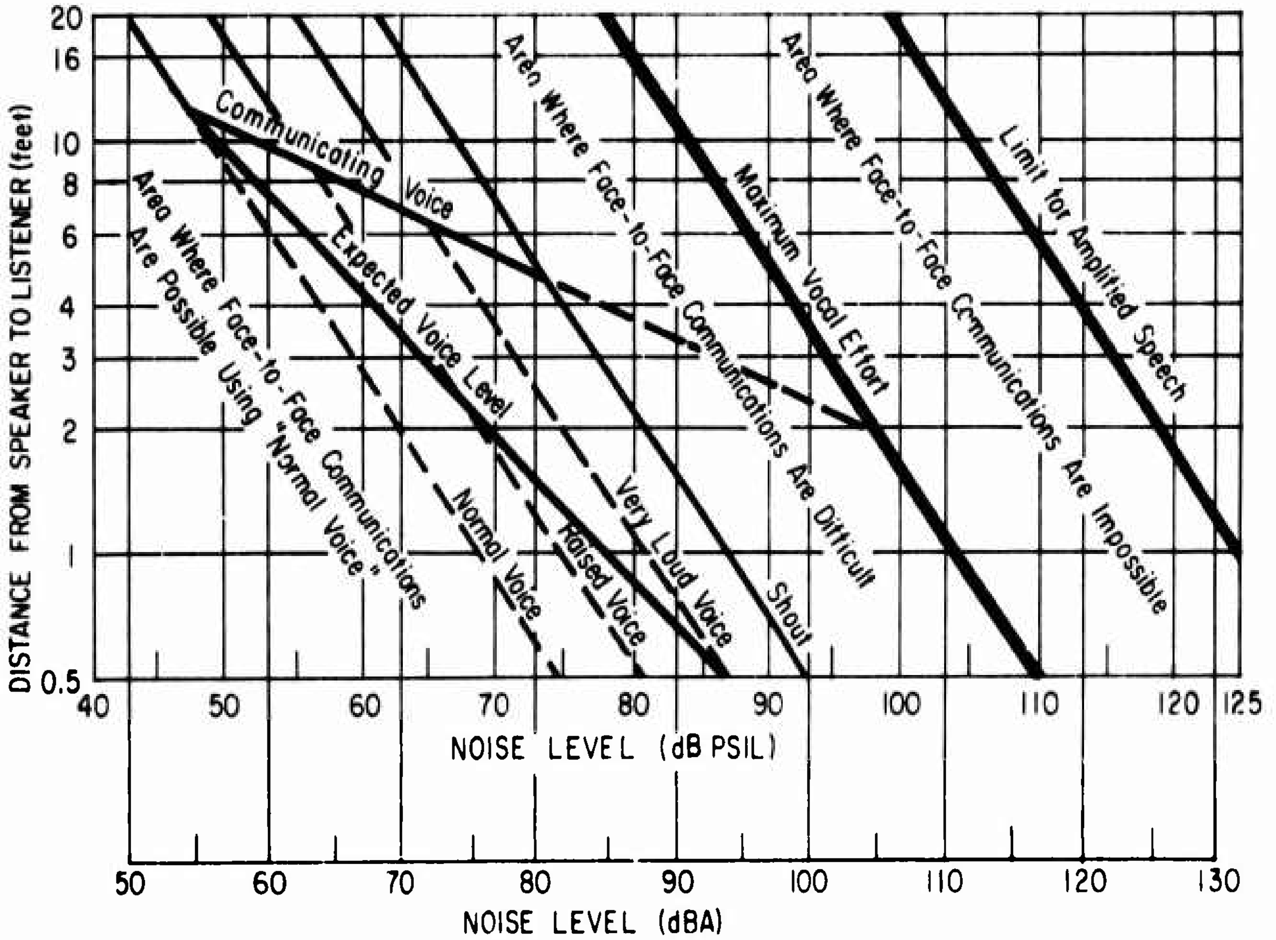


Figure 4. Voice level and distance between talker and listener for satisfactory face-to-face speech communications as limited by ambient noise level (Webster, 1969).

Performance in Industrial Settings

A variety of studies have been conducted in factories and offices to test the value of noise reduction in terms of worker productivity. Judged by scientific standards the results of most such studies are discounted because of inadequate control of all other conditions that could have affected productivity, such as learning, motivation, and physical changes other than noise in the work situation. One of the most difficult factors to control is motivation. Quite often any special attention shown to a particular group of workers is likely to improve their motivation and thereby their work output. This is the well known "Hawthorne Effect," first recognized in experiments at the Hawthorne plant of the Western Electric Co.

What appear to have been the best controlled and most reliable industrial field studies were reported by Weston and Adams (1932; 1935) in England. They conducted three separate studies on the work performance of weavers. In the normal working environment the noise level was about 96 dB. Ear plugs were used to reduce this noise level by from 10 - 15 dB. In one experiment 10 weavers wore such ear plugs on alternate weeks for 6 months. In two other experiments matched groups of workers were compared, one group wearing ear plugs and the other not. One study was continued for 6 months, the other for 12 months. All three studies showed a gain in worker efficiency of about 12 per cent from wearing of ear plugs. At least for the one-year study the difference between the two groups had diminished considerably by the end of the experiment. This suggests that at least some of the gain in efficiency was a result of increased motivation rather than decreased noise.

Another widely quoted industrial study was conducted by the Aetna Life Insurance Company, and referred to by Kryter (1950) in his review. Sound absorbing material was installed in the company offices, and productivity of typists and other workers was compared for a year before and a year after the installation. Rather surprising gains in productivity were claimed, but there was no control over any of the other factors, such as worker skill and motivation, that could have been changing during the periods before and after the installation of sound absorbing material.

Results exactly opposite to those of the studies just referred to were reported by Kornhauser (1927) for a study of typists. A comparison was made of typing efficiency in quiet and noisy offices. Typing speed was slightly greater and wastage was considerably less for the noisy condition. But this study suffered from a small number of subjects, only four, and lack of control of other physical conditions in the quiet and noisy offices.

The lack of definitive and reliable results from industrial field studies should not be interpreted as showing that noise reduction is not worthwhile in noisy factories and offices. Even though gains in productivity may be uncertain, gains can certainly be expected in ease of communication and reduction of hearing losses.

Effect of Noise on Senses Other than Hearing

Persons exposed to very high noise levels, above about 140 dB, typically have reported rather vague nonauditory sensations, such as muscular weakness, loss of equilibrium, and nausea. Some of these effects may be caused by sound vibrations transmitted to body tissue. Quite likely there is also some stimulation of the vestibular sense organs by intense sounds. Vestibular effects of broadband noise were studied in an experiment by Nixon, Harris, and von Gierke (1966) using a "Rail Test." This test measures the ability of subjects to stand and walk on rails of various widths. The subjects were exposed to broadband noise of 120 dB for two experimental conditions and 70 dB for a control condition. The sound pressure level for each ear was reduced to 80 dB with ear defenders (balanced condition) and 100 dB at one ear and 80 dB at the other ear (unbalanced condition). Only minor and not statistically significant differences in balance time were found for the control and noise conditions. The greatest impairment was for the unbalanced condition.

A later study using the rail test was made by Harris and Sommer (1968), using pure tones of 100, 260, 590, 1500, and 2500 Hz. Tones were presented through ear phones at 95 dB for the balanced condition and 95 and 75 dB for the unbalanced condition. Performance tended to be slightly poorer for the unbalanced condition. The results are suggestive of some direct effects of noise on the vestibular sensory system. A subsequent study by Smith, Lingh, and Eischens (1969) used most of the same noise stimulation conditions as Harris and Sommer (1968), but used a two-dimensional postural tracking test. This study showed no evidence of effects on equilibrium from unsymmetrical noise stimulation. Bensel, Dzendolet, and Meiselman (1968) introduced 5 sec. bursts of 70 and 90 dB noise while measuring body sway during 20 min. of standing. The data suggest a possible effect from the 70 dB noise, but not from the 90 dB noise.

In a World War II study of the effects of aircraft noise Stevens et al. (1941) included several sensory tests, using an experimental condition of 115 dB, and a control condition of 90 dB. Although some differences appeared, the authors concluded that the results were indeterminate for tests of muscular tension, speed of visual accommodation, saccadic eye movements, body sway, hand steadiness, reversible perspective, and dark adaption. On a test of distance judgment there was clearly no effect from noise. Broussard, Walker, and Roberts (1952) compared brightness contrast discrimination with noise exposures of 45 and 90 dB. Threshold differences and response times were slightly higher for the 90 dB condition. There have been other studies, such as by Krakov (1934), reporting effects of noise on visual thresholds. These effects are quite small, however, and in the range of amplitudes to which people are normally exposed, any effects of noise on senses other than hearing can be disregarded as insignificant.

Reaction Time

Simple reaction time was one of the earliest tests conducted under noise conditions, this study being done by Cassel and Dallenback (1918). For noise they used a hammer striking an anvil, and applied the noise both continuously and intermittently. The effect on reaction time was inconsistent. Miles (1953) in the BENOX study also obtained no consistent decrements in reaction time from high intensity (128 - 135 dB) jet engine noise. A more complex "Serial Disjunctive Reaction Time" test was used by Stevens et al. (1941), which used four lights and hand and foot response switches. There were no differences in response time between exposures to 90 and 115 dB aircraft noise. Under the same noise conditions, however, a "Coordinate Serial Reaction Time" test showed a speed reduction of 5.4 per cent. On this test the subject used an airplane stick and rudder pedals to direct a beam of light at a target following an irregular path.

Another complex serial reaction time test used by Broadbent (1953) also has rather consistently shown decrements during noise. This test presents five neon lights, and five corresponding electrical contacts. Using a stylus the subject responds to each light by touching the metal contact, thereby bringing on the next light. The test can be scored in terms of speed, errors (touching the wrong contact) and blocks (exceeding a specified response time). Broadbent (1953), comparing performance in 70 and 100 dB broadband noise found no decrement in speed, but about 50 per cent more errors at 100 dB. In a later study Broadbent (1957b) used recorded machinery noise at 80, 90, and 100 dB. The noise was filtered to pass only frequencies below or above 2,000 Hz. Again, errors on the serial reaction test were increased with no change in speed. The error increase was somewhat greater for the high frequency noise. The same test was also used by Wilkinson (1963), who compared the effects of 100 dB white noise against quiet conditions, with sleep deprivation and knowledge of results as additional variables. In this experiment the increase in errors as a result of noise was not a consistent finding. This deviation from Broadbent's results was attributed by Wilkinson to the subjects having a greater degree of experience on the test in his (Wilkinson's) experiment.

In summary, it appears that relatively simple tests of reaction time do not show decrements with noise. On the other hand more complex and highly demanding reaction time tests are likely to show decrements.

Vigilance

In the typical vigilance or watchkeeping test the subject is called upon to detect infrequent and inconspicuous signals, usually on visual displays. One might expect that noise would keep the subject more awake or alert, and thereby improve vigilance performance. Such, however, does not seem to be the case, except possibly for variable sounds. Broadbent (1954) used a steam-gauges vigilance test, and also a lights test, with broadband noise exposures of 70 and 100 dB. On the easier lights test there were no effects of noise, but for the steam-gauges test the number of detected signals was 30 per cent less during the 100 dB noise exposures. Jerison (1959) used a 3-clock (Mackworth) test of vigilance that required the subjects to detect double jumps of a clock hand, with white noise exposures of 83 and 114 dB. Slightly more signals were missed under the higher noise condition, and the difference in vigilance performance was greatest near the end of the 2-hour noise exposures.

Some investigators have compared the effects of steady versus intermittent noise on vigilance performance. For this purpose Kirk and Hecht (1963) required subjects to detect a momentary deflection of a spot on a cathode ray tube. Comparisons were made among quiet (61 dB), steady noise (64.5 dB) and variable noise (64.5 dB average) conditions. Performance was slightly better under the variable noise than under the other two conditions.

Tracking and Manual Manipulation

While it has been a popular type of test for other studies of environmental effects, tracking has not been used a great deal in noise studies. Most of those used have not been the common compensatory tracking type, with a cathode ray tube display and a joy stick control. Unlike the situation for acceleration and vibration environments there is no apparent mechanical reason why tracking ability should be impaired by noise. For this reason, perhaps most experimenters have not used tracking tests.

Laird (1933) had subjects spend 4-1/2 hours inserting a stylus in holes as they moved by, a task intended to resemble work in a factory. He used a variety of noises, a broadband noise, a low tone (64 Hz), and a high pitch tone (4096 Hz). He used both a steady and a warbling noise. Some of his results, showing a reduction in performance as the noise level was increased, are shown in Figure 5. He also found more effect from a warbling than a steady noise, and from a high than a low pitch tone. There is some question whether the task used by Laird should be classified as a tracking task, although it has some elements of tracking.

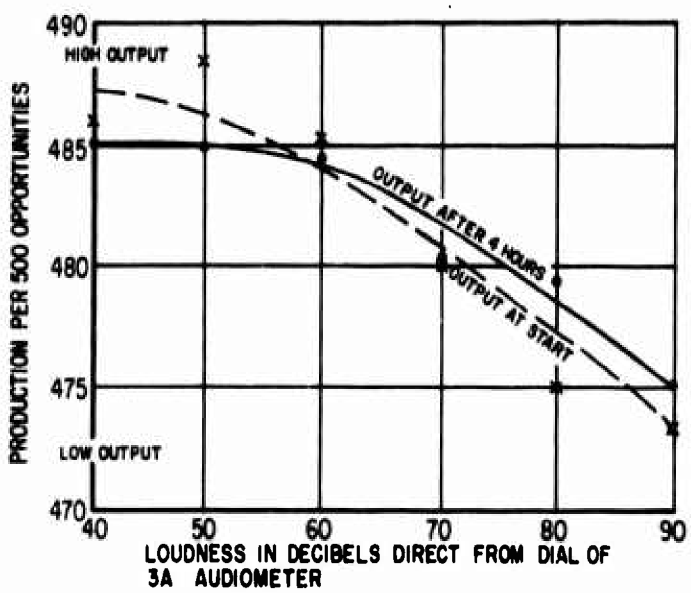


Figure 5. Production output at dexterous repetitive work under various intensity levels of complex noise (Laird, 1933).

The major study by Stevens et al. (1941) included two tests of tracking, a coordinated Serial Pursuit Test (three-dimensional compensatory tracking) and a Fast-Speed Pursuit Rotor. Both of these tests were classified among those showing no effects from 115 dB aircraft noise. Another World War II study at Tufts College (1942) measured azimuth tracking and range finding using a fire-control device. The subjects worked for 4 hours during which time loud noises (120 to 130 dB) were inserted for 2-3 minute periods. The results were somewhat variable, and sometimes noise caused improved performance, apparently by breaking the monotony and alerting the subjects. Plutchik (1961) used a conventional compensatory pursuit test and also a mirror tracing test. Neither test showed any decrements from intermittent tones (1000 and 2500 Hz) at 115 to 122 dB.

Several experimenters have used what is often called either a lathe test or a two-hand coordination test. As on a lathe, two cranks at right angles to each other are used to control the position of a stylus in following a moving target or irregular path. Viteles and Smith (1946) used such a test for 4-hour exposures to noise levels of 70, 80, and 90 dB. Errors on this test increased significantly as a function of noise level. Miles (1953), in the BENOX study, used a two-hand coordination test during exposures to 125-135 dB jet engine noise. He reported a small decrement. More recently Grimaldi (1958) used a lathe-type test in which subjects followed an irregular pattern around a generally circular track. He scored errors, response time for returning to the track, and speed (number of times around the pattern). Noises were separated into six octave bands from 75 - 150 Hz up to 2400 - 4800 Hz. Noise levels were quiet (37 dB) and 70, 80, 90, and 100 dB. Exposures were of 30 minutes duration. All measures on the lathe test showed some decrements as a function of noise. Also, the higher frequencies had more effect on performance than did the lower frequency bands. Some of his results are shown in Table 3.

TABLE 3

Overall Differences Per Subject of Performance Between Quiet and Noisy Conditions (Grimaldi, 1958)

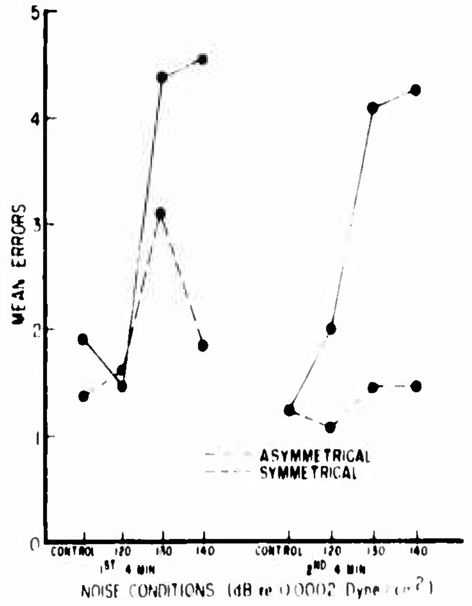
	Errors		Total Response Times (Minutes)		Productivity Scores	
	Quiet	Noise	Quiet	Noise	Quiet	Noise
Mean	207	227	1.95	2.59	22.89	21.85
Probability	0.01		0.02		0.5	

In summarizing the tracking studies, the more conventional compensatory tracking tests generally show no decrements during noise exposures. On the other hand a lathe type of tracking task, or a task requiring insertion of a stylus in moving holes (Laird, 1933) does show significant decrements.

Somewhat related to tracking tests, in that they involve eye-hand coordination, are various tests of manual dexterity or other forms of manual manipulation. Pollock and Bartlett (1932) had subjects remove pegs from a moving trolley while they were exposed to noise up to 90 dB. Although initially there was a slight decrement in performance, this disappeared as the subjects became accustomed to the noise. A block assembly test was used by Miles (1953) and his results suggest some decrement during exposures to jet engine noise (128 - 135 dB).

Using very high levels of white noise (120, 130, and 140 dB) Harris (1968) had subjects wear ear protective devices to produce both symmetrical and asymmetrical reductions from the ambient noise level. Thus, while the subjects' bodies were exposed to the high noise levels the ears received considerably lower levels of noise. During these exposures the subjects performed the Bennett Hand Tool Dexterity Test. Statistically significant decrements appeared at the 130 and 140 dB noise levels, and results were about the same for the symmetrical and asymmetrical conditions, as shown in Figure 6. On this test the high sound levels produced noticeable vibrations of small test parts, and Harris thought that at least some of the decrement was due to this mechanical effect.

Figure 6. Mean errors for noise conditions for asymmetrical and symmetrical exposures (Harris, 1968)



Time Estimation

An interesting effect of noise found by some investigators is a tendency of subjects to overestimate the passage of time. This effect apparently was first noted by Jerison and Smith (1955), who asked their subjects to press a switch after passage of what were judged as 10-minute intervals while they were also occupied at other assigned tasks. Comparison was made between a control condition (77.5 dB) and a noise condition of 111.5 dB. The average interval judged to be 10 minutes was actually about 9 minutes for the control and 7 minutes for the noise condition. Similar findings were reported by Hirsch, Bilger, and Deatherage (1956), who compared time estimations when the noise levels were different during presentation of a standard interval and the subjects attempted to repeat that interval. Again, noise caused an increase in the estimated duration of time. Another study by Jerison, Crannel, and Pownall (1956) involved estimation of when a moving target, which suddenly disappeared, would arrive at a cross hair. Noise caused changes in the judgment of when the target would have reached the cross hair. In a fairly close duplication of the study by Jerison and Smith (1955), Loeb and Richard (1957) also asked subjects to estimate 10-minute intervals, while exposed to either 80 or 110 dB noise. Although the higher noise level caused a slight overestimation of time, the difference was smaller than that reported by Jerison and Smith, and lacked statistical significance.

Intellectual Functions

The type of test that has been used most frequently in noise experiments is what I have loosely classified as intellectual functions, although in some of these tests the demands are primarily perceptual rather than intellectual. I refer here to tests involving letter and number checking or pattern matching. The rather large number of experiments that have used intellectual tests are summarized in Table 4. In further discussion of this area emphasis will be given to the more recent work, particularly that reported since the reviews by Kryter (1950) and Broadbent (1957a).

Among the tests that are most demanding and involve a maximum of central neural activity are those requiring mental arithmetic. Normally these tests are quite sensitive indicators of an environmental stress, such as hypoxia. As will be seen in Table 4, however, all seven experiments using such tests found little or no decrement caused by noise. Where there was any decrement it often vanished as the subjects became accustomed to the noise. This suggests that the mechanism of action is through distraction of the subjects' attention rather than any basic impairment of arithmetic ability.

In the experiment by Broadbent (1958) the subject was shown a 6-digit number in a slot. After he had memorized this number he pushed a button to cause a 4-digit number to appear in the slot. This number the subject subtracted mentally from the memorized 6-digit number, and then recorded his answer. He then repeated the process. Of three experimental groups, one worked in quiet (70 dB noise) conditions on both days, one worked in quiet the first day and 100 dB noise the second, and the third group were exposed to 100 dB noise on the first day. There were no consistent effects of noise. While on the first day the group exposed to the 100 dB noise appeared to show slight deterioration, on the second day the group exposed to noise surpassed the two groups working in quiet.

TABLE 4

Summary of Data on Intellectual Tests as Affected by Noise

Author	Tests	Noise Conditions	Major Effects of Noise
Morgan (1917)	Learning of Paired Associates	Buzzer and fire gong, intermittent	Slight but temporary decrement
Tinker (1925)	Intelligence	Intermittent bell	No decrement
Hovey (1928)	Intelligence	Intermittent bell	Slight decrement, not significant
Ford (1929)	Mental Addition	Auto horn	Temporary decrements following onset and cessation
Vernon & Warner (1932)	Mental Arithmetic	Phonograph, bells, whistles and sirens	Slight improvement after adaptation to noise
Harmon (1933)	Mental Arithmetic	Recorded office and street noise up to 75 dB	Decrement, diminishing with time
Viteles and Smith (1946)	Mental Multiplication, Number Comparison, Grid Location, Visual Maze	70, 80 and 90 dB noise, 4 hour exposures	Increased speed on mental multiplication and number comparison; increased errors on mental multiplication; fewer errors on grid location
Broadbent (1958)	Mental Substraction	70 and 100 dB noise	No consistent effects
Park and Payne (1963)	Mental Division	98 - 108 dB noise, 20 min. exposures	No effect

TABLE 4 (Continued)

Author	Tests	Noise Conditions	Major Effects of Noise
Wilbanks, Webb & Tolhurst (1956)	Numerical Ability, Mechanical Reasoning, Abstract Reasoning, Clerical Speed and Accuracy	110 - 114 dB noise	Improved performance on clerical test. No effect on other tests
Smith (1951)	Minnesota Clerical and Form Board Tests	100 dB noise, intermittent bursts	Slightly increased speed and items correctly completed, but more errors
Corso (1952)	Minnesota Clerical and Form Board Tests	100 dB noise, 100 - 3,000 Hz, intermittent	Slightly increased speed and items correctly completed, but more errors
Luckiesk (1931)	Visual Detection of Patterns Among Confusing Lines	Factory noise	Small decrement
Davies & Hockey (1966)	Visual Cancellation	95 dB noise	No effect
Harris (1962)	Visual Pattern Discrimination	120, 130 and 140 dB noise, with subjects wearing ear protection. Symmetric and asymmetric stimulation	Increased errors for asymmetrical stimulation
Morgan (1916)	Code Manipulation	Bells, buzzers and other noise makers	Temporary decrements at onset of noise
Stevens et al. (1941)	Coding, Card Sorting	90 and 115 dB aircraft noise, 7 hr. exposures	No effects

TABLE 4 (Continued)

Author	Tests	Noise Conditions	Major Effects of Noise
Warner (1969)	Letter Checking	80, 90 and 100 dB noise, intermittent	Decrease in errors
Woodhead (1964)	Visual Search for Numbers	70 and 100 dB noise bursts	No general decrement. Some increase in errors immediately after 110 dB bursts
Shoenberger & Harris (1965)	Tsai-Partington Numbers Test	85, 95 and 115 dB noise, 15 and 30 min. exposures	Slight decrement
Woodhead (1959)	Mackworth Multi-Channel Test	85, 95 and 115 dB noise in 0.95 sec. bursts	Slightly more errors following loudest bursts
Jerison (1959)	Complex Mental Counting	77.5 and 111.5 dB noise, 90 min. exposures	No significant decrements
Teichner, Arees & Reilly (1963)	Letter Checking	57, 69, 81, 93 & 105 dB noise. Constant as well as changing noise levels	Change in noise level, either increase or decrease caused decrement (see Figure 7). No effect of constant noise

Another experiment that demanded quite complex and difficult intellectual performance was one reported by Jerison (1959). The subject was faced with three lights flashing at different rates. For each light there was a switch the subject was required to operate when that light had flashed a specified number of times. Performance was measured during 2-hour sessions including 90-minute exposures to 111.5 dB white noise, and a control condition of 77.5 dB. There was a decline in performance during the 2-hour session. Although there was a slight decrement during noise, this effect was not statistically significant.

Of special interest is an experiment by Teichner, Arees, and Reilly (1963) on the effect of changes in noise level, both upward and downward. The subjects were shown a group of ten letters. They were required to indicate which of certain three-letter combinations were included in the ten-letter group. White noise was used at 57, 69, 81, 93, and 105 dB. During 1-hour sessions some subjects experienced constant noise, others experienced a shift upward or downward from the 81 dB level. Although performance did not decline with increases in noise level, a change in the level, either an increase or decrease, caused a decrement in information transmission on the task. The key results are shown in Figure 7.

A paper and pencil test of visual pattern discrimination was used by Harris (1968). Boxes containing six symbols were compared, and the subjects recorded the number of differences between them. Noise levels of 120, 130, and 140 dB were modified by ear protection so as to obtain both symmetrical and asymmetrical auditory stimulation. Particular interest centered in the possible effects of asymmetric stimulation. Only at the two highest noise levels and asymmetrical stimulation was there a decrement in performance. This decrement was caused by an increased number of

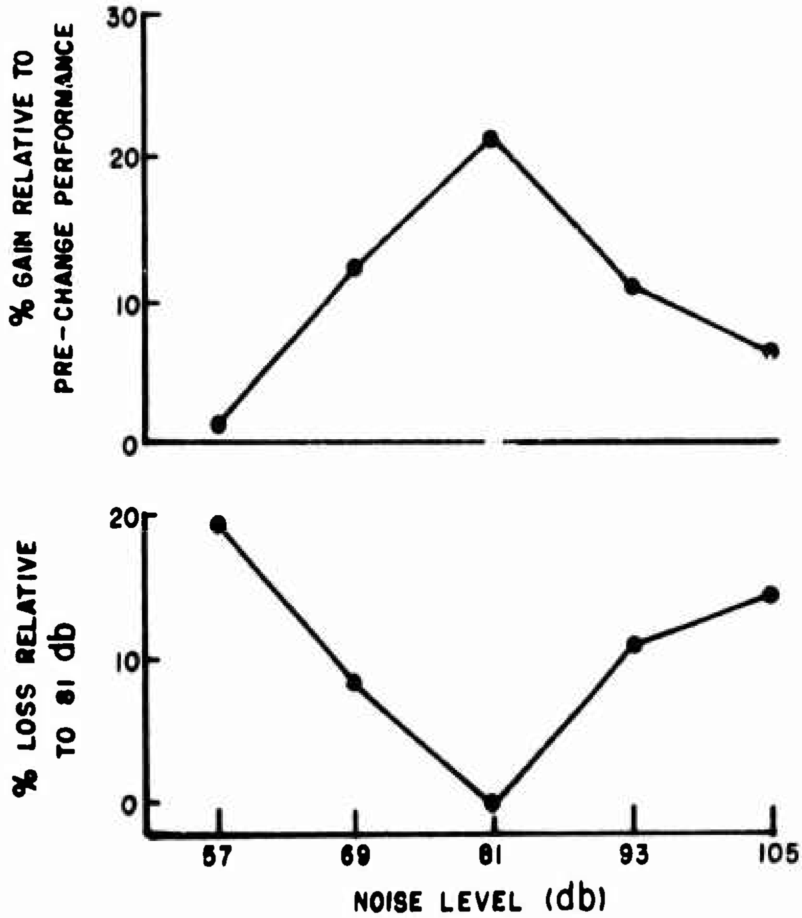


Figure 7. Effects on information transmission related to changing noise level from 81 dB to higher and lower noise levels (Teichner, Arees and Reilly, 1963).

errors rather than a reduced number of items attempted. In another experiment Shoenberger and Harris (1965) used the Tsai-Partington Test. The subject has a page on which numbers from 1 to 25 are randomly located. His task is to draw a line to each number in succession beginning with the number 1 at the center. Noise levels were 85, 95, and 110 dB. This test showed a considerable improvement through learning, and learning was greatest during quiet conditions. A shift from quiet to 110 dB noise caused a small decrement in the number of patterns completed.

A test used by Woodhead (1964) also required the subject to search for numbers. Ten digits appeared in a window for 2 seconds. On some exposures one of these numbers had a circle around it. On this and subsequent exposures, until another circled number appeared, the subject was to cross out all other digits of the same number. There were three noise conditions, quiet, 70 dB bursts, and 110 dB bursts. There were no overall differences between noise conditions. It was found, however, that immediately following the 110 dB bursts the subjects frequently missed seeing the circled digit. Thus, there was a temporary increase in errors.

Some Special Kinds of Noise

So far in this review I have discussed only noises in the audible region of the spectrum, and those that are continuous or interrupted. There are also some other varieties of noise that have been of concern in terms of the effects on human performance.

Aircraft flying at supersonic speed produce an N-shaped pressure wave in the atmosphere, which to a human observer sounds much like the shock wave from an explosion. How this sonic boom affects people has been a matter of particular interest in relation to public acceptability of overflights by commercial supersonic aircraft. The most significant research has been community reaction studies. Rather than objectively measurable degradation of performance, the sonic boom effects can be described as startle, annoyance, interference with ongoing activities, and disruption of sleep or relaxation. Obviously such effects are greatly influenced by the subject's previous experience and foreknowledge concerning the boom, as well as its loudness.

During 1961 and 1962, the city of St. Louis was experimentally subjected to sonic booms (Nixon, 1965; Nixon and Borsky, 1966), ranging from 0 to 5 lb/ft^2 overpressures produced by aircraft flights. Interviews were conducted to obtain community reactions. Some of the major findings, taken from Nixon and Borsky (1966), are shown in Table 5.

TABLE 5

Percentage of 1145 Interviewed in the St. Louis Area Who Reported Various Interferences Due to Sonic Booms and Resulting Annoyance

	Percentage of Total Interviewed Who Reported	
Nature of Interference Reported	Interference	Annoyance
House shaking	93	38
Startled	74	31
Sleep interrupted	42	22
Rest and relaxation interrupted	24	16
Conversation interrupted	22	10
Radio and television interrupted	14	0

A second community reaction study was conducted at Oklahoma City (Nixon, 1969), beginning in 1964. For this study overpressures at ground level from booms produced by aircraft ranged up to 1.60 lb/ft^2. Almost

3,000 of the residents were interviewed to obtain their reactions to the sonic booms. Some of the results as reported by Nixon (1969) are shown in Figure 8. Note that three of the five indicators of human reaction show a general upward trend during the course of the exposures.

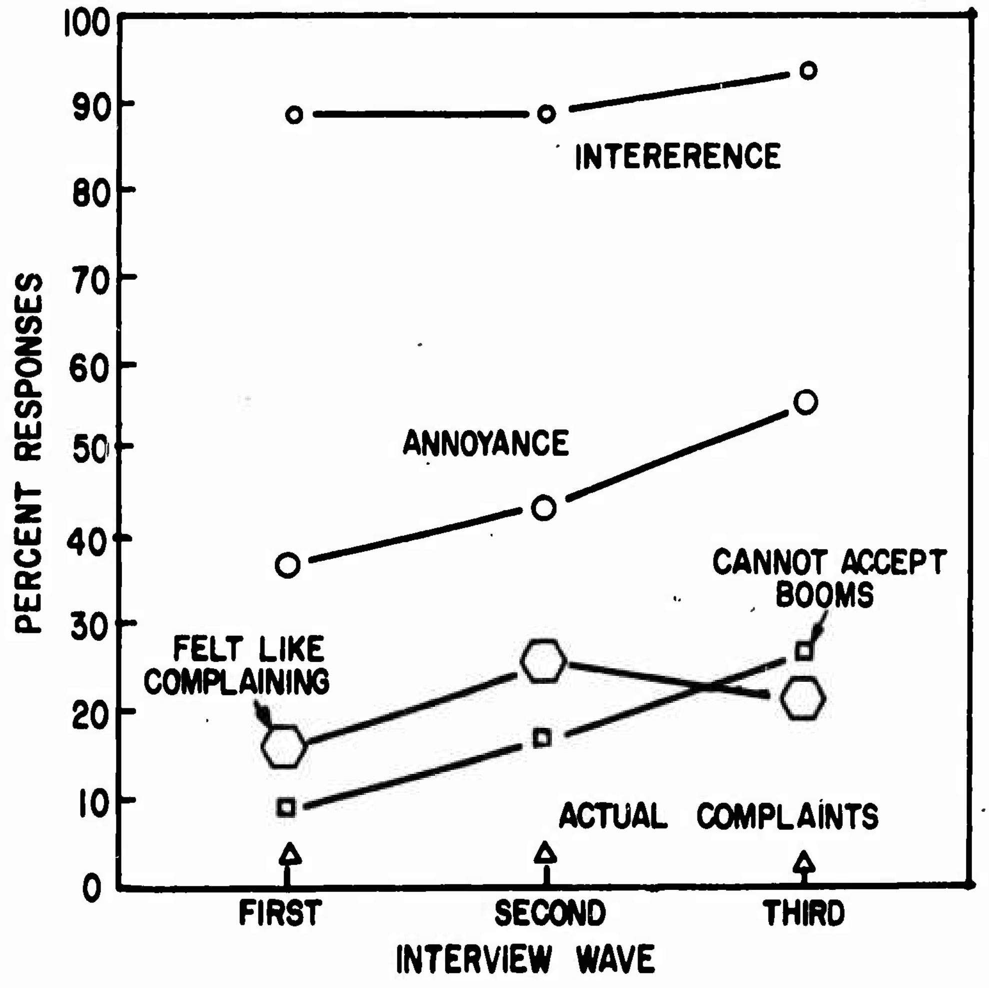


Figure 8. Overall community reactions. Summary of major public reactions during each of three interview waves (Nixon, 1969).

Aside from the community reaction studies there have also been laboratory measurements of human performance immediately after exposure to electronic reproductions of sonic booms. Woodhead (1969) measured performance on a symbol recognition test during 30 sec. periods following simulated booms of 0.80, 1.42, and 2.53 lb/ft^2. Only after the most severe booms was there an impairment of performance. Another study y Lukas, Peeler, and Kryter (1970), using a tracing task, also found some performance loss caused by simulated booms of 2.5 lb/ft^2.

There are sound waves either too high (ultrasonic) or too low (infrasonic) to be audible. Although there are no sharp limits to the audible spectrum, it is generally considered to run from 100 to 10,000 Hz. During and shortly after World War II there was considerable interest in the possible harmful effects of ultrasonic frequencies generated by jet aircraft engines, but it was soon found that these are harmless to people at the energy levels that could be encountered. More recently there has been interest in sound frequencies below the audible range, since rather high amplitude infrasonic energy is generated by large rocket engines.

Sound energy in the infrasonic range, roughly 1-100 Hz, tends to be more felt than heard, and, in terms of frequency, perhaps should be considered as vibration rather than noise. Certainly the range of frequencies includes those normally classified as vibration. Since we are concerned here with energy transmitted through the atmosphere ratner than by direct contact, however, it seems proper to treat this type of energy as sound. In terms of its possible effects on human performance the infrasonic range has been virtually untouched, most likely because of the unavailability of energy sources suitable for experimental purposes. Such an energy source will be available at the Aerospace Medical Research Laboratory when the Dynamic Pressure Chamber is ready for use.

Using a variety of sound sources that have high energy levels in the infrasonic range, a preliminary study was conducted by Mohr, Cole, Guild, and von Gierke (1965). They used a variety of sound sources producing energy in the 1-100 Hz range. The most significant results were obtained with the Sonic Fatigue Facility at Wright-Patterson AFB, which provided the highest energy levels. Voluntary subjective tolerance was reached at about 154 dB for frequencies in the range from 50 to 100 Hz. Sounds in this frequency range and near this energy level produced a number of subjective nonauditory symptoms, such as mild nausea, giddiness, and tingling. Most important for human performance, there was a significant decrement in visual acuity for all three subjects during maximum exposures to 43, 50, and 73 Hz. Other tests, one-leg stand, target dotting with eyes closed, handwriting, and circle tracing, showed no decrements. There was a small decrement in speech intelligibility at the highest energy levels.

General Summary of Effects of Noise on Performance

When viewed as a whole the research on the effects of noise seems confusing, contradictory, and inconsistent. Nevertheless, there are some generalizations that can be extracted from the studies of nonauditory effects covered in this review.

1. Some types of tests typically show no decrement, or at most, decrements that are slight and temporary. These tests are: simple reaction time, simple pursuit and compensatory tracking, mental arithmetic and clerical work.

2. Some other types of tests fairly consistently show performance decrements. These are complex reaction time, lathe or two-hand coordination, vigilance, and time estimation.

3. Many studies have shown improvement rather than impairment of performance during exposure to noise.

4. Intermittent and changing noises appear to have a greater effect than constant noise.

5. In many studies where decrements have appeared, they were greatest after onset, and diminished during exposure to noise. Some studies have also found decrements following cessation of noise.

6. In many studies performance degradation has been in terms of errors, with no impairment of speed.

Theoretical Mechanisms of Action

A number of theories or hypotheses can be advanced to help clarify the mechanisms whereby noise affects nonauditory human performance.

Noise as a Distractor

A reasonable and widely used explanation is that noise, and variations in noise level, distract the attention of the subject from his primary ongoing task. Such an explanation would seem to account for the frequent finding of a decrement at the onset of noise, and a return to normal performance as the subjects become accustomed to the noise. Distraction can, in a similar manner, account for the reported decrements following cessation of noise. The concept of noise as a distractor is supported by the finding of Teichner et al. (1963) that a change in noise level, either up or down, causes a decrement. The finding of generally greater decrements from interrupted and variable as opposed to constant noise levels is compatible with the distractor explanation.

It is plausible, also, to use a distraction interpretation to account for the greater susceptibility of some tests to the effects of noise. The more susceptible tests may require a greater concentration of attention than do others, and therefore, more readily show impairment from distraction by noise.

The Internal-Blinks Analogy

Broadbent (1957) has offered an explanation of some of the noise effect data by drawing an analogy to eye blinks in vision. Just as eye blinks cause momentary blocks in the visual sense channel, he suggests that noise may cause momentary blocks to the intake of information into the central nervous system. If such blocks occur at critical times they could cause impaired performance. On a vigilance test, for example, external signals come at unpredictable times, and could coincide with and be blocked by internal blinks. In this way Broadbent accounts for the noise-produced decrements on vigilance tests. Some other tests could also have unique sensitivity to internal blinks.

Actually, Broadbent's internal blink analogy is not greatly different from the previous explanation in terms of noise as a distractor. We need only consider that noise-caused distractions are fluctuating or momentary events which cause eye-blink-like deviations in the subject's attention.

Impairment of Short-Term Memory

A distinction is normally made between short-term and long-term memory, and such a distinction has utility for explaining much that we know about human learning and retention. Normally, information is held in short-term memory for only one or two seconds, and then lost forever, unless transferred to more permanent memory storage. Jerison (1959), following up a verbal remark attributed to Miles, suggested that noise causes increased difficulty in retaining information in short-term memory. He reasoned that a test which forces the subject to hold and use rapidly changing information should be disrupted by noise. Thus he devised his complex counting task, in which the subject had to keep a mental count of the number of flashes from each of three lamps. This test did not turn out to be particularly sensitive to noise, nor do other data seem to support impairment of short-term memory by noise.

Noise and Arousal

None of the theoretical mechanisms discussed thus far offer any explanation of the occasional finding that noise causes improved performance. For this there is a ready-made concept in terms of "arousal" and the "activation hypothesis." According to this concept, nerve impulses to the reticular formation in the midbrain can result in activation of cortical activity, or "arousal." In terms of external manifestations, such activation shows up as increased activity, alertness, and motivation of the organism. Noise is one of the stimuli that can cause arousal, and some of the research reported in this review was stimulated by the researcher's interest in testing the effects of noise as an arousing stimulus. For those instances where noise has been found to improve performance, this hypothesis, or at least some type of activating effect, offers a plausible mechanism of action. Using this explanation we must further assume that, for unknown reasons, experimental subjects under quiet conditions were operating at less than maximum alertness or motivation.

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As might be expected there are wide individual differences among people in their susceptibility to hearing loss from noise exposures. Also some hearing loss occurs normally as a function of age and disease processes. Because of these complicating factors and the accumulative effect of repeated exposures over a long period of time, it is difficult to distinguish between hearing loss caused by noise and that caused by age or other factors. In actual practice the identification of effects from noise involves analysis of statistical data on rather large populations of people whose noise exposure history can be rather accurately quantified.

Because of its importance to public welfare considerable effort has been devoted to the setting of noise exposure criteria for avoidance of hearing loss or damage. Such data are normally referred to as damage-risk criteria. Damage-risk criteria prepared by the American Standards Association (Rosenblith, 1954), as reproduced by Kryter (1960), are shown in Figure 1. This figure shows that the tolerable exposures for pure tones are about 10 dB lower than for wideband noise. It also shows the variations of tolerable exposure with frequency and with age of the subject. Data such as these have been used as guides for control of human exposures to noise; one implementing document for control is Air Force Regulation No. 160-3 (1956), Hazardous Noise Exposures. More recently a Federal Standard has been implemented by the Department of Labor (1969). The exposure values specified by this standard are given in Table 2. The tolerance limits or damage-risk criteria, shown in Figure 1 and Table 2 will be useful in evaluating the nonauditory effects of noise reviewed in ensuing sections.

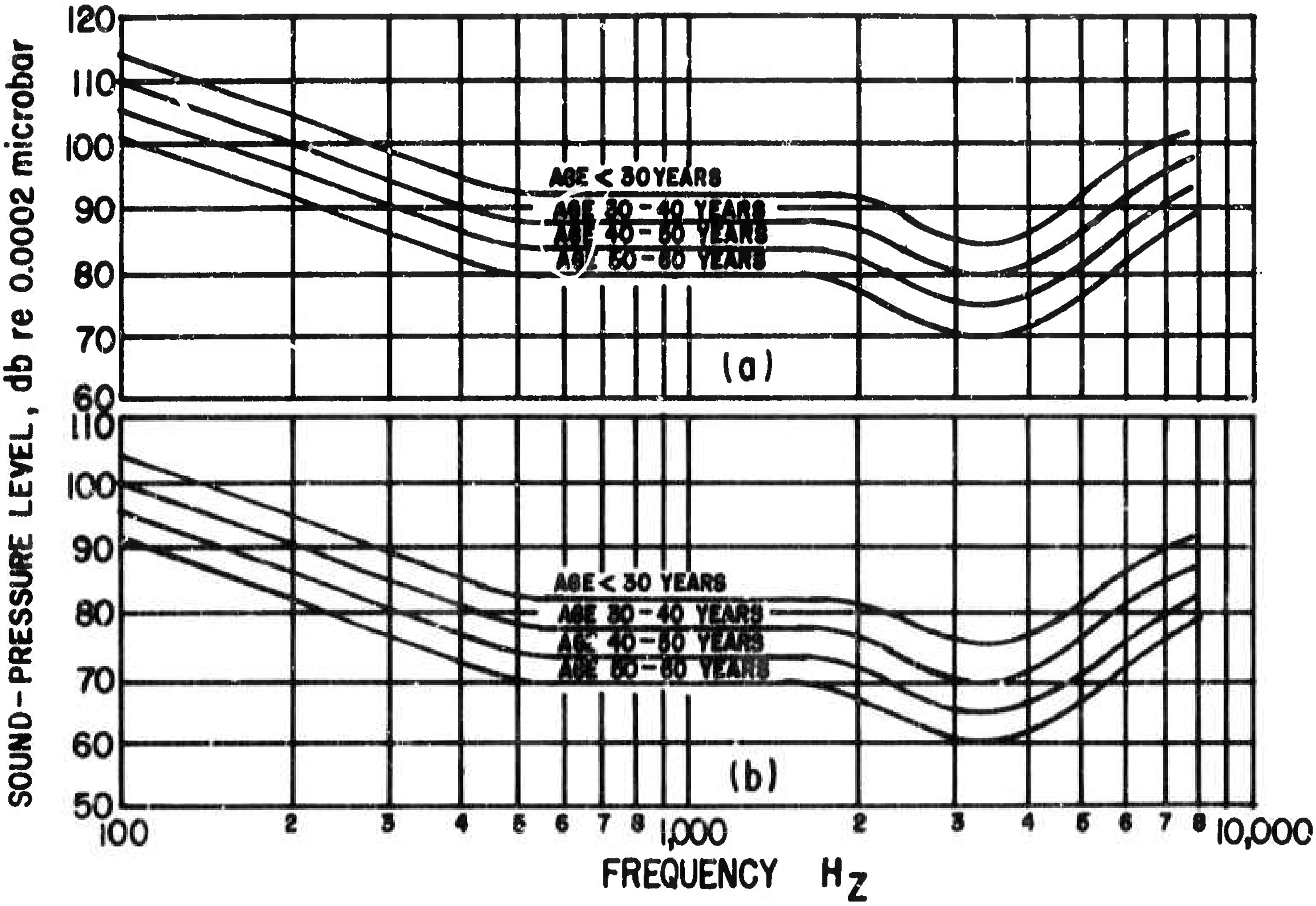

Figure 1. Proposed damage risk criteria for (a) wideband noise measured by octave, 8 hr. continuous exposure, and (b) pure tones or critical bands of noise (Rosenblith, 1954, from Kryter, 1960).

TABLE 2

Permissible Noise Exposures

Duration Per Day, Hours	Sound Level dBA
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

Masking

The most important effect of noise in degrading human performance is through masking or direct interference in the hearing of wanted sounds. Most serious is the interference with speech as used in person to person contact and through radio and telephone communication. Masking also interferes with hearing of tones and other nonspeech sound signals. A relatively large amount of research effort has been devoted to the study of masking and speech interference, and as a result the physical and auditory relationships are fairly well quantified. Considerable use is made of masking data in the design and evaluation of communication systems. In this review only some of the more general phenomena of masking will be discussed. For more detailed information the reader is referred to reports by Hawkins and Stevens (1950), Kryter (1950), Hirsch (1952), Hawley and Kryter (1957), Webster and Klumpp(1965), and Webster (1969).

In simple terms masking can be considered as an elevation of the absolute threshold for a wanted sound by a simultaneous unwanted sound. Generally, the masking sound is a broadband noise including a wide range of frequencies. But the masking effect is greatest from those sound frequencies closest to the tone or other sound for which the threshold is being measured. The greater the difference in frequency between the two sounds the less the masking effect. For pure tone thresholds, the elevation of absolute thresholds as the level of the masking sound is increased is shown in Figure 2 taken from Hawkins and Stevens (1950). Although the masking illustrated in this figure is produced by broadband noise the loudness of the masking sound is indicated in terms of noise level per cycle. The overall noise level for a 7,000 cycle band of noise would be about 40 dB higher.

It can be seen in Figure 2 that except at the lowest levels, the threshold increases seem to be a linear function of the masking noise level. This is better shown in Figure 3, also from Hawkins and Stevens