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SIX INDICES FOR PREDICTING SPEECH INTERFERENCE WITHIN AIRCRAFT

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FOREWORD

This research was conducted by the Noise and Hearing Conservation Function of the Otolaryngology Branch under task No. 775508 during the period 1 October 1968 through 6 July 1970. The revised manuscript was submitted for publication on 23 October 1970.

This report has been reviewed and is approved.

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ABSTRACT

Acoustic noise within aircraft during flight often causes some degree of interference with aural communication. Several methods have been used over the years to identify and predict degrees of speech interference. Six of these methods are discussed: four involve octave-band averaging; two use frequency weighting. The assessment is based on application of each of the six indices to noise levels measured within the cockpits of 191 fixed-wing and 58 rotary-wing aircraft, grouped into 11 categories by engine type. Equivalent speech interference levels obtained from the use of each of the six indices are provided for the acoustic spectra developed for the 11 classes of vehicles. The operational considerations which influence speech interference values are described. Noise attenuation provided by headset devices commonly used by Air Force aircrew members is shown for different groups of noise spectra. Criteria are given for evaluating protected and unprotected exposures to noise that compromise communications.

SIX INDICES FOR PREDICTING SPEECH INTERFERENCE WITHIN AIRCRAFT

I. INTRODUCTION

Many methods are available for estimating degrees of speech interference. The majority of methods, however, fail to provide valid assessments of speech interference encountered by pilots during flight. The contemporary methods of industry are not applicable to aerospace operations.

Somewhat like the aeronautical engineer of the late 1930s who used conventional engineering principles to prove that the bumblebee *could not fly*, the aeromedical evaluator today who attempts to measure speech interference in the cockpit by conventional means will have to conclude that most pilots *cannot* understand voice communications during most phases of airborne operation. Luckily, neither the bumblebee nor the pilot realize that they cannot do what they are doing.

Speech is a complex acoustic stimulus and the ultimate intelligibility of speech is not entirely dependent upon the fidelity of the acoustic signal nor the auditory acuity of the receiver (16, 35, 38, 39). Often, speech communications may be completely unintelligible to a naive listener but understandable to a more experienced listener—even though both have the same degree of auditory acuity. Many modifying factors must be considered (7, 16, 27, 35, 37, 38, 45) in the use of speech interference criteria, for example: prior knowledge (ability to anticipate the word to be used), previous experience with language used, redundancy of the message set (aural components of a given message which when grouped together comprise an understandable phrase or sentence; i.e., "now turning on final"), and use of limited vocabularies (2, 27).

Rare is the aeromedical evaluator who is not impressed when he attempts to listen to the same acoustic signal as the pilot of an aircraft and discovers that the pilot understands the message which he can barely discern as human speech. Experience and prior knowledge have a significant effect on success in accomplishing a given listening task.

This report will: (1) identify the noise spectra which provide the basis for the study; (2) describe methods of assessing degrees of speech interference; (3) provide a comparison of four averaging methods and two weighted-frequency methods as applied to the spectra identified; and (4) compare attenuated and nonattenuated conditions of noise exposure.

II. NOISE SPECTRA

Ambient noise measured within the cockpits of 249 aircraft during conditions of normal cruise provide the basic spectra for this study. The noise samples are grouped by aircraft engine type under 11 headings, 7 of which comprise the 191 fixed-wing aircraft and 4, the 58 rotary-wing vehicles.

Categories	*Number tested*
Fixed-wing aircraft	
Reciprocating:	
Single-engine	22
Dual-engine	40
Four-engine	19
Total	81

Categories	*Number tested*
Turboprop:	
Dual-engine	13
Four-engine	21
Total	34
Turbojet/fan:	
Internal and semi-internal	51
External	25
Total	76
Rotary-wing aircraft	
Reciprocating:	
Single-rotor	19
Two-rotor	4
Total	23
Turboshaft:	
Single-rotor	26
Two-rotor	9
Total	35

Noise envelopes representing the measurements within each category of aircraft are shown in figures 1 through 9 (two figures cover the 4 categories of rotary-wing aircraft). The data from which these envelopes were derived represent typical unprotected exposures encountered within the cockpits of the various aircraft during normal cruise conditions. (Extreme or unique types of noise have not been included in this study.) Noise environments within the cockpits varied with differences in type, number, and location of powerplants, environmental control systems, and auxiliary power systems (11, 13, 15). Many aircraft presently included within the military inventory of aerospace vehicles can perform diverse missions. Although the type of missions flown by an aircraft tend to modify further the character of noise exposures experienced by aircrew members (5, 9, 13, 17, 28), individual noise measurements for varying modes of operation were not made because of the difficulty of defining and evaluating them.

Fixed-wing aircraft

The following descriptions and illustrations depict the types of noise exposures which have been measured within the cockpits of 7 categories of fixed-wing aircraft during conditions of normal cruise. Of the 191 aircraft in the fixed-wing category, 91 are powered by reciprocating engines. The two most significant sources of noise associated with this type of aircraft are the aeroelastic disturbances generated by propellers, and engine exhaust (10, 17, 28). The noise produced by both of these components is most intense within the lower frequency range (9, 13, 17).

The most intense noise from propeller disturbances occurs in close proximity to the plane of rotation of the airscrew (17). Within most multiengine aircraft, propeller-generated noise is most intense at occupant stations just forward of the propeller plane (12), or in other words, within a half- to a full-propeller-diameter distance forward of the propeller plane.

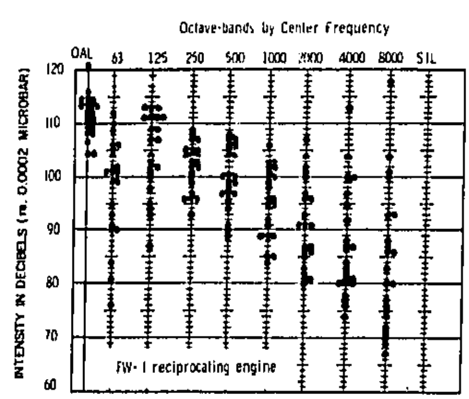


FIGURE 1

Noise levels within 22 fixed-wing, single-reciprocating-engine aircraft during conditions of normal cruise.

Single reciprocating engine. Noise measurements were obtained within the cockpits of 22 single-reciprocating-engine aircraft (fig. 1). A range of noise data is plotted for each of eight octave bands and for the overall levels. The relatively narrow range of the overall plottings—from 104 to 121 dB—can be seen. Generally, the most intense noise occurs within the lower octave bands. It can be noted that the average octave-band levels decrease about 3.3 dB at octaves above 125 Hz.

In this report "octave band" refers to preferred octave-band center frequencies. The geometric center frequencies, with corresponding octave-band limits, are: 63 (44 to 87), 125 (87 to 175), 250 (175 to 350), 500 (350 to 700), 1000 (700 to 1400), 2000 (1400 to 2800), 4000 (2800 to 5600), and 8000 (5600 to 12,000)—all in Hertz. All dB levels are reference 0.0002 microbar.

Contrary to general belief, the noise produced within an aircraft with a single reciprocating engine does not "fall off" in the higher frequencies as much as might be expected (5, 20). In fact, when mean values are considered, only a 20-dB downward slope is seen in the data plots within the six peak octaves above 87 Hz. This slope amounts to a roll-off of approximately 3.3 dB per octave, beginning at 125 Hz.

With one exception, the overall (OAL) noise levels (fig. 1) encompass a narrower range (17 dB) than the data points found at any octave. Two octaves, 250 and 500 Hz, show the closest clustering. Below and above these octaves, the plottings are more scattered. The data points in the two lowest octaves (63 and 125 Hz), which tend to expand the range, are found within the lower intensities (below 90 dB). In the higher octaves, especially above 1000 Hz, the levels recorded above 100 dB tend to expand the envelope.

Dual reciprocating engines. Noise measurements obtained within 40 fixed-wing aircraft, each powered by two reciprocating engines, are plotted in figure 2. The range of the overall levels extended from 92 dB to 121 dB, and the mean levels recorded at each octave reveal an average progressive decrease of 4.4 dB per octave. One difference between the plots of figure 2 and figure 1 is the greater clustering of individual data points for two-engine aircraft as compared with single-engine aircraft.

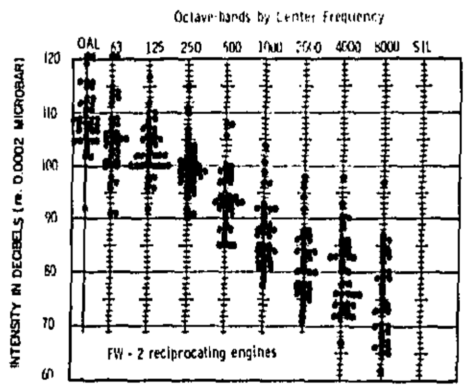


FIGURE 2

Noise levels within 40 fixed-wing, dual-reciprocating-engine aircraft during conditions of normal cruise.

Analysis of the data led to the following generalization: The range of the envelope is relatively wide. For the eight octaves, this range averaged 29.5 dB, but the average range was 26 dB for the lower four octaves and 33 dB for the upper four octaves. The overall levels had a range of 29 dB. For the data points recorded, those at the lowest octave, 63 Hz, and at the highest two octaves, 4000 and 8000 Hz, demonstrate the greatest scattering.

Four reciprocating engines. Plots were made of measurements obtained within 19 aircraft powered by four reciprocating engines (fig. 3). The overall levels extended from 95 to 110 dB—a range of 15 dB. The mean levels indicate a decrease of 4 dB per octave. The average range for all eight octaves was 19 dB. The relatively narrow range of the composite

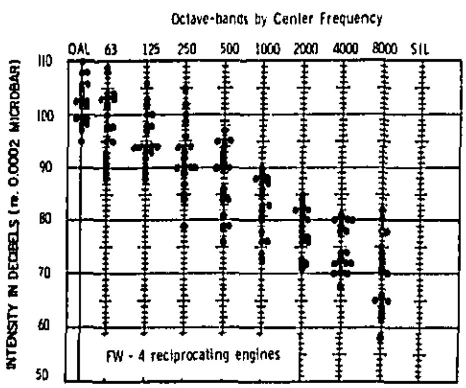


FIGURE 3

Noise levels within 19 fixed-wing, four-reciprocating-engine aircraft during conditions of normal cruise.

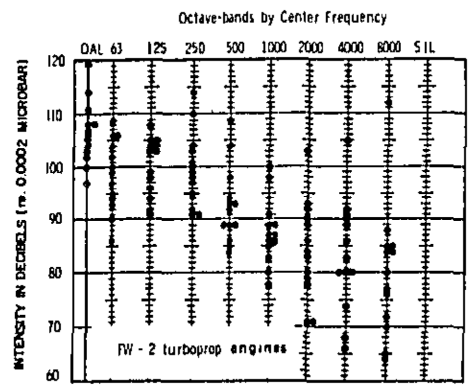


FIGURE 4

Noise levels within 13 fixed-wing, dual-turboprop-engine aircraft during conditions of normal cruise.

envelope is especially noteworthy. The octave bands 250 and 8000 Hz demonstrate the greatest range of data plots.

Turboprop-engine types. In some respects, the noise measured within the cockpits of turboprop aircraft closely resembles that measured within reciprocating-engine aircraft. The most prominent noise component is still that created by propeller disturbances, but exhaust noise is not so noticeable within turboprop aircraft. In fact, the exhaust noise of a turboprop powerplant is rarely audible at cockpit positions within the vehicle during flight (12, 17).

Generally, the propellers of turboprop aircraft rotate at higher blade-tip speeds than those of reciprocating airscrews (17). This feature, together with the fact that most contemporary turbopropeller systems contain four blades, causes the noise to have a spectral character somewhat different from that generated by reciprocating engines. Another feature of turbopropeller aircraft, which may account for differences in the magnitude of the noise measured within the vehicle, is that many are pressurized. Usually, the noise which invades occupied areas within pressurized aircraft is less intense than that within similar nonpressurized aircraft (10, 17).

Two basic subgroups are described and illustrated for turbopropeller aircraft: (a) aircraft fitted with two engines, and (b) vehicles mated to four engines.

Dual turboprop engines. A noise envelope was derived from plottings of noise levels measured within the cockpits of 13 aircraft powered by dual turboprop engines (fig. 4). The low-to-high range for each octave varied considerably, with an average range being slightly more than 29 dB.

Clustering of data points is not as evident for dual-turboprop aircraft as for those with two reciprocating engines (fig. 2). Although the range of the data varies widely from one octave band to another, the levels recorded at and above octave 2000 Hz represent the greatest variation.

Study of the mean values for the data reveals a dropoff of about 4 dB per octave above 250 Hz. The three lowest octaves (63, 125, and 250 Hz) do not reveal the extent of sloping with increases in frequency as that for the three lowest octaves reported for aircraft powered by two reciprocating engines. The mean values recorded for these three octaves

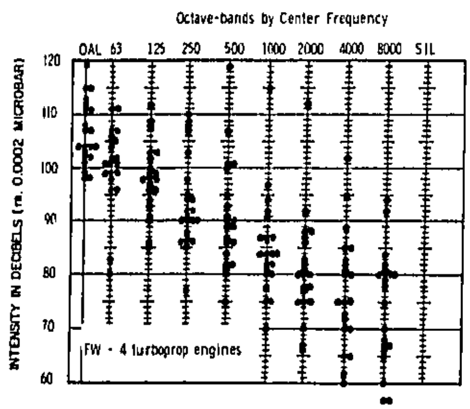


FIGURE 5

Noise levels within 21 fixed-wing, four-turboprop-engine aircraft during conditions of normal cruise.

(63, 125, and 250 Hz) were 99, 100, and 100 dB for the two-turboprop class, and 105, 103, and 100 dB, respectively, for the two-reciprocating-engine aircraft. Apparently, the magnitude of acoustic noise (within these three octaves, with increased frequency) does not decrease to the same extent in dual-turboprop aircraft as in dual-reciprocating-engine aircraft.

Four turboprop engines. A noise envelope evolved from plots of the levels in 21 fixed-wing four-turboprop aircraft (fig. 5). The overall levels extended from 98 dB to 115 dB—a range of 17 dB. The range of levels recorded throughout the eight octaves, however, extended from 27 dB at octave 125 Hz to as much as 46 dB at 2000 Hz—an average range of 38 dB. Obviously, the spread of data points for the overall levels encompassed a narrower range than was evidenced within any of the eight octave bands. The lowest four octaves rendered a composite mean of 34 dB, and the highest four octaves provided a mean of 42 dB.

Study of the values recorded for the eight octaves reveals that the average acoustic noise present within them decreased about 4 dB per octave. This slope encompassed all eight octaves. As with previous envelopes, a few extreme data points tend to distort the levels recorded within some octave-band ranges. Obviously, the one set of relatively high levels recorded at octaves 500 through 4000 Hz tends to distort the shape of the envelope reported for aircraft powered by four turboprop engines.

Turbojet and turbofan engine types. Most of the modern high-performance, fixed-wing aircraft are powered either by jet or fan-jet engines. The noise within the cockpit of most of these aircraft differs considerably from that previously described. In almost all jet-powered aircraft, the cockpit is positioned forward of the engines; and, in that position, the unprotected cockpit areas are not dominated during normal flight conditions by the intense noise commonly associated with the jet-exhaust stream (10, 12, 38).

Several aircraft-to-engine mating configurations now exist. These configurations, together with different performance and operational characteristics, produce differences in the character of noise in the aircraft (11). The following two types of aircraft-to-engine matings were used in the study: (a) aircraft in which the engine is installed internally or semi-internally (integral fittings); and (b) aircraft with engines fitted externally (within the structure of the wings or in external pods, and connected by short pylons either below the wings or at the far aft sides of the main fuselage).

The primary sources of noise within the cockpits of jet-propelled aircraft include aerodynamic disturbances and other forms of aeroelastic disturbances resulting from the operation of the various environmental control systems (10, 14). Aerodynamic noise is created when the outer sections of the fuselage, canopy, or windshield encounter aerodynamic loadings imposed by the surrounding atmosphere through which the vehicle travels.

Although several of the aircraft included within this section possess supersonic speed capability, noise levels were measured within cockpits during conditions of subsonic flight only.

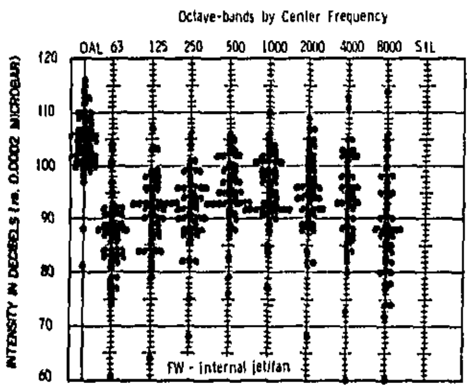


FIGURE 6

Noise levels within 51 fixed-wing aircraft powered by internally and semi-internally mounted turbojet/fan engines. Measurements were made during conditions of normal cruise.

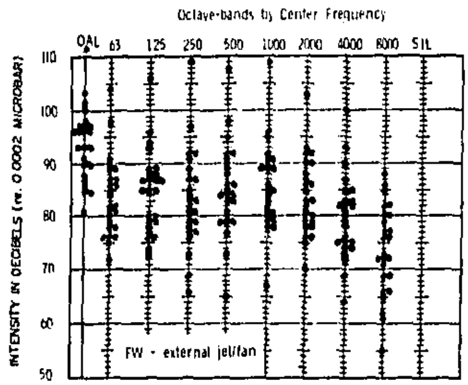


FIGURE 7

Noise levels within 25 fixed-wing aircraft powered by externally mounted turbojet/fan engines. Measurements were made during conditions of normal cruise.

Internally and semi-internally mounted turbojet and turbofan engines. Aircraft covered in this section include attack, fighter, and trainer types. Single, tandem, and side-by-side seating arrangements, as well as single- and dual-engine matings, are represented.

The envelope shown in figure 6 is composed of noise measurements obtained within 51 different aircraft fitted with internal or semi-internal single or dual engines. The overall measurements ranged from a low of 81 dB to a high of 116 dB—a total range of 35 dB. The average range for the eight octaves is 43 dB. Although a few extreme data points tend to expand the range of the envelope, the clustering of data points around the mean serves to describe the difference between this type of noise and that for all types of fixed-wing aircraft powered by either reciprocating or turboprop engines. The maximum noise level is most evident within four octave-bands: i.e., 500, 1000, 2000, and 4000 Hz.

Externally mounted turbojet and turbofan engines. The noise envelope shown in figure 7 represents noise measured within the cockpits of 25 aircraft fitted with turbojet/fan engines mated externally to the fuselage. The mean levels recorded are approximately 10 dB less intense than those within aircraft powered by internally and semi-internally mounted engines.

Once again, a few data points tend to expand the upper and lower range of the noise envelope. The range of the overall levels was 31 dB. The average range of data points for the eight octaves was 37 dB.

Rotary-wing aircraft

The development and growth of rotary-wing aircraft have been phenomenal. Previously, most of these vehicles were powered by reciprocating engines. Now, most of them receive power from turboshaft-type systems (6, 9, 17). This report deals with only two of the numerous design profiles which now exist: helicopters fitted with reciprocating engines, and those powered by turboshaft powerplants. Also, distinction is made between the data recorded within the single-rotor and dual-rotor groups.

Acoustic disturbance created by main rotors closely resembles that produced by conventional propellers (6, 9, 17, 36). Of course, rotors do not rotate at a shaft speed equivalept to that of propellers; but, because rotors do have larger diameters even at low speeds, the blade tips achieve velocities which approach high blade-tip speeds of conventional smaller diameter (but higher speed) propellers (6, 9, 17). Therefore, rotors do generate rather significant noise during most phases of operation. In general, rotors create acoustic disturbances which are found to be most intense within the lower frequency range.

Transmissions and gear-distribution systems produce noise that may assume major significance when such units are located near occupied spaces within the vehicle (6, 9, 15, 17, 37). Therefore, these sources of noise are most evident in helicopters in which the cockpit is located near transmission and gear-distribution units. The noise produced by these systems is rich in narrow-band noise components, usually distributed in octaves above ± 250 Hz (9, 15). Helicopters fitted with dual rotors have two major types of rotor configuration: tandem (or in-line) and intermeshing. Generally, discrete pure-tone components, most evident at locations near transmissions and gear and shaft distribution systems and components, are present within the cockpits of helicopters fitted with two rotors (17). For this reason, a distinction is made between data measured in the cockpits of one-rotor and two-rotor helicopters.

Noise produced by the various types of helicopter engines differs considerably. In general, at least within the cockpit area, the noise from reciprocating engines is more intense than that from turboshaft engines (9, 17).

Gas turbine (or turboshaft) systems do not produce as much noise as reciprocating engines, especially within the cockpit area (6, 11, 12, 15, 17, 36). In general, turboshaft engines are installed in a helicopter at locations which are further aft of the cockpit than in vehicles

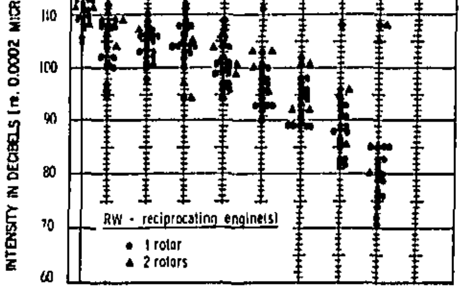


FIGURE 8

Noise levels within 19 single-rotor and 4 dual-rotor helicopters powered by reciprocating engines. Measurements were made during conditions of normal cruise.

powered by reciprocating engines. This feature, together with the fact that noise produced by the exhaust of turboshaft engines is less intense than that produced by reciprocating engines, results in less noticeable noise within the cockpit (15). Also, modes of vibrations mechanically induced by gas turbines are less intense (6, 38).

Reciprocating engine types. Noise levels were recorded in 23 rotary-wing aircraft powered by reciprocating engines (fig. 8). The envelope contains noise measured in two types of helicopters powered by reciprocating engines: single-rotor and dual-rotor. The range of overall levels recorded for the single-rotor vehicles (of which there were 19) was 13 dB; and for the dual-rotor vehicles, 6 dB. The most significant variation in range is found in the highest two octave-bands—4000 and 8000 Hz.

When combined, the range for all eight octaves averaged 20 dB. Considered separately, the average range was 20 dB for the single-rotor vehicles and 13 dB for the dual-rotor helicopters.

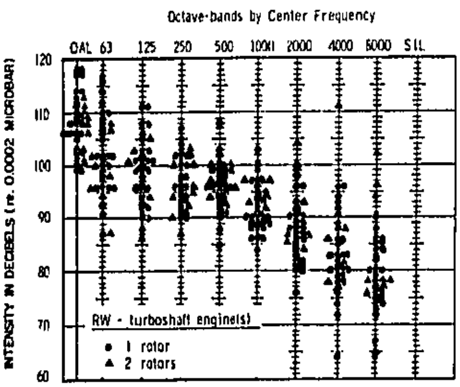


FIGURE 9

Noise levels within 26 single-rotor and 9 dual-rotor helicopters powered by turboshaft engines. Measurements were made during conditions of normal cruise.

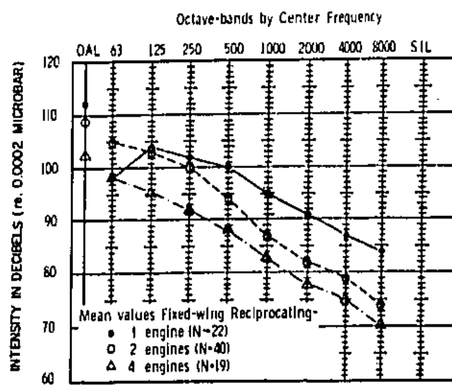


FIGURE 10

Means of noise levels for 3 categories of fixed-wing reciprocating-engine aircraft. (N = number of aircraft tested.)

Turboshaft engine types. A composite noise envelope was plotted for data obtained within the cockpits of 35 helicopters powered by turboshaft engines (fig. 9). Although the overall shape of the envelope is similar to that for vehicles with reciprocating engines (fig. 8), the upper and lower ranges of the envelope are considerably different. Also, the magnitude of the levels recorded at each octave is generally less. The mean values—except for the lowest and highest octave (63 and 8000 Hz)—are about 10 dB less intense than those obtained within vehicles powered by reciprocating engines.

The range of overall levels recorded for the 26 single-rotor helicopters was 19 dB; for the 9 dual-rotor vehicles it was 12 dB.

Summary of noise envelopes

Noise envelopes (figs. 1 through 9) illustrate the types of noise within the 249 aircraft during normal cruise conditions. The mean values extracted from the noise data are illustrated and compared in figures 10 through 13.

Mean values for overall and octave-band levels for the 3 categories of fixed-wing aircraft, all with reciprocating engines, are illustrated in figure 10. The mean levels for the single-engine aircraft reveal peak values, except for the lowest octave (63 Hz). Levels shown for the dual-engine aircraft are next to the highest; and the levels for four-engine aircraft constitute the lowest values derived from the entire study of mean levels for all 81 vehicles.

Comparison of the mean values (fig. 10) reveals an average difference of 6.3 dB between single- and dual-engine aircraft at octaves above 63 Hz. Comparison of the differences between two- and four-engine aircraft rendered an average of 5.5 dB at all octaves, and comparison between the single- and four-engine data disclosed an average of 11.6 dB at all octaves above 63 Hz. Data reveal that the mean levels recorded for the lowest octave, 63 Hz, are most intense within the cockpits of two- or four-engine aircraft; whereas, the mean level recorded in the 125-Hz octave is most pronounced within the single-engine aircraft.

Mean values were obtained from 34 fixed-wing aircraft powered by turboprop systems

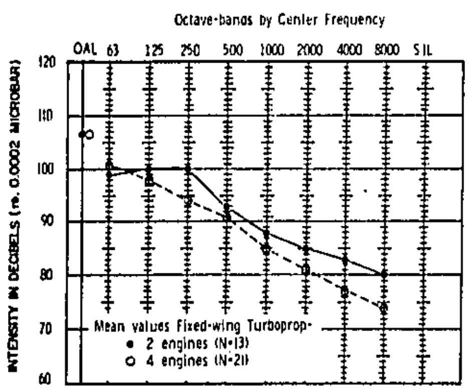


FIGURE 11

Means of noise levels for 2 categories of fixed-wing turboprop aircraft. (N = number of aircraft tested.)

(fig. 11). Although the mean overall levels for two- and four-engine aircraft were the same, differences in mean levels were recorded within various octaves. An average difference of 4.2 dB was found between the means reported for two- and four-engine aircraft at octaves above 63 Hz. The mean levels for two-engine turboprop aircraft were approximately equal in the three lowest octaves (63, 125, and 250 Hz). Mean values for four-engine aircraft, however, showed considerable variance, with the lowest octave band of 63 Hz containing the highest mean level.

Plots were also made of the mean levels extracted from data on 76 fixed-wing aircraft with turbojet/fan systems (fig. 12). The average levels for 51 aircraft with internally and semi-internally mounted engines are higher than those for 25 aircraft with engines mounted externally to the fuselage of the aircraft. Levels reported for internally and semi-internally mounted engines averaged 9.4 dB higher in each octave band than those for externally mounted engines.

Two sets of mean levels are shown in figure 13. One set was obtained by combining the data for 23 single- or two-rotor helicopters with reciprocating engines; the other set combines data for 35 single- or dual-rotor helicopters with turboshaft engines. The average difference between the two spectra is 5.1 dB.

The means recorded for three octaves—63, 125, and 250 Hz—constitute the highest levels for vehicles powered by reciprocating engines (fig. 13). The level in the lowest octave, 63 Hz,

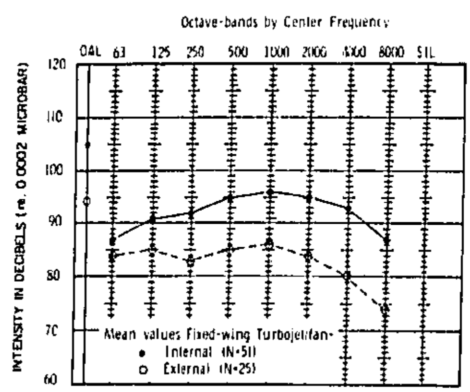


FIGURE 12

Means of noise levels for 2 categories of fixed-wing turbojet/fan aircraft. (N = number of aircraft tested.)

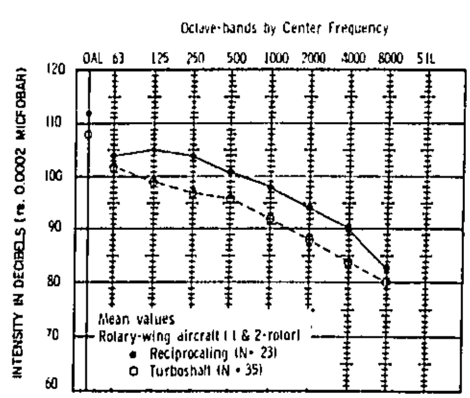


FIGURE 13

Means of noise levels for 2 categories of helicopters. (N = number of aircraft tested.)

represents the highest value within vehicles powered by turboshaft engines.

Prominent octave bands. The mass of data contained in the foregoing discussion and illustrations fails to point up those octaves containing the highest noise levels for all vehicles. To provide concise information, sets of data are presented (figs. 14 and 15) to show the octave bands in which the highest levels of noise were recorded for each of the groups of fixed- and rotary-wing aircraft. The octave-band levels for each of the 249 aircraft were studied; and every octave was noted which contained the peak (maximum) and/or levels within 3 dB of the peak. Therefore, figures 14 and 15 identify the octaves where the peak and near-peak (within 3 dB of maximum) levels were found.

Plotted in figure 14 are the octave bands which contain the highest levels for each aircraft in the sample of 191 fixed-wing vehicles. To obtain the relative percentages for each category of aircraft, the number of occurrences noted for each octave was divided by the total number of aircraft in a given category. For example, 5 of 22 single-reciprocating-engine aircraft demonstrated maximum or near-maximum levels within the octave of 63 Hz; this

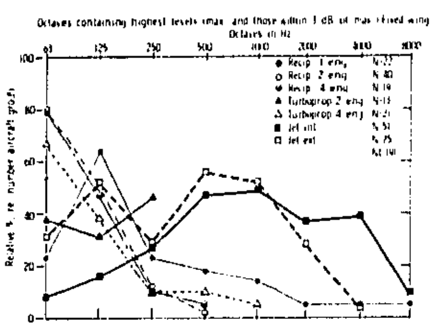


FIGURE 14

Percent distribution of peak noise levels by octave bands within all categories of fixed-wing aircraft. (N = number of aircraft in each category; Nt = total aircraft.)

rendered a relative percentage of 23%. Replication is evident, because many spectra contained peak and near-peak levels which occurred at more than one octave band.

The three lowest octaves of 63, 125, and 250 Hz contained the most intense noise components for fixed-wing aircraft powered by either reciprocating or turboprop systems (fig. 14). The noise spectra within single-reciprocating-engine vehicles contained the greatest proportion of intense noise within the second octave of 125 Hz, whereas dual- and four-reciprocating-engine aircraft contained proportionally more noise in the lowest octave band (63 Hz). Also, although the proportion of maximum and near-maximum levels reported for aircraft powered by a reciprocating engine is most pronounced within the lowest three octaves, the presence of near-maximum levels is evident at higher frequency ranges for the aircraft powered by a single engine.

The relative distribution of maximum and near-maximum levels is essentially equivalent for spectra reported for aircraft powered by either two or four reciprocating engines.

Data for the 2 groups of aircraft powered by turboprop systems reveal that the three lowest octaves (63, 125, and 250 Hz) contain the maximum levels within aircraft powered by two engines. Aircraft fitted with four turboprop engines revealed noise spectra in which the level present in the lowest octave, 63 Hz, was proportionally higher than that found at 125 Hz.

The distribution of the most intense noise components within aircraft powered by two turboprop engines was 38% at 63 Hz, 31% at 125 Hz, and 46% at 250 Hz. For aircraft powered by four turboprop engines, the 63-Hz octave band contained 67% of the maximum levels; the 125-Hz, 38%; and the 250-Hz, 10%.

For turbojet/fan aircraft, the peak and near-peak levels within a given octave differ considerably from those described for all groups of propeller-driven aircraft (fig. 14). The most noticeable difference is the greater incidence of maximum and near-maximum levels at octaves above 250 Hz. Also, a larger proportion of octave bands contains levels which are either at or within 3 dB of the maximum levels for all octaves (fig. 14). The proportion of maximum levels at the lowest two octave bands (63 and 125 Hz) is greater within aircraft fitted with externally mounted engines than within those with internally and semi-internally mounted engines, but the proportion of highest levels at the highest three octaves (2000, 4000, and 8000 Hz) indicates the opposite relationship.

Data are also reported for the 2 major categories of rotary-wing aircraft: those with reciprocating engines, and those with turboshaft systems (fig. 15).

The highest levels were in the 250-Hz octave in single-rotor vehicles with reciprocating engines. Octave 125 Hz contained the greatest proportion of peak and near-peak levels for two-rotor vehicles with reciprocating engines. Accordingly, the highest noise levels in different octaves lie within the three lowest bands (63, 125, and 250 Hz) in single-rotor helicopters with reciprocating engines, whereas the highest levels lie within the two lowest bands (63 and 125 Hz) in dual-rotor vehicles fitted with reciprocating engines.

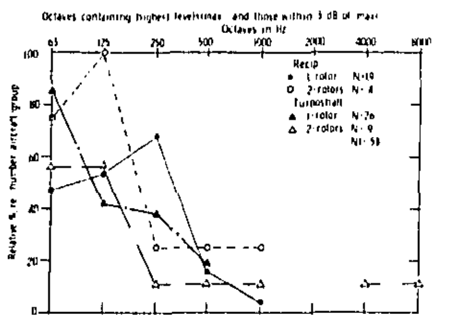


FIGURE 15

Percent distribution of peak noise levels by octave bands within all categories of rotary-wing aircraft. (N = number of aircraft in each category; Nt = total aircraft.)

The octave band 63 Hz contains the largest proportion of peak and near-peak levels for turboshaft-engine helicopters fitted with single rotors, whereas the two lowest octaves, 63 and 125 Hz, contain equivalent distributions for vehicles fitted with dual rotors (fig. 15). The presence of fairly intense narrow-band components in the higher frequency ranges is evidenced by the relative occurrences depicted at the two highest octave bands, 4000 and 8000 Hz.

III. METHODS AND CRITERIA FOR EVALUATING SPEECH INTERFERENCE

Many methods have evolved for identifying and classifying degrees of speech interference. Most of these methods relate to subjects with normal hearing and are based on speech discrimination performance obtained under controlled listening conditions. Test stimuli used to establish different values of speech discrimination in the presence of noise range from simple sentences to single-syllable words or nonsense syllables.

A review of the most commonly used methods and criteria for measuring and predicting degrees of speech interference provides insight into the related problems and assumptions.

The type of test stimuli used to establish speech intelligibility should be carefully considered because single-syllable words are more difficult to understand in noise than are sentences or phrases. Therefore, the criteria should be more stringent for situations requiring use of single-syllable words than for those involving sentences or phrases.

Articulation index

Since French and Steinberg (8) proposed the use of the articulation index (AI) in 1947, vigorous efforts have been made by researchers to improve this proposed methodology. Details concerning the articulation index are too extensive for inclusion here. A 1962 publication by Kryter (25) constitutes the most valuable single reference for those attempting to utilize the AI concept, as well as its modifications and changes. An additional source of information on this subject is in a book edited by Morgan et al. (27). Minor and major alterations in the basic method for computing AI have enlarged upon its applications, especially for systems employed in ground and airborne aerospace operations.

To predict approximate speech intelligibility for electrical communication systems, the articulation index (in one form or another) is probably the best method currently available (18, 19, 21-24, 26, 29-33, 40, 41, 43).

Modifications to articulation index

In 1955, Pickett and Kryter (29) described an extension in the use of the AI, through which predicted articulation in noise could be assessed by physical acoustic measurements of full-octave bands.

Methods of evaluating speech intelligibility in high-level ambient noise have been the subject of considerable study during the past decade, especially since greater demands are being placed on retention of speech communications in environments where intense noise exists. Pickett and Pollack (30), in 1958, completed a study of speech interference factors in noise ranging up to 130 dB sound pressure level (SPL) in which speech and noise signals were electronically combined and presented to listeners via headsets. Five combinations of speech and noise were evaluated: speech frequency emphasis of 0 and +6.0 dB per octave; and random noise spectra with slopes of 0, +6.0, and −12.0 dB per octave. By retaining constant signal-to-noise ratios, large decrements in speech intelligibility could be created for all noise spectra as the level of the noise was increased. Essentially, Pickett and Pollack sought to evaluate various methods in use in 1958 to predict speech intelligibility for such intense speech-masking conditions. Basically, three methods were considered for predicting the degree of speech intelligibility comparable to the scores which they actually obtained during their study: (a) overall signal-to-noise ratio, (b) articulation index (20-band method) proposed by French and Steinberg (8), and (c) the articulation index (octave-band method) suggested by Beranek and Newman (1). Pickett and Pollack (30) found that, at least for their study, the most accurate index for predicting speech intelligibility in high-level noise is that proposed by French and Steinberg (with slight modifications by Pickett and Pollack). The simplest method was the overall signal-to-noise ratio, which renders reasonably accurate predictions when corrections for intense noise levels are applied.

Use of the original 20-band method or of the modified octave-band method to define the articulation index was the best approach available to predict speech intelligibility related to communication systems.

Speech interference level

To evaluate the intelligibility of face-to-face communications in noise, the primary method recommended is the speech interference level (SIL), which consists of using averages of noise levels in certain octave bands.

Considerable emphasis has been given to the use of octave-band averaging methods to predict or establish acceptable noise levels for various environments. Beranek and Newman (1) presented a paper at the thirty-ninth meeting of the Acoustical Society of America in 1950, in which they proposed the use of simple octave-band averaging to rate noise conditions in offices. This technic has been used quite effectively by numerous investigators and offers a fairly accurate estimate of acceptability of noise conditions that exist where face-to-face speech communications are routinely conducted. Many investigators have suggested using the average of various octave bands.

Beranek study. Beranek (3, 4), and others of the staff of Bolt, Beranek and Newman, Inc., working independently or under Government contract, have greatly expanded the knowledge concerning speech interference and the assigning of criteria related to the acceptability and feasibility of speech communications in various noise environments. The criteria for noise in buildings, as proposed by Beranek in 1957 (3), have been used extensively in connection with computations and determinations concerning speech interference. The basic criteria curves—noise curves (NC) and alternate noise curves (NCA)—and the noise condition criteria recommended for rooms and office spaces have, together, provided guidelines for design engineers and others. Apparently the criteria proposed by Beranek in 1957 have proved their value, especially if use is the measure of effectiveness. These criteria have been widely distributed in publications in the United States and in foreign countries. Unfortunately, the NC and NCA contours have limited value when applied to various aerospace vehicle environments (39).

Specialists in human engineering are currently faced with noise environments having noise levels above those to which previous criteria for predicting speech interference are applicable (such as the NC and NCA described by Beranek) because the previous contours extend only to an upper range of NC-70 and NCA-70 (13, 34). Webster (42, 43), and Webster and Klumpp (41), formulated a set of speech interference (SI) curves that, in essence, extend Beranek's noise ratings into a higher range, from which critical levels of speech interference can often be predicted. Essentially, these speech interference contours extend beyond the basically esthetic considerations (for comfort, loudness, and annoyance) that are essential features of the NC and NCA contours from Beranek's noise criteria.

U.S. Navy study. Webster and Klumpp (45) recently completed a comprehensive study of methods of evaluating speech-interfering noises. The basis of their study was research on 16 noises commonly encountered by U. S. Navy personnel. The results of this series of studies revealed the following:

1. Noise environments in typical U. S. Navy spaces exceed those in civilian areas where equivalent communication tasks are performed.

2. Data on 16 noises led to three conclusions:

a. The best single method is the averaging of three octaves (i.e., 300-600, 600-1200, and 1200-2400 Hz).

b. The next to the best method consists of weighting networks (A-scale or DIN-3) of sound-level meters, or of finding the SIL in the octaves from 300 or 600 to 4800 Hz.

c. The least effective method consists of fitting spectral noise peaks to noise criteria rating curves, of which the NCA was found to be better than the contours for either the conventional NC or the ISO (International Organization for Standardization).

3. The articulation index, a more complicated method, served well to measure speech interference, and the simpler 5- and 6-octave methods used to establish equivalent AI, employing a generalized speech spectrum, were found to be almost as good as the more elaborate 20-band method.

4. The use of contours and curves (NC, NCA, or ISO) to predict degrees of speech interference was of value if both of the following were observed: Only the part of the contour that centered at 500, 1000, and 2000 Hz was used, with the curves averaged through spectral peaks and valleys of the noise spectra.

5. Speech in quiet environments required, for half-intelligibility, frequencies above and below a value from 1600 to 1900 Hz; but as the ratio of speech signal-to-noise decreases, the required frequency range dropped to about 800 or 1000 Hz.

6. The maximum noise level at which unprotected face-to-face voice communications could be accomplished was an SIL (500/1000/2000 Hz) of 95 dB.

7. The maximum SIL (500/1000/2000 Hz) for effective speech communication via noise-proofed sound-powered phones is: 84 dB, if the talker is in a quiet environment and the listener is in a noisy area; 95 dB, if

both the talker and the listener are in noisy environments; and 114 dB, if the talker is in a noisy area and the listener is in a quiet environment.

8. Amplified speech communications with earphones and use of noise-cancelling dynamic or condenser microphones appeared possible in a 500/1000/2000 Hz SIL of 120 dB. This assumes the use of noise-shielding at the mouth and ear, a speech bandwidth of at least three or more octaves centered between 1000 and 1800 Hz, a low sidetone level, employment of automatic volume control (AVC), and peak clipping (44).

9. Amplified speech communications with loudspeakers (sound-field) appeared possible in 500/1000/2000 Hz SIL levels of 80 dB. If earplugs or earmuffs (noncommunication type) are worn, the SIL can be extended to 95 dB (44, 45).

Webster (42) also devised a set of speech interference contours through which relative degrees of speech interference could be evaluated. Recently, Beranek stated that his staff was attempting to revise the current set of NC and NCA contours to reflect the changes necessary to make the contours more valid (7).

Webster's speech interference curves, especially for A-scale levels that exceed about 60 dB, clearly indicate an attempt to consider frequency-dependent factors that influence speech intelligibility in moderate to high-level ambient noise. The rationale underlying this assumption was reported by Webster and Klumpp (41) in 1963, and by Webster (43) in 1964. The latter publication contains a description of information and data (from a survey of contemporary literature and from practical and laboratory research conducted at the U. S. Navy Electronics Laboratory) from which Webster's initial speech interference curves were derived. These curves definitely reflect the influence of the articulation index (43).

The results of the comprehensive studies by Webster and Klumpp provide insight and guidance to aeromedical evaluators, bioenvironmental engineers, and others who must measure and define speech interference. Anyone who has to evaluate a noise environment in which the ambient noise is suspected of producing interference with voice communications should carefully study the collected reports of Webster and Klumpp (45).

IV. COMPARISON OF THE SIX RATING METHODS

Six indices were used in predicting speech interference levels for the noise spectra of this study.

1. ISO-4. This index was developed by the International Organization for Standardization, and consists of the averaging of octave bands 250, 500, 1000, and 2000 Hz.

2. PSIL—the average of 500, 1000, and 2000 Hz octave bands.

3. $PSIL_1$—the average of 500, 1000, 2000, and 4000 Hz octave bands.

4. SIL—the average of 1000, 2000, and 3000 Hz octave bands.

5. L_A—the computed, or measured, A-scale level (A-scale weighting network of a sound-level meter).

6. L_C—the C-scale weighting network of a sound-level meter.

Note: No methods employing tangent-to-curve interpretations were used. Preliminary study of three such contours (the NC, NCA, and ISO sets) revealed that the task of reporting mass data made the use of such contours far too complicated for inclusion in the study.

The two most common octave-band averaging methods used as simple indicators of speech interference employ averaging octaves 500, 1000, and 2000 Hz; or octaves 1000, 2000, and 4000 Hz. Table I contains relative degrees of speech interference associated with four levels of voice effort; i.e., normal, raised, very loud, and shout. Two methods of averaging are shown: method A, which consists of averaging

TABLE I

Relative degrees of speech interference under four conditions of vocal effort as measured by two octave-band averaging methods

Distance (in feet)	Normal voice		Raised voice		Very loud voice		Shout	
	A*	B†	A	B	A	B	A	B
0.5	71	76	77	82	83	88	89	94
1	65	70	71	76	77	82	83	98
2	59	64	65	70	71	76	77	82
3	55	60	61	66	67	72	73	77
4	53	58	59	64	65	70	71	76
5	51	56	57	62	63	68	69	74
6	49	54	55	60	61	66	67	72
12	43	48	49	54	55	60	61	66

*Method A (average of 1000, 2000, and 4000 Hz).
†Method B (average of 500, 1000, and 2000 Hz).

the three octaves 600 to 1200, 1200 to 2400, and 2400 to 4800 Hz (identified in table I by preferred octaves 1000, 2000, and 4000 Hz); and method B, which consists of averaging the levels in the octaves 500, 1000, and 2000 Hz. The relative values of speech interference presuppose limits of acceptable discrimination for single-syllable (or nonsense) words, no reverberation, face-to-face nonamplified speech effort, and no message set or language clues (46). A difference of 5 dB exists between the speech interference values obtained by use of the two averaging methods. A constant of 6 dB is provided for each doubling, or halving, distance. Essentially, the method which averages octave-band levels in the higher frequency range, method A, is set at levels which are 5 dB more stringent than values derived from averaging the set of octaves which account for acoustic noise present within a slightly lower frequency range, i.e., method B (average of 500, 1000, and 2000 Hz).

Figures 16 through 19 contain mean values of acoustic noise obtained in aircraft included in the current study. Mean levels are reported for five octaves corresponding to the ones used by the four averaging methods. Index points arrived at by use of the four octave-band averaging methods—ISO-4, PSIL, $PSIL_1$, and SIL—are also shown. In addition, mean values are shown for measurements relative to the A-scale weighting network of a standard sound-level meter (L_A), and C-scale levels acquired by use of a sound-level meter (L_C).

Figure 16 shows mean values which evolved from the data acquired on 81 fixed-wing aircraft powered by reciprocating engines. The

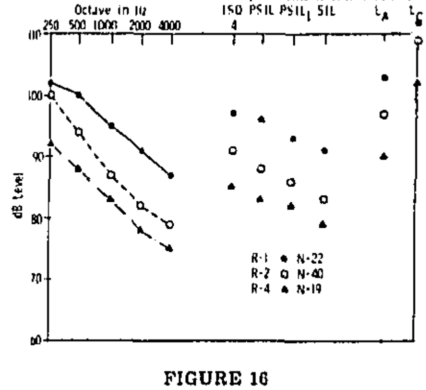


FIGURE 16

Means of noise levels for 3 categories of fixed-wing reciprocating aircraft. Corresponding speech interference indices, as determined by six different methods, are shown.

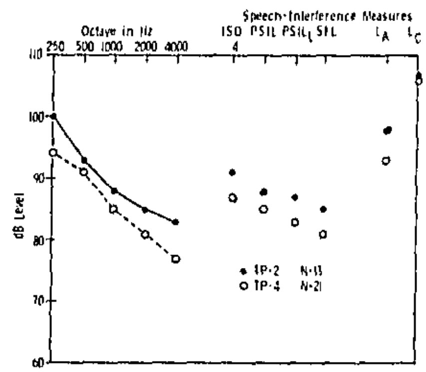


FIGURE 17

Means of noise levels for 2 categories of fixed-wing turboprop aircraft. Corresponding speech interference indices, as determined by six different methods, are shown.

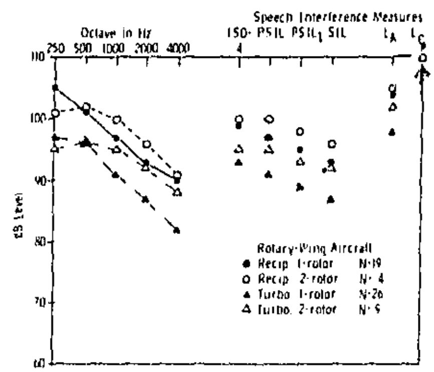


FIGURE 19

Means of noise levels for four categories of rotary-wing aircraft. Corresponding speech interference indices, as determined by six different methods, are shown.

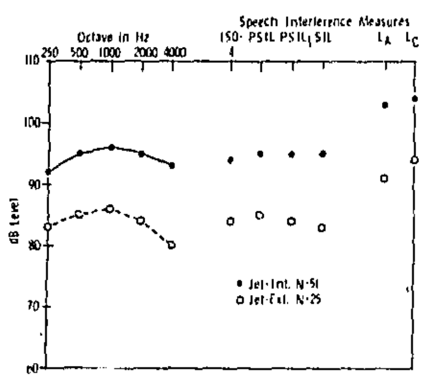


FIGURE 18

Means of noise levels for 2 categories of fixed-wing turbojet/fan aircraft. Corresponding speech interference indices, as determined by six different methods, are shown.

dominance of acoustic noise within the frequency range of 250 Hz is evident. Since the octave band of 250 Hz contains the most pronounced noise, averaging which includes this octave results in the highest index point. Regardless of whether the aircraft is fitted with one, two, or four reciprocating engines, the four averaging methods differ from each other by approximately 2 dB when the sequence of octaves used to obtain averages extends from the lowest to the highest frequency range. Essentially, the total range of mean values found for the four averaging methods is about 6 dB, with the method identified by SIL rendering the lowest and the ISO-4 rendering the highest. Differences noted between L_A and L_C are 9 dB for aircraft powered by single reciprocating engines and 12 dB for both two- and four-engine vehicles.

As illustrated in figure 16, the highest acoustic noise levels were found within the cockpits of aircraft powered by single reciprocating engines. The next highest values were measured in two-engine aircraft. The lowest levels were found within vehicles having four engines. Generally, the mean levels recorded for aircraft powered by two engines were 7 to 8 dB less than those obtained within vehicles powered by single engines, and the levels recorded within aircraft powered by four engines were about 5 dB less intense than those found within vehicles fitted with two engines. Since differences noted between the four averaging methods used in this study remain relatively constant regardless of the type of aircraft-to-powerplant mating used, the following generalizations can be made: The mean speech interference levels measured in aircraft powered by two reciprocating engines are about 7.5 dB less than those within aircraft powered by single engines, and levels obtained within vehicles powered by four reciprocating engines are 5 dB less than levels obtained within vehicles powered by two engines and 12.5 dB less than levels obtained within aircraft powered by single engines. Since the levels of noise measured within various octaves tend to decrease as frequency increases, the averaging methods which include levels in the lower octave-band range will render higher values than those which include levels measured within the higher octave-band range.

Figure 17 depicts a set of data similar to that shown in figure 16, except here the data apply to fixed-wing aircraft powered by either two or four turboprop engines. The octave 250 Hz contains the most pronounced noise found within the five octaves used within the four averaging methods. Here also, the acoustic noise decreases with increases in frequency. This observation is confirmed by the finding that averaging methods yield lower values when the higher octaves are used to obtain the average. Generally, the four methods differ from each other by a value of about 2 dB. The highest values are found by use of the ISO-4 method and the least intense levels were acquired by using the SIL method. A total range of 6 dB exists between the highest and lowest values obtained with the four averaging methods. Interestingly enough, this total range is found for both groups of aircraft; those fitted with either two or four turboprop powerplants.

The levels provided for L_A and L_C measurements reveal that L_A is 9 dB lower than L_C for aircraft fitted with two turboprop engines and L_A is 13 dB below L_C within aircraft fitted with four turboprop engines.

Figure 18 illustrates mean values which evolved from plotting data obtained in aircraft fitted with internally and semi-internally mounted turbojet/fan engines and vehicles where the engines are mated externally. In these aircraft the mean levels (averages of five octaves) are more nearly equal than those reported for propeller-type aircraft. As a consequence the four averaging methods yield almost the same levels of speech interference. Essentially, aircraft fitted with engines that are installed within the fuselage (or engines fitted semi-internally) render mean speech interference levels that are about 11 dB higher than those obtained within the cockpits of aircraft where the engines are installed in the main body of the wings, or mated to the wings by pylons, or installed at the far aft end of the fuselage and attached by short pylons. Also internally and semi-internally mounted engines render a mean L_A value that is only 1 dB less than L_C. The mean L_A is 3 dB less than the mean L_C on vehicles in which the engines are installed externally. The near equivalence of values of L_A and L_C emphasizes the contribution of mid- and high-frequency noise components to the overall noise spectra reported for those two groups of aircraft.

Figure 19 illustrates mean values which evolved from data obtained on 58 rotary-wing aircraft. Data points for the 4 categories of helicopters reveal that those fitted with single rotors (reciprocating and turboshaft) have sloping spectra in which the 250-Hz octave contains the predominant acoustic noise. The 2 categories of dual-rotor vehicles (powered by reciprocating and turboshaft engines) demonstrate mean spectra in which the octaves 250, 500, and 1000 Hz share almost equal magnitude. Values derived from all four averaging methods reveal that the highest index points are encountered within both groups of vehicles fitted with dual rotors.

The data shown for all four averaging methods indicate that interference values obtained within single-rotor vehicles powered by reciprocating engines are about 6 dB higher than index points derived from noise levels within single-rotor helicopters powered by turboshaft engines. A similar finding applies to dual-rotor vehicles; the index points for aircraft powered by reciprocating engines are about 5 dB higher than those for turboshaft engines.

Single-rotor helicopters fitted with reciprocating engines yielded a mean L_A value 6 dB higher than the L_A value of single-rotor vehicles powered by turboshaft engines, and the mean L_A value for dual-rotor helicopters fitted with reciprocating engines was about 3 dB greater than that for vehicles powered by turboshaft engines.

The data depicted in figures 16 through 19 illustrate the range of values obtained from the use of the four octave-band averaging methods and the two overall weighted methods. It is obvious that the content of the spectrum from which the four averaging methods derive plays an important role in determining the relative magnitude and equivalence between the various methods. Spectral content, therefore, directly influences the magnitude and equivalency of the resulting averages. Except for the data obtained on both groups of fixed-wing aircraft fitted with turbojet/fan engines, each of the averaging methods which include higher octave-band levels yielded lower mean values. Generally, except for both groups of fixed-wing aircraft fitted with turbojet/fan engines, the ISO-4 method will yield higher values than the PSIL method; the PSIL will furnish levels that are greater than those obtained with $PSIL_1$; and the $PSIL_1$ will exceed levels obtained by the SIL method. All four octave-band averaging methods yield essentially equivalent levels when the spectrum is representative of fixed-wing aircraft powered by turbojet/fan powerplants.

Shown in figure 20 are the mean spectral levels which evolved from the study of 191 fixed-wing aircraft. Plots of mean spectra for the 7 categories of fixed-wing aircraft illustrate the influence that spectral shape has on the resulting octave-band averaging methods and weighted values, especially on the L_A, where the contribution of acoustic noise present within the mid- and high-frequency range is more significant.

Shown in figure 21 are the mean spectral levels for 58 rotary-wing aircraft. Here again, overall mean spectra decreases in magnitude with increases in frequency range. The slope of the spectra for the rotary-wing aircraft resembles that of propeller-driven fixed-wing aircraft at octaves above 250 Hz, but below 250 Hz reveals a flatter contour.

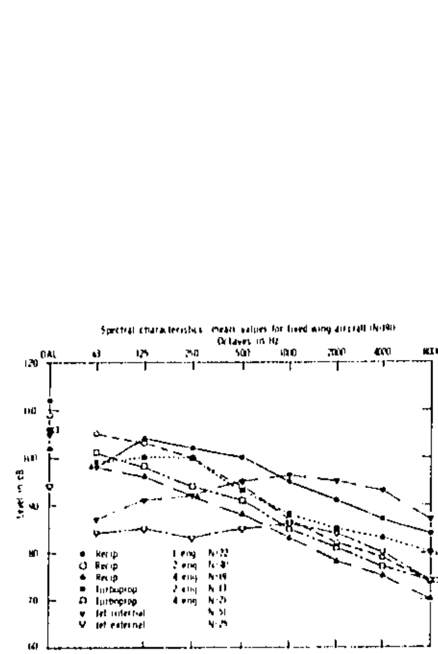


FIGURE 20

Mean spectral characteristics of 7 categories of fixed-wing aircraft. (N = number of aircraft in class.)

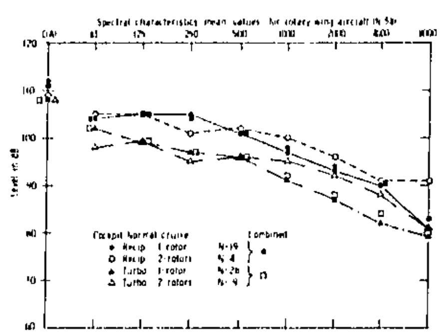


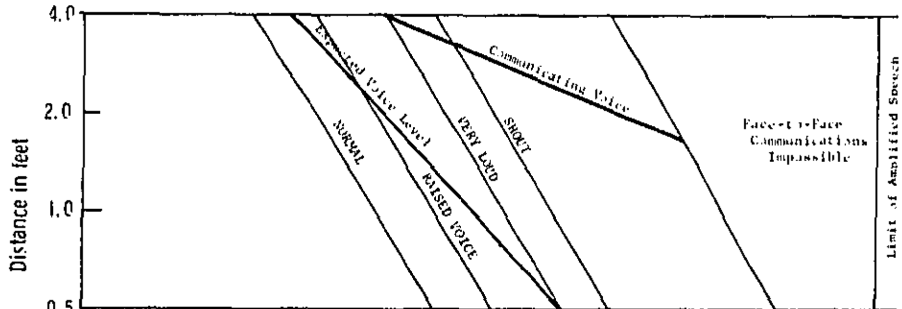
FIGURE 21

Mean spectral characteristics of 4 categories of rotary-wing aircraft. (N = number of aircraft in class.)

Equivalent values

A summary of the speech interference indices resulting from application of each method is presented in figure 22. The levels which evolved from the study of the 249 aircraft

Equivalent values of different measures related to determining speech interference.
Data applicable to ambient noise levels measured in fixed-and rotary-wing aircraft.



ISO-4	42(40)	52(50)	62(60)	72(70)	82(80)	92(90)	102(100)	112(110)	122(12
PSIL	40(41)	50(51)	60(61)	70(71)	80(81)	90(91)	100(101)	110(111)	120(12
$PSIL_1$	38(41)	48(51)	58(61)	68(71)	78(81)	88(91)	98(101)	108(111)	118(12
SIL	36(41)	46(51)	56(61)	66(71)	76(81)	86(91)	96(101)	106(111)	116(12
L_A	47(47)	57(57)	67(67)	77(77)	87(87)	97(97)	107(107)	117(117)	127(12
L_C	56(50)	66(60)	76(70)	86(80)	96(90)	106(100)	116(110)	126(120)	136(13

Levels noted in ( ) are to be used when evaluating speech interference in fixed-wing aircraft powered by turbojet/fan engines.

FIGURE 22

Equivalent values of six measures of speech interference.

included in this study yielded equivalent values which are entered at the bottom of the chart. The values not shown in italics refer to equivalent values measured within all fixed- and rotary-wing aircraft, except fixed-wing aircraft powered by turbojet/fan engines. Equivalent values for fixed-wing aircraft fitted with turbojet/fan engines are shown in italics at the right side of each appropriate column.

Parameters of vocal effort similar to those proposed by Webster and Gales (46) are shown in figure 22. The parameters presuppose nonprotected ears, nonreverberant sound field, face-to-face communications, and no language or message-set clues. The line identified as expected voice level presupposes that vocal effort increases approximately 3 dB for each 10-dB increase in masking noise, and that the need to communicate is not critical. If the need to communicate is critical, the increase in vocal effort is about 5 dB for each 10-dB increase in ambient noise.

Generally, the length of time an individual will attempt to communicate at a shout is very limited. Webster (44) has specified that 70 dB PSIL should be avoided in spaces where people must conduct communications, and noise-proofing of people and spaces must be considered when a PSIL of 90 dB, and above, is encountered. Webster has further emphasized that, when a PSIL exceeds 100 dB, the need for ear protection is mandatory and, if communications are to be successfully accomplished, noise-proofing of people and space is essential.

Table II is a comparison of the four octave-band averaging and the two overall frequency-weighting methods. The values shown are mean levels resulting from the application of the six methods to means for each category of aircraft. Part A of table II contains values which can be used to compare differences among the indices for all aircraft categories in this study other than jet. The values provided

TABLE II

A. Comparable values for aircraft categories other than jet

	ISO-4	PSIL	$PSIL_1$	SIL	L_A	L_C
ISO-4		-2	-4	-6	+6	+15
PSIL	+2		-2	-4	+7	+17
$PSIL_1$	+4	+2		-2	+9	+19
SIL	+6	+4	+2		+11	+21
L_A	-6	-7	-9	-11		+9
L_C	-5	-17	-19	-21	-9	

B. Comparable values for turbojet/fan aircraft

	ISO-4	PSIL	$PSIL_1$	SIL	L_A	L_C
ISO-4		+1	+1	+1	+9	+11
PSIL	-1		0	-1	+7	+9
$PSIL_1$	-1	0		-1	+7	+9
SIL	-1	+1	+1		+8	+10
L_A	-9	-7	-7	-8		+2
L_C	-11	-9	-9	-10	-2	

in part B can be used in comparing any of the six indices when the values were derived from turbojet/fan aircraft.

The values contained in part A and part B were derived from differences noted between mean levels for the six indices included in this study. For example, a PSIL of 96 dB obtained within a fixed-wing aircraft fitted with two turboprop engines corresponds to an ISO-4 of 98 dB, or +2 (as shown in part A, table II). Also, the expected A-scale of a sound-level meter (L_A) would be 103 dB (+7 dB). Therefore, the values contained in parts A and B of table II provide correction factors which can be used to compare different methods that have been studied in this paper.

The common statement that people who must work and communicate in noise get used to it requires some qualification. Although the idea is generally accepted, changes and compromises do result when noise intrudes into the communicating environment. Observation indicates that individuals subjected to noise usually tend to limit their vocabulary, to select and use reduced message sets, to rely on visual codings and clues, and to employ other similar modifications. Although most communicators can compensate for many undesirable effects of noises, the communicators may achieve only limited success.

Experience in and knowledge of the communication tasks commonly performed amid interfering noise significantly improve the margin of success attained when the need to communicate arises. For this reason, distinction should be made between the naive and the sophisticated listener or communicator. Essentially, the limiting levels contained in figure 22 should be considered as applicable to relatively naive listeners with normal hearing acuity (within the speech range). Hence, the next phase of study will be the extent to which the levels of predicted speech interference can be adjusted to identify different degrees of listening experience encountered in the aerospace environment.

Table III contains a summary of mean values, or levels, of speech interference which were obtained from noise data from the 11 categories of aircraft included in this study. The mean values obtained from octave-band averaging methods (ISO-4, PSIL, $PSIL_1$, and SIL) demonstrate consistently higher values when lower octaves are included, except for a single category—the fixed-wing aircraft powered by turbojet/fan engines. Only one other group of data might be considered as almost insensitive (according to which octave band is included in a given three- or four-band averaging)—namely, the data for two-rotor helicopters powered by turboshaft systems (Ts-2r). Data (table III) reflect the finding that, of the 249 vehicles studied, all but 85 (i.e., 76 of

TABLE III

Means of speech interference by aircraft category as determined by six different methods

Category	Number of aircraft	ISO-4	PSIL	$PSIL_1$	SIL	L_A	L_C
Single-recip.	22	97	96	93	91	103	112
Dual-recip.	40	91	88	86	83	97	109
Four-recip.	19	85	83	81	79	90	102
Dual-turboprop.	13	91	88	87	85	98	107
Four-turboprop.	21	87	85	83	81	93	106
Turbojet (int.)	51	94	95	95	95	103	104
Turbojet (ext.)	25	84	85	84	83	91	94
Single-rotor recip.	19	99	97	96	93	104	112
Dual-rotor recip.	4	100	100	98	96	105	110
Single-rotor turboshaft	26	93	91	89	87	98	108
Dual-rotor turboshaft	9	95	95	93	92	102	108

the fixed-wing aircraft with turbojet/fan engines, and 9 two-rotor helicopters with turboshaft systems) contained acoustic noise within the lower range of octaves (especially 250 and 500 Hz) greater than that within the higher range (1000, 2000, and 4000 Hz). Review of the mean levels plotted for all octaves (figs. 21 and 22) substantiates this finding.

Data derived from this study have two inherent limitations: First, since the data measured within 249 vehicles have been combined into categories, only generalized assumptions can be made. Individual variations are known to exist. Therefore, unique acoustic features may be evidenced by a few aircraft, even though the vehicle is included in a specific category. Second, the data extracted for the 249 vehicles represent only acoustic exposures which exist during conditions of normal cruise.

V. EFFECTS OF ATTENUATION ON NOISE LEVELS

The following section provides data to evaluate equivalent levels of speech interference under attenuated and nonattenuated conditions of noise exposure. A simple method of predicting relative degrees of speech interference with the use of circumaural earphones is given.

Nature of the auditory signal

The complicated nature of the temporal signal routinely encountered by pilots is illustrated in figure 23. The final signal processed by the auditory system is a composite of part of the noise which exists in the surrounding environment, the desired auditory signal

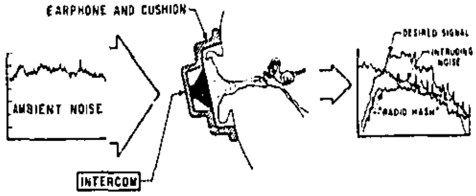


FIGURE 23

Complexity of listening task associated with airborne operations.

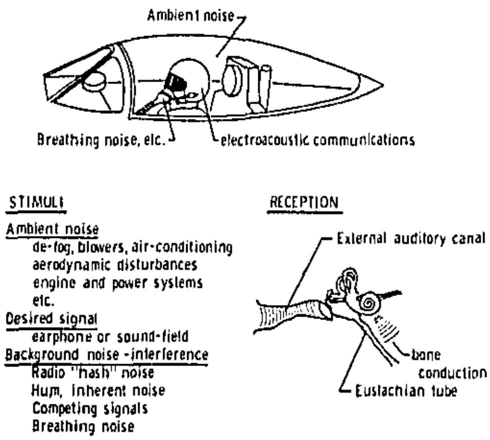


FIGURE 24

Pathways of acoustic stimuli.

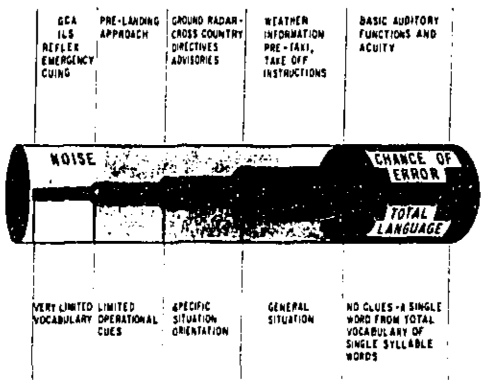


FIGURE 25

Elements related to success versus failure in auditory communications.

(speech), and noise inherent within the intercom-radio system. Figure 24 further expands these basic concepts. A variety of acoustic stimuli are mixed with the desired signal. Some of these extraneous acoustic stimuli constitute a continuous masking effect, such as that part of the ambient noise that has passed through the noise-attenuating device (earphone cusions). Other stimuli intrude in an intermittent manner, such as breathing noise and noise which enters the cavity of the middle ear through the eustachian tube during periods of ventilation.

Modifying factors

We have previously discussed the many modifying factors which affect speech interference criteria—factors such as prior knowledge, language usage, redundancy of the message set, and others. Figure 25 displays five degrees of probability related to failure to understand a given speech communication during ground and airborne operations. The experienced pilot can perform listening tasks in noise environments which would produce almost total masking of a given signal to the naive listener.

The effect of auditory masking noise on flying personnel is the topic of current research being conducted at the USAF School of Aerospace Medicine. The purpose of this research is to identify acoustic characteristics of the auditory signal which contribute to failure in receiving and successfully understanding speech communications and to identify those features which compromise accomplishment of successful auditory functions in subjects with normal and those with nonnormal hearing.

Data base for noise attenuation studies

Figure 26 contains data points which represent amounts of noise attenuation provided by seven types of circumaural headsets commonly used by persons who routinely fly fixed- and rotary-wing vehicles. Noise attenuation values shown in figure 26 represent "average" attenuation. These values can be used to estimate degrees of attenuation to be expected within the five octaves germane to this study; i.e., 250, 500, 1000, 2000, and 4000 Hz. Values of "expected attenuation" are: 5 dB at 250 Hz, 10 dB at 500 Hz, 25 dB at 1000 Hz, 30 dB at 2000 Hz, and 35 dB at 4000 Hz. These levels of attenuation are generalized; under ideal conditions, even greater amounts of noise attenuation may be achieved.

Figures 27 through 31 demonstrate attenuated and nonattenuated mean exposure levels recorded for 249 fixed- and rotary-wing aircraft within five octaves (250, 500, 1000, 2000, and 4000 Hz; by center frequencies). Corresponding predicted speech interference levels, as determined by each of four averaging methods (ISO-4, PSIL, $PSIL_1$, and SIL) are also plotted.

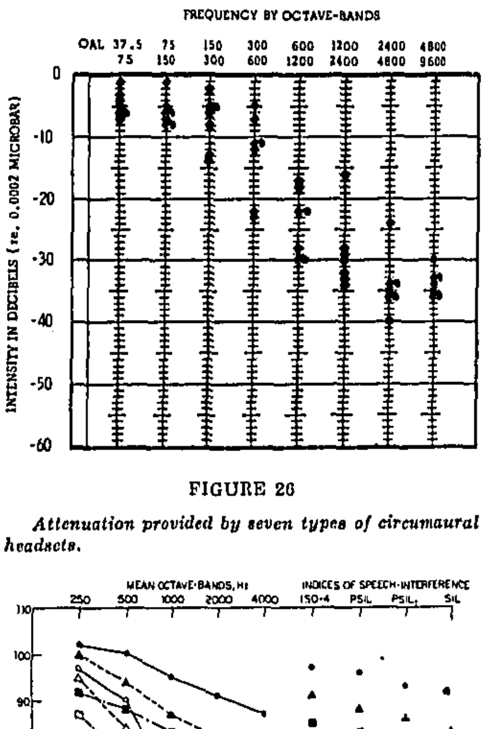


FIGURE 26

Attenuation provided by seven types of circumaural headsets.

Figure 27 illustrates attenuated and nonattenuated mean levels for three categories of fixed-wing aircraft powered by reciprocating engines. Rank ordering of the four octave-band averaging methods reveals that ISO-4 yields the highest level at which speech interference may be expected to occur, then follow PSIL, $PSIL_1$, and SIL. Examination of means recorded for octaves 250 through 4000 Hz helps clarify the reason for this distribution. The averaging method which employs levels in octaves which are most intense, such as the lower frequency range, yields the higher values.

Figure 28 provides similar findings derived from the study of noise levels recorded within the cockpits of aircraft fitted with turboprop powerplants.

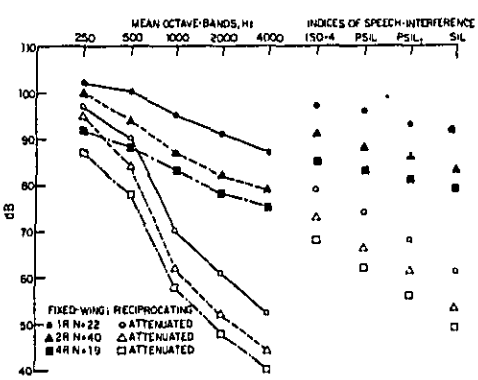


FIGURE 27

Means of noise levels (attenuated and nonattenuated) for 3 categories of fixed-wing reciprocating aircraft. Corresponding speech interference indices, as determined by each of four averaging methods, are shown.

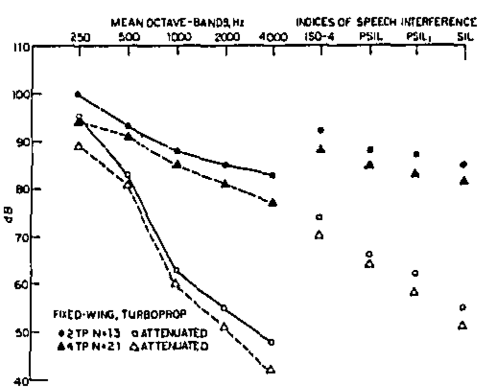


FIGURE 28

Means of noise levels (attenuated and nonattenuated) for 2 categories of fixed-wing turboprop aircraft. Corresponding speech interference indices, as determined by each of four averaging methods, are shown.

Once again, the octave-band averaging method which employs levels recorded within the lower frequency range, where the magnitude of the noise spectra is greatest and circumaural headsets provide minimal amounts of attenuation, yields values of "predicted speech interference" greater than derived from averaging methods which use levels measured within higher octaves.

Figure 29 contains plottings of nonattenuated and attenuated mean octave-band levels and indices of speech interference for fixed-wing aircraft fitted with turbojet/fan engines. Since the shape of the two mean spectra is essentially flat, the nonattenuated values of speech interference yield equivalent mean levels. Differences noted between the four attenuated speech interference levels occur because the amount of noise attenuation provided by earphones is not the same at all frequencies.

Figures 30 and 31 contain plottings of nonattenuated and attenuated spectra (250 through 4000, center frequency) and four octave-band averaging methods for 4 categories of rotary-wing vehicles. Figure 30 contains results derived from noise measurements obtained within 23 single- and dual-rotor helicopters powered by reciprocating engines.

The data demonstrated in figure 31 provide similar plottings for 35 single and dual rotary-wing aircraft powered by turboshaft powerplants.

Comparison of data reported in figures 30 and 31 reveals that helicopters fitted with reciprocating engines contain exposures that are about 6 to 8 dB greater than levels measured within vehicles powered by turboshaft engines.

Figure 32 contains plottings of mean indices for the four octave-band averaging methods for the 11 categories of aircraft studied.

Data plotted in figure 32 reveal that the highest values of SIL for all aircraft groups are obtained with the use of ISO-4, and the lowest values are derived from use of the basic SIL method.

Method for predicting speech interference with earphone attenuation

Figure 33 provides two matrices which can be used to determine equivalent levels of speech interference for attenuated exposures.

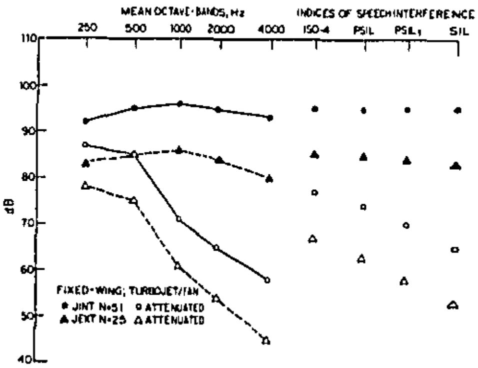


FIGURE 29

Means of noise levels (attenuated and nonattenuated) for 2 categories of fixed-wing turbojet/fan aircraft. Corresponding speech interference indices, as determined by each of four averaging methods, are shown.

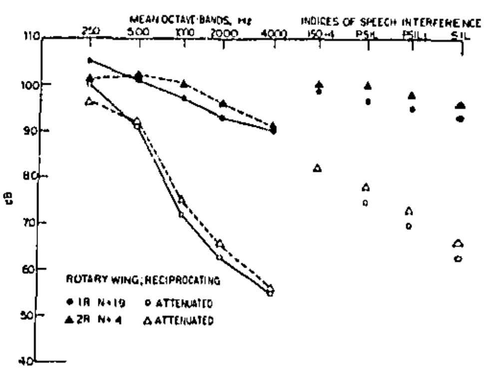


FIGURE 30

Mean values of noise levels (attenuated and nonattenuated) for 2 categories of rotary-wing reciprocating aircraft. Corresponding speech interference indices, as determined by each of four averaging methods, are shown.

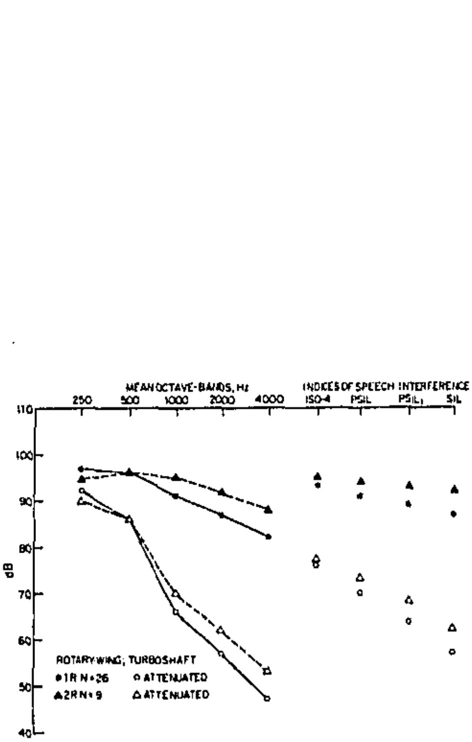


FIGURE 31

Mean values of noise levels (attenuated and non-attenuated) for 2 categories of rotary-wing turboshaft aircraft. Corresponding speech interference indices, as determined by each of four averaging methods, are shown.

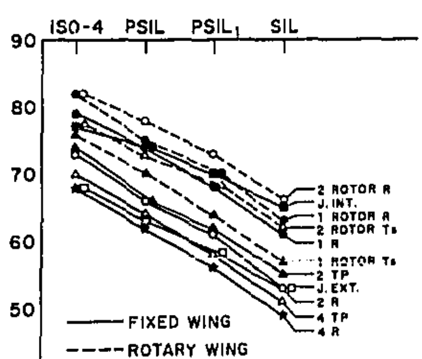


FIGURE 32

Comparison of four indices of speech interference under attenuated conditions derived from 11 categories of fixed- and rotary-wing aircraft.

The top matrix provides values for use with noise exposures encountered within all fixed- and rotary-wing aircraft, except fixed-wing vehicles powered by turbojet/fan engines; the lower matrix covers the latter type. The blocks shown in the upper matrix are divided into two sections for each element in the matrix. The upper left part applies to fixed-wing aircraft and the lower right part (separated by the diagonal line) is for rotary-wing aircraft.

The procedure for using these two matrices is simple. For example, with an attenuated value computed for SIL of 65 dB, the equivalent PSIL (500, 1000, 2000 Hz) would be 6.5 dB less (fixed-wing reciprocating engine aircraft); thus, the PSIL value would be 58.5 dB.

Definite limitations exist with the use of the methods which have been discussed in this report. It must be clearly understood that this approach assumes many generalities, but the results derived from this study do provide valuable insights regarding a recurring question associated with the operation of aerospace vehicles—"How can degrees of speech interference be determined within aerospace vehicles?"

EQUIVALENT VALUES

NON-JET FIXED-WING AND ALL ROTARY-WING (TYPE AIRCRAFT (WING): FIXED / ROTARY)

TO CONVERT ↓ / TO →	ISO-4	PSIL	PSIL1	SIL
ISO-4		-6.5 / -5.3	-12.0 / -10.5	-19.2 / -17.3
PSIL	6.5 / 5.3		-5.5 / -5.2	-12.7 / -11.9
PSIL1	12.0 / 10.5	5.5 / 5.2		-7.2 / -6.8
SIL	19.2 / 17.3	12.7 / 11.9	7.2 / 6.8	

FIXED-WING JET/FAN

TO CONVERT ↓ / TO →	ISO-4	PSIL	PSIL	SIL
ISO-4		-3.5	-8.0	-13.0
PSIL	3.5		-4.5	-9.5
PSIL1	8.0	4.5		-5.0
SIL	13.0	9.5	5.0	

FIGURE 33

Equivalent values for four indices of speech interference for use in comparing conditions of attenuation.

VI. SUMMARY AND CONCLUSION

Use of the four octave-band averaging methods in this study revealed several interesting findings. Any octave-band averaging method which includes frequency bands below about 1000 Hz will render protected, or attenuated, levels greater than those found with averaging methods which employ levels in octaves 1000 Hz and above. The reason for this is twofold: the spectral content of the noise measured within all aircraft, except fixed-wing turbojet/fan vehicles, is greatest within octaves below 1000 Hz; and the amount of noise attenuation provided by circumaural headsets is less at frequencies below 1000 Hz than above.

The average amounts of attenuation which can be considered appropriate for circumaural headsets for the four octave-band averaging methods included in this study are: 18 dB for octaves 250 through 2000 Hz (ISO-4); 22 dB for octaves 500 through 2000 Hz (PSIL); 25 dB for octaves 500 through 4000 Hz ($PSIL_1$); and 30 dB for octaves 1000 through 4000 Hz (SIL).

The results of this study support the general assumption that the noise environments encountered within most fixed- and rotary-wing aircraft used by the military do represent degrees of speech interference which should be given further attention.

The author is currently conducting research which will help define criteria for speech interference appropriate for use in aerospace operations. Establishing the validity of undesirable effects of noise, especially those related to speech interference, is a task which requires further study. Results of field studies thus far accomplished indicate that the "boundaries" for protected exposures where the intrusion of ambient noise begins to create noticeable interference with aural communications are 92 dB for ISO-4 and PSIL, and 90 dB for $PSIL_1$ and SIL methods.

It should also be emphasized that one variable is paramount—the pilot has control over the level of the desired signal, and, therefore, the individual can somewhat counteract the degree of masking imposed by a given external noise condition.

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13. ABSTRACT

Acoustic noise within aircraft during flight often causes some degree of interference with aural communication. Several methods have been used over the years to identify and predict degrees of speech interference. Six of these methods are discussed: four involve octave-band averaging; two use frequency weighting. The assessment is based on application of each of the six indices to noise levels measured within the cockpits of 191 fixed-wing and 58 rotary-wing aircraft, grouped into 11 categories by engine type. Equivalent speech interference levels obtained from the use of each of the six indices are provided for the acoustic spectra developed for the 11 classes of vehicles. The operational considerations which influence speech interference values are described. Noise attenuation provided by headset devices commonly used by Air Force aircrew members is shown for different groups of noise spectra. Criteria are given for evaluating protected and unprotected exposures to noise that compromise communications.

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Noise						
Criteria - speech interference						
Masking						
Undesirable effects of noise						
Aircraft noise						
Speech communications						
Communications in aircraft						

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