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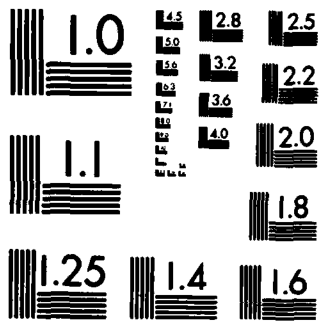

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AUDITORY INFORMATION SYSTEMS IN MILITARY AIRCRAFT: CURRENT CONFIGURATIONS VERSUS THE STATE OF THE ART

Theodore J. Doll, Ph.D.
Dennis J. Folds, M.S.
Linda A. Leiker, B.S.

Systems Engineering Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

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Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas 78235

Volent. Subvenimus

NOTICES

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The Office of Public Affairs has reviewed this report, and it is releaseable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

HARRELL C. SUTHERLAND, JR., M.Ed.
Project Scientist

GEORGE E. SCHWENDER
Colonel, USAF, MC
Supervisor

ROYCE MOSER, Jr.
Colonel, USAF, MC
Commander

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The complete ensembles of auditory signals in selected USAF aircraft (the F-4D, F-15, two models of the F-16, the C-5, and the C-141) are described and evaluated. Human factors research related to the design of speech and non-speech auditory signals is reviewed and the fundamentals of speech synthesis technology are described. Major findings are: that auditory signals are not well standardized among the aircraft, even between those with similar combat roles; that a relatively large number of non-speech auditory signals are used, which may make it difficult for the aircrew to recall the meanings of all the signals; that some non-speech signals are sufficiently similar that they may be confused, particularly in high workload and stressful conditions; and that the criticality of the warnings is not reliably indicated by any characteristic of the signals. Five problem areas requiring further research are discussed: reduction of signal loudness, annoyance, and disruption of other functions; enhancement of the distinctiveness and masking resistance of non-speech signals; effects of concurrent warning signals on aircrew performance in critical operational contexts; additional uses of auditory information in order to

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relieve visual workload; the need for guidelines for deciding which information should be provided aurally, which should be speech versus non-speech, and for designing speech messages; and optimization of synthesized speech for cockpit applications, including its attention-getting capability, distinctiveness, intelligibility, and ease of comprehension.

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INTRODUCTION

A substantial number of auditory signals impinge on the aircrew of modern military aircraft. Auditory signals are currently used chiefly as cautions, warnings, and advisories to the aircrew. In this capacity they have certain advantages over visual signals, but also entail some problems. Some of the benefits of using auditory signals in military aircraft, as currently applied are:

(a) They alert the aircrew to dangerous or potentially dangerous conditions irrespective of head position and direction of gaze.

(b) They reduce the need to scan instruments visually, thereby increasing the probability and speed with which the aircrew reacts to emergency conditions.

(c) They provide sensory inputs which are less disrupted by anoxia and positive g forces than are visual inputs (1, 2).

(d) Auditory displays require no space on the crowded front panel of the cockpit.

The need to reduce pilots' visual workload and the availability of speech synthesis technology are motivating research into additional applications of auditory information in aircraft cockpits. For example, Simpson (3) has investigated the application of synthetic speech to produce altitude and glide slope deviation callouts during instrument landing approaches. Mastroianni (4) is studying the use of auditory signals as alternative or auxiliary flight control information when the pilot is temporarily visually disabled.

In addition to these current and potential benefits, the use of auditory signals, especially as warnings, creates certain problems. In a study of auditory warning signals in civil aircraft, Patterson (5) states the problem with current systems as follows:

> ...the existing systems achieve their success at considerable cost, in that they flood the flight deck with very loud, strident sounds. This has two unfortunate side effects: First, it makes the auditory warning systems unpopular with flight crews. Second, and perhaps more important, many of the existing warnings disrupt thought and prevent crew communication, which at a critical moment makes an already difficult situation worse. (p. 1)

Reflecting on aircrew attitudes toward auditory signals, Patterson continues as follows:

> To the flight crew existing warning systems must seem rude and selfish; they burst onto the flight deck with shouts of 'emergency' disrupting and preventing other activity until they are cancelled. Furthermore, they are totally lacking in a sense of perspective. When a warning occurs it is usually either a false warning or the direct result of a standard flight procedure.... Even when a true warning occurs, it almost always indicates a potential problem rather than a sudden emergency. (p. 5)

The problems cited by Patterson have been confirmed in systematic studies of pilot opinion and performance (6, 7, 8, 9, 10).

It is clear that the design of auditory signals can strongly affect the safety and effectiveness of military aircraft. Yet very little information has been available on the exact configurations of auditory signals in military aircraft. Such information is, however, available in the open literature for commercial aircraft (11). The military standards applicable to auditory warning signals are either in the form of general guidelines (MIL-STD-1472C) which leave the designer considerable latitude, or they specify the characteristics of only a few signals (MIL-STD-411D). As a result, the military standards provide only very general and incomplete information on the auditory signals in military aircraft. A further complication is that changes and additions have been made to the auditory information systems of many of the older aircraft and documentation of such changes is not generally available. The result is that the questions about the adequacy of auditory signals in military aircraft have received little attention.

A need exists, then, to describe and evaluate the complete set of auditory signals in military aircraft. The purpose of the effort reported here was to begin to fill this need. The four objectives pursued were as follows:

(1) To review the available research findings related to the design of auditory signals (speech and non-speech) for military aircraft.

(2) To describe and evaluate the ensemble of auditory signals presently in selected USAF aircraft.

(3) To review the state of the art in auditory information systems technology.

(4) To recommend possible applications of more complex auditory information systems for military aircraft.

Although not a part of the original objectives, the current effort also offers recommendations for improvements in the design of existing auditory information systems.

The remainder of this report is organized into three major sections. The second section reviews and summarizes research findings, and the recommendations of experts concerning the design of auditory information systems. This section also briefly describes the fundamentals of speech synthesis technology. The third section presents the information gathered on auditory signals in selected USAF aircraft and identifies areas where improvements are possible, based on the principles summarized in the preceding section. The last section presents conclusions regarding the current configurations of auditory signals in military aircraft, describes some possible new applications of auditory information systems, and discusses problem areas in which further research and development could be particularly beneficial.

Appendix A is an annotated bibliography of articles related to auditory caution/warning systems in aircraft. Appendix B contains extractions from relevant military standards. Data collection forms are presented in Appendix C.

HUMAN FACTORS CONSIDERATIONS

Background

The increasing use of the auditory channel for the display of information in the cockpit is apparently due to two distinct factors: (a) efforts to reduce demands on the visual channel, that is, to free the pilot's eyes for other tasks, and (b) an increased awareness of situations in which the auditory signal is superior, or at least more appropriate. Although new technologies such as head-up-displays (HUDs) and multifunction displays have helped address many of the visual workload problems, they have not substantially reduced the amount of information presented via the visual channel, and have generated new questions and problems themselves (Manaker, 8). Perhaps the most promising source of relief for the overburdened visual channel is the proper use of the auditory channel. Whereas in the past auditory displays were rather limited by their reliance on non-speech signals (and the realization that pilots should not be expected to remember the meaning of more than a few signals), recent advances in speech synthesis systems have made it possible to have auditory displays with unprecedented flexibility and capacity, as compared with the bells, horns, and buzzers of the past.

Discounting communication with other humans, the auditory channel is primarily used for the presentation of caution/warning (C/W) information. The auditory channel has an obvious advantage for the transmission of such information: the information may be received irrespective of the pilot's head position or locus of visual fixation. Although there are standards for some audio displays (MIL-STD-411D) and guidelines for audio signals in general (MIL-STD-1472C), the disagreement over the principles to be followed in the design of aircraft C/W systems has been documented in the literature (Cooper, 12). It is self-evident that auditory C/W systems provide the pilot with important and often critical information. It also appears likely that more and more information will be transferred to the auditory channel through the use of synthetic speech. It is, therefore, imperative that human factors principles be given prime consideration in the design of such systems.

The remainder of this section first addresses the existing guidelines for conventional (non-speech) auditory C/W signals, some of which also apply to speech signals. These guidelines are evaluated in the light of recent research, and some problems are identified which the guidelines do not address. Next, the fundamentals of speech synthesis technology are reviewed, and guidelines for speech signals are presented. These guidelines are also evaluated in the light of recent research. Finally, the discussion of human factors considerations is summarized.

General Guidelines for Auditory Signals

The military standards for the use of auditory displays are contained in Section 5.3 of MIL-STD-1472C. The following are guidelines from Section 5.3 that seem particularly pertinent to the human factors of auditory C/W systems in aircraft:

Audio signals should be provided, as necessary, to warn pilots of impending danger, to alert an operator to a critical change in system or equipment status, and to remind the operator of a critical action or actions that must be taken (5.3.2.1).

Caution signals shall be readily distinguishable from warning signals and shall be used to indicate conditions requiring awareness, but not necessarily immediate action (5.3.2.3).

When used in conjunction with visual displays, audio warning devices shall be supplementary or supportive . The audio signal shall be used to alert and direct operator attention to the appropriate visual display (5.3.2.4).

The frequency range shall be between 200 and 5,000 Hz and, if possible, between 500 and 3,000 Hz...(5.3.3.1.1)

A signal-to-noise ratio of at least 20 dB shall be provided in at least one octave band between 200 and 5,000 Hz at the position of the intended receiver (5.3.4.1).

Signals with high alerting capacity should be provided when the system or equipment imposes a requirement on the operator for concentration of attention. Such signals shall not, however, be so startling as to preclude appropriate responses or interfere with other functions by holding attention away from other critical signals (5.3.4.2.1).

When earphones will be worn in the operational situation, a dichotic presentation should be used whenever feasible (5.3.4.2.3).

When the operator is wearing earphones covering both ears during normal equipment operation, the audio warning signal shall be directed to the operator's headset as well as to the work area...(5.3.4.2.4).

When several different audio signals are to be used to alert an operator to different types of conditions, discriminable differences in intensity, pitch, or use of beats or harmonics shall be provided. If absolute discrimination is required, the number of signals to be identified shall not exceed four (5.3.4.3.1).

Audio alarms intended to bring the operator's attention to a malfunction or failure shall be differentiated from routine signals (5.3.4.3.5).

The following evidence, summarized by Deatherage (13), is supportive of many of the guidelines listed above:

> The normal human ear is most sensitive in the 500 - 3,000 Hz range.
>
> In the presence of noise, an auditory signal should exceed its masked threshold by at least 15 dB for good discrimination.
>
> The threshold for detection of a dichotic signal is generally lower than when the signal presentation is diotic or monaural.
>
> The maximum number of signals that can be absolutely discriminated on the basis of intensity alone is four.

Finally, there are two special situations in which an auditory signal is considered superior to a visual signal. The auditory sense is generally less degraded by anoxia and by high positive g forces than is the visual sense. The latter condition is of particular concern because it is encountered with some frequency in the operation of tactical aircraft.

Discussion of the General Guidelines

The auditory channel has undeniable advantages for the transmission of C/W information in that it is independent of the pilot's head position and locus of visual fixation. The visual channel, of course, has advantages as well. Existing auditory C/W systems tend to supplement a visual display such as an annunciator panel. The principal advantage of adding an auditory signal to the master warning light/annunciator panel system is that the auditory signal virtually eliminates situations in which the master warning light goes unnoticed for a lengthy time period. Bate (14) compared reaction times to C/W signals using a master warning light/annunciator panel system with and without an alerting tone. Due to several trials in which the subjects apparently did not detect the master warning light for several minutes, the mean reaction times for the No-Tone condition were much longer than for the Tone condition. These data resulted in heterogeneous variances and Bate, accordingly, analyzed the median reaction times. He found that the median reaction times for the No-Tone condition were significantly longer than the Tone condition median reaction times. It should be noted, however, that his subjects were not pilots, although the primary experimental task involved a simulated navigation task. His subjects may not have been as sensitized to the importance of the master warning light as pilots would be while actually flying. Nevertheless, it is clear that there are flight situations in which it is important for the pilot to maintain visual surveillance outside the aircraft as much as possible. Examples of these situations include final approach to landing and air-to-air combat. Although head-up-displays help alleviate the pilot's need to look at his instrument panel in some situations, particularly final approach to landing, the use of the auditory channel for the presentation of C/W information during these situations is clearly advantageous in that it eliminates the monitoring of low probability/high priority visual displays, thus reducing the pilot's visual workload. Furthermore, the superiority of the auditory channel in the special conditions mentioned above (anoxia and high positive g forces) clearly establishes that C/W information alerting the aircrew to these conditions should be presented through the auditory channel (15).

The guidelines concerning the frequency, intensity, and dichotic headphone presentation of audio signals are designed to enhance the detectability of those signals. There are, however, several unanswered questions concerning the optimal design of auditory C/W systems. First, the current guidelines establish four as the maximum number of signals to be used when absolute discrimination (i.e., identification) is required, which assumes that only one parameter of the sound is varied. However, no auditory C/W system is likely to be designed that requires absolute discrimination of only one parameter of sound. Instead, these systems typically use complex sounds that are distinguished from one another in several dimensions; examples include horns, whistles, sirens, bells, buzzers, chimes, gongs, and clackers. The human can effectively identify a fairly large number of different sounds, if the sounds vary on multiple dimensions (16, 17, 18). The pressing question is not whether the pilot can be expected to identify the various sounds themselves, that is, be able to tell that a given sound is a bell or a buzzer, but whether the pilot can be expected to remember the meaning of each sound. Identification of warning sounds based on their physical characteristics is a necessary but insufficient condition for guaranteeing the correct interpretation of those sounds. As Erlick and Hunt (1) have noted, the optimal audio warning signal should not only be detectable, attention-getting, and discriminable, it should also be "infinitely" retainable as a function of time with regard to its meaning. Patterson and Milroy (19) selected 10 auditory warnings and tested non-pilot subjects on the learning and retention of the meaning of the signals. Their results indicated that although subjects learned the meaning of the ten signals quite well, they did not retain them perfectly. One week after learning the set of 10 signals, the subjects returned for retest. Most subjects correctly recognized 8 or 9 of the 10 signals. Interestingly, Patterson and Milroy's analysis of errors showed that the most likely source of confusion was temporal similarity (repetition rate and on/off ratio) even though large spectral differences were involved. They concluded that temporally similar audio signals are "prone to confusion" (p. 12). The probability that a pilot will correctly recall the meaning of a given auditory signal undoubtedly varies as a function of several variables, including the stressfulness of the situation. In fact, Deatherage (13) recommends against using a non-speech signal in situations where stress might cause the listener to forget the meaning of a signal. Other variables that could affect the recall of the meaning of a warning signal include the extent of the pilot's training, the frequency of occurrence of the signal in the pilot's prior experience, the presence or absence of ancillary conditions that might prompt anticipation of the problem (pragmatic context), and the pilot's concurrent workload when the signal occurs.

Another question involves the effect of one auditory signal on response to another audio signal. Current standards require that signals be presented at intensities well above the ambient noise; for example, MIL-STD-1472C specifies a signal-to-noise ratio of at least 20 dB. However, signals 15 dB above their masked thresholds are difficult to miss (Patterson & Milroy, 20). Although the presence of an audio signal may affect the masked thresholds for other audio signals somewhat, the probability of one signal rendering another signal literally inaudible is quite low. Both signals would almost certainly have to be continuous with similar spectral characteristics. Therefore, in order to reduce potential instances of masking, intermittent signals should be used.

A more salient concern is the effect of multiple concurrent C/W signals on the aircrew's performance. Section 5.3.4.2.1 of MIL-STD-1472C requires that signals not interfere with functions associated with other critical signals. Concurrent signal situations have been given little if any attention in the literature, but it seems possible that such situations could be highly confusing. Patterson (5) argues that existing warning signals in commercial aircraft cause a temporary disruption of cognitive function of the flight crew. Two or more such signals, occurring together in time, could be highly disruptive and interfere with response to either signal and other critical tasks.

A final issue for consideration is the loudness of warning signals. The existing guidelines ensure that warning signals are loud enough to be above the normal masked thresholds but not so loud as to induce pain or hearing loss. The only other requirement related to loudness is that the signal not be so startling as to preclude appropriate responses or interfere with other critical functions, as mentioned above. Cooper (12) reported that there was general agreement that continued loud sounds tend to have a detrimental effect on the pilot and crew. Patterson (5) evaluated the warning signals of two commercial airliners and found most of them to be too loud. The important point is that a signal can be below the level at which pain or hearing loss will be induced but still be perceived as annoying by the pilot. Annoyance is a variable that has proven to be difficult to study; what is annoying at one time may not be annoying at another time, and what is annoying to one person may not be annoying to another person. However, sounds in excess of 90 dB tend to be rated as annoying by almost everyone. Patterson (5) recommended a minimum level of 15 dB above the predicted masked threshold to insure detectability and a maximum level of 25 dB above the predicted masked threshold to guard against annoyance and disruption of thought and communication. Patterson also presented a method for predicting the masked threshold of complex sounds given the power spectral density of the sound and an idealized power spectrum of the masking noise. It should be noted that increasing the loudness of a warning signal that is already perfectly audible does not enhance detection or recognition. Signals within the limits recommended by Patterson should prove to be perfectly audible but not annoying nor disruptive.

Speech Synthesis Technology

Recent advances in speech synthesis technology allow unprecedented flexibility in the design of aircraft C/W systems. One can expect a pilot to remember the meaning of only a limited number of non-speech auditory signals. However, the number of speech messages that can be recognized and understood is virtually unlimited. Synthesized speech also has the advantage of being capable of providing diagnostic and corrective action information as well as alerting the pilot and identifying the general nature of the problem. A full appreciation of the application potential of speech synthesis requires a basic understanding of the technology.

Two basic methods are used to generate synthetic speech: constructive synthesis and analysis/synthesis (Smith and Crook, 21). Constructive synthesis refers to the production of synthesized speech based on a set of rules that prescribe what sound is represented by a letter or combination of letters in a given word. The level of construction largely determines the level of accuracy (i.e., the degree to which the correct sound is chosen) and the "naturalness" of the resultant synthesized speech. A letter-by-letter level of construction would obviously have unacceptable inaccuracy given the irregularity in the way sounds are represented by conventional English spelling. A more detailed level of construction is the phonemic level. A phoneme is the basic unit of sound in a language. American English can be represented by approximately 36 phonemes, approximately 4 complex units called diphthongs (sounds produced by voicing during transition from one phonemic position to another; an example is the pronunciation of the word "I"), and up to 10 other variants in sound that are used to impart meaning to the spoken language. The exact number of phonemes used to represent the language may vary slightly, depending on the linguistic authority cited and whether the phonemic categorization attempts to codify certain dialectic variants. Additionally, silence is used to impart meaning, such as in defining the difference between "let us pray" and "let us spray". Phonemic construction gives far greater accuracy than letter-by-letter construction, but the resultant synthesized speech still tends to sound unnatural and mechanical. An even more detailed level of construction is the allophonic level. Each phoneme in the language is actually a family of allophones. Each allophone within the family is a slight variation of the phoneme sound. These variations on a phoneme are not used to indicate differences in meaning (else they would qualify as separate phonemes) but are more a function of the preceding and subsequent sounds in human speech production. For example, the voiceless bilabial stop, /p/, is released in the pronunciation of the word "appetite" but is unreleased in "apt". Each allophone is acoustically distinct, and the use of an incorrect allophone, but the correct phoneme, yields a word that is generally understandable but sounds "funny". An incorrect phoneme, on the other hand, results in a mispronounced word that may well be misunderstood. Therefore, the selection of the correct string of phonemes is essential to the understandability of the synthesized word, whereas the selection of the correct allophone for each phoneme is a large part of producing natural-sounding synthesized speech. The remaining factor in producing natural-sounding synthesized speech is the incorporation of the normal prosody of the spoken language. Prosody - the variations in pitch and stress patterns - defines the difference between normal speech and monotonic speech. Correct prosody also gives spoken language its natural flow and avoids the impression of a word-by-word pronunciation. It is obvious that a constructive synthesis that incorporates allophonic and prosodic elements of speech entails the use of far more memory than simple phonemic construction, but also results in more natural-sounding synthesized speech.

The analysis/synthesis method entails the analysis of actual human speech. Depending on the sophistication of the analytic procedures, the speech synthesized with this method can closely resemble real human speech. The vocabulary unit is not limited to words, but can include phrases or complete sentences as individual items in the vocabulary as well. There are several analytic procedures in use in current speech synthesis systems. The currently popular technique is linear predictive coding (LPC). Other analytic techniques include pulse-code modulation, delta modulation, and a variation of delta modulation called variable-sloped-delta modulation. The LPC approach is distinguished by its particular strategy in encoding and compressing the parameters of an analog sound signal (e.g., frequencies and amplitudes) into a digital representation that can be reconstructed into an analog output. The LPC seems to be the current "winner" in terms of encoding efficiency (and thus memory requirements). Obviously, the more parameters encoded and the more frequently those parameters are sampled, the better the quality of the output and the greater the memory requirements of the system. Waveform encoding procedures generally are more successful in obtaining a nearly exact reproduction of the original signal, but do so at high memory requirements (the most sophisticated require mainframe memory capabilities). LPC samples certain parameters of the analog signal, rather than encoding the entire waveform, and can produce intelligible output by the use of a model of the human vocal tract in the production of the output signal.

A comparison of the two methods reveals that a sophisticated constructive approach such as an allophonic level of construction requires considerably less memory than an analysis/synthesis approach of high efficiency such as LPC. However, LPC memory requirements are not so great as to preclude its use in an aircraft cockpit, especially as more and more memory is fit into the same physical space by memory chip manufacturers. The Texas Instruments system described by Smith and Crook (21) combines allophonic construction and LPC into an apparently quite versatile system. Any English word can be pronounced by the system, although some words must be intentionally misspelled in order to get the correct pronunciation.

The nature of the optimal speech synthesis system for an aircraft is a function of what the system is intended to do. If the system is limited to the production of a fixed set of C/W messages, each message could be encoded by a technique such as LPC, stored in read-only memory (ROM) and activated by current aircraft malfunction sensors. A more flexible system should incorporate a constructive synthesis system so that any message could be activated without substantial hardware changes. Such a system could be used for far more than delivery of warning messages. It is not implausible to envision the transmission of encrypted secure messages to an aircraft where they would be decrypted, delivered as synthesized speech, and stored in memory for later reference. It is also possible that pilots whose native language is not English could transmit a radio message in their native tongue that could be received, translated, and delivered to an American pilot as English (and vice-versa). The aircraft of the future may also have voice recognition/voice activation capabilities. Given such possibilities, the flight station of the future may well be one in which the pilot can talk to the machine and the machine can talk back.

Guidelines for Speech Warnings

MIL-STD-1472C, Section 5.3, also contains the following guidelines for the use of speech warnings:

> A verbal warning shall consist of an initial non-speech signal to attract attention and to designate the general problem and a brief, standardized verbal message which identifies the specific condition and suggests appropriate action (5.3.5.1).
>
> Verbal warnings for critical functions shall be at least 20 dB above the speech interference level at the operating position of the intended receiver (5.3.5.2).
>
> The voice used shall be distinctive and mature (5.3.5.3.1).
>
> Verbal warnings shall be presented in a formal, impersonal manner (5.3.5.3.2).
>
> In selecting the words to be used in the message, priority shall be given to intelligibility, aptness, and conciseness in that order (5.3.5.5).

Deatherage (13) recommends the use of speech rather than non-speech signals under the following conditions:

> For flexibility.
>
> To identify a message source.
>
> When listeners are without special training in coded signals.
>
> There is a necessity for rapid two-way communication.
>
> The message deals with a future time requiring some preparation.
>
> Situations of stress might cause the listener to forget the meaning of a coded signal.

In a 1981 study, Woodson (cited by Edman, 22) suggested the following criteria for the use of speech message:

> When communication flexibility is necessary.
>
> When it is necessary to identify the source of a message.
>
> When a stressful situation might cause the listener to forget the meaning of a code.
>
> When a single coded signal cannot adequately give directions or instructions to the listener.

When ambient masking noise obviates the use of simple tonal signals.

When other complex tonal signal possibilities have been exhausted.

For "start and stop" timing.

For continuous information where the rate of change is low.

Werkowitz (23) made the following recommendations for the use of synthesized voice warnings in military aircraft:

Voice warnings should be used in military aircraft to enhance safety.

Voice warning systems should be reprogrammable/ expandable to allow for evolutionary improvement.

It should be insured that warnings say the right thing at the right time.

Both the discriminability and the intelligibility of the messages should be maximized through experimentation and standardization.

Other uses of synthesized speech in the cockpit should be investigated and validated.

Pilot opinion and preferences should be incorporated into the design of the systems.

Discussion of the Guidelines for Speech Warnings

It seems clear that the technology to be used in voice C/W systems in aircraft should employ speech synthesis rather than prerecorded tape, given the difficulties of using tape in extremely cold environments, such as is encountered at high altitudes, and in high vibration environments. Although the technology is rapidly improving, synthesized speech is generally less intelligible than prerecorded speech (Edman, 22). Therefore, as Werkowitz (23) recommended, words should be carefully chosen for their intelligibility. Other potential problems include the masking of radio transmission voice messages and a general saturation of the auditory channel.

The requirement that verbal warnings be preceded by an alerting tone (MIL-STD-1472C, Section 5.3.5.1) has been questioned in the literature. Simpson and Williams (24) tested the pilot's total response time, i.e., the time from the onset of a warning signal to pilot response, in a flight simulator using four commercial pilots qualified in the Boeing 727. They found that while response time measured from the beginning of the verbal message was shortened when preceded by an alerting tone, the addition of 1 sec

(0.5 sec for the tone and 0.5 sec of silence to preclude forward masking) resulted in a net increase in response time as measured from the onset of the warning (the onset of the tone or the verbal message, depending on the experimental condition). According to their review of the literature, several writers (and MIL-STD-1472C) recommend the use of an alerting tone, but no experimental evidence has been offered to support the recommendation.

Two points need to be made regarding the Simpson and Williams (24) study. First, using their reported means and standard deviations, the one standard error ranges for the means of each condition are shown as follows:

	No Tone	Tone
keyword warning	4.70-5.58 sec	5.40-6.10 sec
semantic context	4.71-5.43 sec	5.43-6.05 sec

These ranges are for total system response time and clearly support the conclusion that response time is reliably longer when a tone is used. However, Simpson and Williams note that if the initial 1-sec overhead for the tone is disregarded, response time was faster in the tonal condition. Since the addition or subtraction of a constant value to a distribution does not affect the variability of the distribution, the standard error ranges for each of the conditions ignoring the 1-sec constant for the tone would be as follows:

	No Tone	Tone
keyword warning	4.70-5.58 sec	4.40-5.10 sec
semantic context	4.71-5.43 sec	4.43-5.05 sec

These ranges suggest that the presumed advantage for response time in the tonal condition if the 1-sec overhead is ignored is unlikely to be statistically significant, given the degree of overlap of the standard error ranges. However, as Simpson and Williams point out, ignoring the overhead is operationally unrealistic. They explored the possibility of reducing the 1-sec interval to the minimum values indicated in the literature, namely, 300 msec for the tone and 140 msec for the pause between tone and message. If the standard error ranges are adjusted for these minimum values, and assuming the shorter interval would have no effect on response times, the standard error ranges for total response time would be as follows:

	No Tone	Tone
keyword warning	4.70-5.58 sec	4.84-5.54 sec
semantic context	4.71-5.43 sec	4.87-5.49 sec

These ranges indicate that system response time using the minimum values for the length of the alerting tone and pause would result in total system response times that are virtually identical for the Tone and No-Tone conditions. It seems that the question of whether to use an alerting tone must be decided on some basis other than response time. An additional variable to be considered is whether synthetic speech is also to be used for information other than C/W information. If so, it may be that an alerting tone, or perhaps some feature of the synthetic voice, should be used to indicate that

C/W information is being presented. In any event, the current military standard also requires that warning sounds be differentiated from routine sounds (5.3.4.3.5) in addition to requiring an alerting tone.

A second point concerns the practical significance of the reported differences in total response time. The workload conditions of Simpson and William's experiment were described as low with respect to cognitive workload, moderate with respect to visual workload, and varied with respect to auditory workload. Under these conditions, it is doubtful that the approximately 0.7-sec difference in response time amounts to a practically significant difference. During high workload conditions, the difference is possibly though not clearly important, and one must wonder whether workload interacts with the Tone/No Tone variable. It may be that one of these conditions is clearly superior in high workload conditions; however, there is as yet little evidence on which to base a speculation as to which method is better.

The work of Wickens and his associates (25) has addressed the compatibility of modalities of input, central processing, and output. They tested combinations of auditory vs. visual input, verbal vs. spatial processing, and speech vs. manual output. Their work, incidentally, included flight simulation tasks as well as basic laboratory tasks. Their work suggests that verbal processing tasks are performed best when the input and output modes are auditory and speech, respectively, whereas spatial processing tasks are best suited for visual input and manual output. Their work may have important implications regarding the optimal use of both speech synthesis and speech recognition devices in future-generation aircraft.

The requirement that the voice be distinctive is clearly intended to enhance the detectability of the message, in particular to avoid confusion of a C/W message with routine radio/intercom chatter that may be selectively ignored by the pilot. Early verbal C/W systems using prerecorded tape used a female voice, ostensibly to provide contrast with the normal parade of male voices heard in radio/intercom communications. As several writers pointed out, the increasing presence of females both in aircrews and in air traffic control (ATC) stations could reduce the advantage of using a female voice. A speech synthesis device, of course, is not limited to generating male- or female-like voices, but could be designed to produce a distinctively nonhuman voice that would be very unlikely to be mistaken for an overheard, irrelevant message. However, the developmental literature suggests that the attention-getting properties of the female voice may not have been due to the fact that the normally heard voices were male, but instead due to an inherent superiority in attention-getting capability related to the frequencies, stress patterns, and pitch patterns of the female voice (Fernald, 26; Fernald and Simon, 27). Therefore, it may be that synthesized speech messages should mimic the female voice, even if there are other female voices routinely heard.

Much of the experimentation concerning the intelligibility of synthesized speech in aircraft applications has been done by Carol Simpson and her associates (Hart & Simpson, 28; Simpson, 29; Simpson, 3; Simpson & Marchionda-Frost, 30; Simpson & Williams, 24). Simpson (29) compared the intelligibility of synthesized speech using common phraseology as opposed to the specialized phraseology typical of air traffic communications. She tested two groups: aircraft pilots and police officers. The police officers were selected as a comparison group under the assumption that they would be experienced in two-way radio communications, as are pilots, but unfamiliar with the specialized air traffic phraseology. She found that the two groups did not differ in their ability to understand common phraseology but that the pilots were significantly better at understanding the specialized phraseology. These results suggest that the intelligibility of synthesized messages can be enhanced by using words and phrases with which pilots will be familiar. These results are supported by previous findings that indicate the intelligibility of spoken messages is higher when the messages come from a fixed and known vocabulary rather than an "open" vocabulary (cf., studies by Howes in 1957 and by Rosenweis & Postman in 1957, both cited by Werkowitz, 23).

Hart and Simpson (28) compared the intelligibility of synthesized warning messages in sentence format versus two-word (keyword) format. They found the sentence-format messages to be more intelligible both in conditions of no background noise and a background of competing weather broadcasts. Secondary tasking involved verbal estimates of session length and production of an estimated 10-sec interval. Difference in performance of the secondary tasks indicated that the sentence-format messages required less attention for comprehension than did the two-word format messages. These findings are in conflict with the pilot preferences reported by Wheale (31); namely, that pilots preferred the keyword format to sentence format, presumably because they believed reponse time to the keyword messages would be quicker. Hart and Simpson, however, found no difference in response time. The Simpson and Williams (24) study discussed earlier reported a consistent finding. In addition to assessing the effects of an alerting tone prior to a speech message, they again compared sentence and keyword formats for the speech message. The two formats produced no significant difference in response time from signal onset, even though the sentence format was 0.3 sec longer in duration.

Simpson (3) used a jet transport flight simulator to assess the effectiveness of computer-controlled synthesized approach callouts (SYNCALL) during final approach and landing, as compared with the current procedure of having the "pilot not flying" (PNF) make the callouts. The results indicated that airspeed and sink rate performance during nonprecision approaches was better using SYNCALL than when using PNF callouts. There was no difference in performance on precision approaches when using SYNCALL as opposed to PNF callouts. The difference between the results for nonprecision versus precision approaches is attributed to the higher attentional workload required of the pilot and PNF on nonprecision approaches where no direct glide-path information is displayed to the pilot. Simpson also compared the reliability of the PNF procedure to that of the SYNCALL system, i.e., whether callouts were made at the appropriate times. The PNF and SYNCALL were comparable in reliability for normal altitude approach callouts. However, SYNCALL was significantly more reliable than PNF for making airspeed and sink rate deviation callouts.

Simpson and Marchionda-Frost (30) examined various rates and pitches of synthesized speech with respect to the intelligibility of warning messages. They found no significant difference in the intelligibility of the messages using pitches (fundamental frequency of the voice) below, within, and above the highest amplitude octave band of the background noise. They also found no difference in the intelligibility of messages at rates up to 178 wpm, although pilots indicated a preference for a more moderate rate of 156 wpm. Response time did decrease, however, as the rate increased. They also confirmed Hart and Simpson's (28) findings that eliminating redundant words (to reduce the time required to complete message transmission) served to decrease intelligibility and increase response time.

A thorough assessment of the intelligibility and comprehensibility of synthesized speech in the aircraft environment is needed. As long as the synthesized messages are few and familiar to the aircrew, intelligibility may not be a serious problem, as discussed above. However, as the number of speech messages in the cockpit increases, so does the linguistic and semantic uncertainty, and hence the cognitive processing required to comprehend the message. Under such conditions, the background noise, workload, and stress characteristic of the military aircraft environment could well increase the level of message intelligibility required to achieve efficient comprehension and performance.

Summary and Conclusions

The omnidirectionality of the auditory channel, the superiority of audition in conditions of anoxia and high positive g forces, and the generally high visual workload of piloting an aircraft make audition the preferred mode of delivering C/W information.

Current standards for permissible frequencies, signal-to-noise ratios, and dichotic presentation optimize the probability of the detection of an auditory warning.

Although pilots can identify a large number of sounds based on their physical properties, the maximum number of different signals which pilots can be expected to remember the meaning of is not known; nor is the effect of a stressful situation on such recollection known.

Many current warning signals may be so loud as to be annoying and disruptive. The loudness and spectral characteristics of warning signals should follow the guidelines recommended by Patterson (5).

There is apparently little known about the likelihood of occurrence and impact of concurrent auditory signals in real operating conditions for military aircraft. Concurrent signals could seriously impair pilot performance at critical times characterized by high workload and/or stress, especially if the signals were so loud as to disrupt thought or so similar as to be easily confused.

Certain situations, particularly air-to-air combat, demand that the pilot's visual surveillance remain outside the aircraft. The possibility of providing additional critical information by way of the auditory channel in these situations should be investigated.

Speech synthesis devices will allow unprecedented flexibility in the delivery of C/W information to pilots in aircraft of the near future. Additional applications of synthesized speech in the cockpit should continue to be a high priority area of research.

The requirement that a verbal warning be preceded by an alerting tone has no solid experimental support and may, in fact, be contraindicated in terms of response time. However, there may be other reasons for using an alerting tone, such as to make warnings more noticeable in the context of communications. Further research on this question should be performed in conditions of high auditory and visual workload and, if possible, high stress.

The critical qualities of voice that define its attention-getting properties and intelligibility in the aircraft cockpit should be identified through experimental investigation.

The compatibility of modes of input, central processing, and output should be further investigated so as to help identify the optimal allocation of tasks and input/output modalities as a function of aircraft operating conditions.

CURRENT CONFIGURATIONS IN SELECTED AIRCRAFT

Method

One of the main objectives of the present research was to catalogue and evaluate the ensemble of auditory signals in selected USAF aircraft. The information collected on each signal was designed to allow an assessment of the adequacy of the design of that signal and its probable interaction with other auditory information in the cockpit. The information sought for each signal included the following parameters:

1. The name of the signal.

2. The type of signal (e.g., horn, bell, clacker, voice).

3. The message content, if voice.

4. The conditions under which the signal is designed to be activated.

5. The criticality of the condition which the signal denotes.

6. The physical characteristics of the signal.

7. Whether, and in what respects, the operator can control the signal (e.g., volume, enable, cancel, inhibit).

8. Whether the same or related information is also provided by a visual display.

9. The stations within the aircraft at which the signal is received.

10. The device through which the signal is provided (e.g., headset, loud-speakers).

11. The overall frequency of occurrence of the signal in various flight configurations, including instances in which the signalling device was operating as designed and false alarms.

12. The frequency of false alarms in various flight configurations and any information or speculation about the causes of the same.

13. Whether the aircrew has an opportunity to become and remain familiar with the signal by hearing it at times other than during flight operations (e.g., during training, preflight check).

14. Whether, in the pilot's opinion, the signal interferes with his other activities, masks other signals, or is likely to be confused with other signals.

The original data collection plan called for in-depth information to be gathered on a small number of aircraft, i.e., one tactical and another either strategic or transport. The planned approach involved three steps. First, systems requirements information and standards were to be gathered from units of the Air Force Systems Command (AFSC), including the aircraft system project offices (SPOs) and other units of the Aeronautical Systems Division (ASD), and the Air Force Wright Aeronautical Laboratories (AFWAL). Second, aircraft and subsystems manufacturers were to be asked for data on the systems' performance as implemented in the aircraft. Third, pilots were to be interviewed immediately after participating in combat exercises, such as Red Flag, in an attempt to garner information related to the adequacy of the signals' designs in combat flight conditions.

Difficulties were encountered during the performance of the project which forced a change in the data collection method. Permission could not be obtained for project personnel to conduct interviews with pilots after combat exercises. Instead, interviews were conducted with pilots at local operational and logistics units for three of the five aircraft studied. The interviews provided only anecdotal information, since the pilots differed widely in their flight duties and were often unfamiliar with some of the warnings.

The information finally gathered came from different sources for the various aircraft. Table 1 shows the aircraft on which information was obtained and the sources of that information. The local units visited included: (1) 28th Bomb Squadron, SAC 19th Bombardment Wing at Robins AFB, (2) 116 TFW and 116 CAM at Dobbins AFB, and (3) Aircraft Division, Warner Robins Air Logistics Center, Robins AFB. One pilot each was interviewed for the F-15 and the C-141; both a pilot and copilot were interviewed for the F-4.

In the case of the F-16, excellent information was obtained from General Dynamics Corporation. Aerospace Medical Research Laboratory (AMRL) provided information on the F-15 and F-16, which was obtained from the SPO's and other units of ASD. Lockheed Georgia Company provided information on the C-5A and C-141. Information on auditory warning subsystems in the F-15 and F-16 was obtained from SCI Systems, Inc.

Audio recordings were made of those signals that could be generated while the aircraft were on the ground for the C-141 and F-15. Also, a recording of Sundstrand Corporation's Mark II Ground Proximity Warning System was provided by Lockheed Georgia Company.

The basic data collection instrument was a three-part data sheet, shown in Appendix C. Two sets of data sheets were maintained for each aircraft. One set was used to transcribe information from the Technical Orders (Dash 1 manuals) and the other "objective" sources, while the second set was used to record information during interviews of pilots. The two sets were later merged to create summary sheets for each aircraft, as shown in the next subsection of this report.

TABLE 1. SOURCES OF INFORMATION FOR EACH AIRCRAFT STUDIED

Source of information	Aircraft F-16	F-15	F-4	C-5	C-141
Aircraft or subsystem manufacturer	x	x		x	x
System project office	x	x			
Tech. order*		x	x	x	x
Audio recording		x			x
Observed in aircraft		x			x
Maintenance crew			x		
Pilot interview		x	x		x

*These are aircraft manuals with the following numbers:
T.O. 1C-141A-1
T.O. 1F-15A-15-90
T.O. 1F-15A-1
T.O. 1F-15C-15-28
T.O. 1C-5A-1
T.O. 1F-4C-1

The first part of each set of data sheets was used to list all the auditory signals in a given aircraft by type (speech or non-speech). For each signal listed in Part 1, a separate Part 2 or Part 3 data sheet was filled out, depending on whether the signal involved speech or not. Parts 2 and 3 provide space to record information on all the signal variables listed previously.

Results

The data collected for the F-15, earlier production versions of the F-16, more recent versions of the F-16, the F-4, the C-5, and the C-141 are presented in Tables 2 through 8. In the process of reviewing these data, two general categories of signals emerged which are of prime interest. The first category is aircraft status/malfunction--signals that convey information about the aircraft itself. The second is flight configuration--signals that convey information about the way the aircraft is being flown. Signals in the flight configuration category often call attention to potential instances of pilot error. Within each category the criticality of signals may range from informative to emergency. Both speech and non-speech signals are included in each category. These two categories are not exhaustive. Signals not included in either category are either situation-specific signals such as threat warnings and navigation tones, or signals not specifically directed toward the pilot (e.g., bail out alarm, which is manually activated by the pilot). The two categories are generally mutually exclusive; the only exception in the present data is the landing gear warning, which will sound if the pilot fails to deploy the gear or if there is a malfunction in the gear deployment mechanism. The landing gear signal will be counted in both categories. This classification scheme proved to be a useful framework for examining the signals of primary interest. For each aircraft reviewed below, the number of activating conditions that are associated with flight configuration signals and with aircraft status/malfunction signals will be indicated. These data are also presented in Table 2.

The F-15 (see Table 3) has a total of 20 physically distinct signals: 11 non-speech signals, and 9 speech signals. Three of the non-speech signals have a variable physical form (i.e., their frequency and/or interruption rate is a function of the activating condition). The frequencies of the fixed-form non-speech signals range from 250 ± 50 to 1950 Hz. The upper limit of the variable-form signals is 3000 Hz. The interruption rates of the fixed-form signals range from steady (no interruption) to 5 ± 1 Hz. The interruption rate of the angle of attack (AOA) tone could exceed 5 Hz if the AOA reaches $a_1 + 30$. There is a one-to-one correspondence between activating conditions and physically distinct signals in the F-15. There are 5 activating conditions associated with flight configuration signals and 8 activating conditions associated with aircraft status/malfunction signals. The flight configuration signals are the landing gear warning, departure warning, AOA tone, over g tone, and over g voice message. The aircraft status/malfunctions signals are the landing gear warning and seven voice messages: fan turbine inlet temperature (FTIT) left, FTIT right, left engine fire, right engine fire, airframe mounted accessory drive (AMAD) fire, fuel low, and "bingo" fuel. Thus, the F-15 primarily uses speech to convey status/malfunction information and non-speech to convey flight configuration information. The signals not included in either category are the tactical electronic warfare system (TEWS) caution, TEWS launch, weapon (a signal to the pilot that the heat-seeking missile guidance system has locked onto a target), the very high frequency omni range (VOR) Morse code signal, VOR voice signal, the tactical air navigation (TACAN) signal, the identification, friend-or-foe (IFF) mode 4 audio signal, and the loft bombing cue.

TABLE 2. NUMBER OF CONDITIONS ACTIVATING SPEECH AND NON-SPEECH SIGNALS BY TYPE OF ACTIVATING CONDITIONS

Aircraft	Type of Activating Condition: Flight configuration (potential pilot error)		Aircraft status/ malfunction		Other	
	Non-Speech	Speech	Non-Speech	Speech	Non-Speech	Speech
F-16 (Blocks 01,05)	6[a]	0	1[a]	2 (General)	9	0
F-16 (Block 10)	4[a]	0	1[a]	2 (General)	8	0
F-15	4[d,a]	1[d]	1[a]	7	7[e]	1[e]
F-4D	3	1	0	1	12[e]	1[e]
C-5A/B	8[c]	12[c]	4	0	11[e]	1[e]
C-141	12[b]	7[b]	4	0	5[e]	1[e]

[a] The landing gear warning can be activated either by pilot error in configuring the aircraft or by a malfunction and is therefore counted in both columns.

[b] The GPWS on the C-141 produces a "Whoop-Whoop" tone as well as speech in 5 conditions, which are counted in both columns.

[c] The GPWS on the C-5 produces a "Whoop-Whoop" tone as well as speech in 2 conditions, which are counted in both columns.

[d] Over g warning generates both tone and speech and therefore is counted in both columns.

[e] VOR generates both Morse code and recorded speech and therefore is counted in both columns.

TABLE 3. AUDITORY SIGNALS IN THE F-15

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Landing Gear	Landing gear not down when altitude is below 10,000 ft , airspeed is below 200 kts, and descent rate is above 100 ft per minute.	Tone	250 ± 50 Hz interrupted at 5 ± 1 Hz	Y	Disable			No problem with false alarms.	Will activate when Air Delta computer becomes inoperative regardless of altitude, airspeed, or descent rate.
Departure Warning	Yaw rate reaches 30° per sec with landing gear up.	Tone	900 ± 180 Hz interrupted at 1 Hz.						Interruption rate increases to 10 Hz as yaw rate increases to 60° per sec.
Angle of Attack (AOA)	α_1 is reached with landing gear down and weight off wheels.	Tone	1600 ± 160 Hz interrupted at 1 Hz at α_1. Interruption rate increases 2 Hz per AOA degree above α_1.	Y				No problem with false alarms.	α_1 is a predetermined AOA value less than the AOA value that will likely produce a stall.
Tactical Electronic Warfare System (TEWS) *Caution*	Detection of new emitter or change in mode of a previously detected emitter.	Tone	1950 Hz modified sine wave.	Y	Volume				
TEWS Launch	Missile guidance signal detected.	Tone	1950 Hz modified sine wave modulated by 15.2 Hz.	Y	Volume, disable				

TABLE 3. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Weapon	Guidance system for heat-seeking missile has locked onto a heat source.	Buzzy growl			Volume			Extraneous heat sources, including the sun, may activate the system.	
Very High Frequency Omni Range (VOR)	VOR signal is received.	Morse Code Station Identifier	1020 Hz	Y	Volume			A lot of static in the system.	
Tactical Air Navigation (TACAN)	Ground station signal is received.	Morse Code	1350 Hz		Volume				
Identification, Friend-or-Foe (IFF) Mode 4	Mode 4 audio selected and being interrogated.	Tone	300-3000 Hz		on/off				Signal frequency depends on ground station PRF. Simultaneous interrogations by different ground stations will produce a complex tone with components determined by the individual ground station PRF's.
Loft Bombing Cue (PMS - Peace Fox System Only)	Time to start pull-up for loft maneuver.	Tone	550 ± 110 Hz						Signal is presented again upon automatic release of weapon.
Fan Turbine Inlet Temperature (FTIT) - Left [b]	Left engine FTIT too high.	"Warning, FTIT over temp, left"	Female Voice	Y		Headset	Pilot[a]		Message repeats once.
FTIT - Right [b]	Right engine FTIT too high.	"Warning, FTIT over temp, right"	Female Voice	Y		Headset	Pilot[a]		Message repeats once.

TABLE 3. AUDITORY SIGNALS IN THE F-15
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Left Engine Fire[b]	Left engine on fire.	"Warning, engine fire, left"	Female Voice	Y		Headset	Pilot[a]		Message repeats once.
Right Engine Fire[b]	Right engine on fire.	"Warning, engine fire, right"	Female Voice	Y		Headset	Pilot[a]		Message repeats once.
Air-Frame Mounted Accessory Drive (AMAD) Fire[b]	Fire in AMAD.	"Warning, AMAD fire"	Female Voice	Y		Headset	Pilot[a]		Message repeats once.
Fuel Low[b]	Fuel quantity is low.	"Warning, fuel low"	Female Voice	Y		Headset	Pilot[a]	False alarms when fuel sloshes away from sensor.	Message not repeated.
BINGO Fuel	Fuel quantity reaches level preset by pilot.	"Warning, Bingo Fuel"				Headset	Pilot[a]		Message repeats once.
Over g[b]	1. Aircraft is between 85% and 100% maximum g. 2. Aircraft is over maximum g.	1. Tone 2. "Over g, over g, over g, . . ."	[illegible] Hz; Female Voice	Y		Headset	Pilot[a]		1. At 85% max. g tone is interrupted at 4 Hz. Interruption rate increases to 10 Hz at 92% max. g 2. At 100% max. g, "Over g, over g, over g, . . ." repeats until condition is corrected

[a] Signal is also received by copilot in two-seater F-15.

[b] In earlier models of the aircraft the voice warning for all of these conditions was simply "Warning, warning, warning, warning".

TABLE 4. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCKS 01 & 05

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Landing Gear	Landing gear or trailing edge flap not down when airspeed is less than 170 kts, altitude is less than 10000 ft, and descent rate is greater than 250 ft per minute.	Tone	250 ± 50 Hz repetition rate 5.0 ± 1.0 Hz		Silencer, no volume control	Headset	Pilot		
Low Speed	1. Airspeed less than 120 ± 10 kts while gear is up or flaps not extended 2. AOA is greater than 15° while gear is down or flaps are extended	Tone	250 ± 50 Hz steady		Silencer, no volume control	Headset	Pilot		Has priority over landing gear tone.
Angle of Attack (AOA)	1. 12° < AOA < 18° and stores configuration switch in Category III.	Tone	800 Hz		No volume control	Headset	Pilot		Repetition rate = 1 Hz at AOA = 12 and increases linearly to 10 Hz at AOA = 18 .
	2. AOA > 18° and stores configuration switch in Category III.	Tone	800 Hz steady						
Radar Warning Receiver (RWR) Threat Tone	1. In automatic mode when RWR initially selects and locks onto highest priority threat.	Tone	1600 - 5000 Hz depending on PRF of selected displayed threat	Y	Pilot selects RWR mode; volume control on comm panel	Headset	Pilot		

TABLE 4. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCKS 01 & 05 (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
RWR Threat Tone (Cont'd)	2. In manual mode - pilot can sequentially select displayed threats in order of their priorities assigned by the RWR.	Tone	1600 - 5000 Hz depending on PRF of selected display threat	Y	Pilot selects RWR mode; volume control on comm panel	Headset	Pilot		
New Guy (RWR)	Whenever a new threat emitter is detected and displayed by the RWR and when an emitter changes modes.	Tone	1. When RWR is in automatic mode: 1000 Hz, 7 beeps in approx. 7.5 sec. 2. When RWR is in manual mode: PRF of selected threat; 3 beeps	Y	Pilot selects RWR mode; volume control on comm panel	Headset	Pilot		
In[illegible] Missile Launch (RWR)	When threat system turns on, and again when missile launch detected.	Tone	1000 Hz repetition rate [illegible] Hz for approx. 3 sec.	Y	Volume control on comm panel	Headset	Pilot		
Airborne Intercept Missile	Missile locked onto target.	Tone	400 - 2000 Hz		Volume and on-off control	Headset	Pilot		

TABLE 4. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Instrument Landing System (ILS)	ILS signal is received.	Morse Code of station	400 Hz (outer marker) 1300 Hz (middle marker) 3000 Hz (inner marker)		Volume control on ILS Panel	Headset	Pilot		
Tactical Air Navigation (TACAN) System	TACAN ground station signal is received.	3 letter Morse Code station identification	1350 Hz at 30 sec intervals		Volume control on TACAN Panel	Headset	Pilot		
Identification, Friend or Foe (IFF) Mode 4	Mode 4 audio selected and being interrogated.	Tone	300-1000 Hz depending on interrogators. Short bursts.		Volume control on IFF Panel	Headset	Pilot		
Low Altitude/ Terrain	Terrain following radar on and radar altitude less than 75% of pilot-selected clearance.	Tone	800 Hz.	Y*	on/off switch; clearance set on multi-function display	Headset	Pilot		
General Warning	Red master warning light illuminated	"Warning, warning - warning, warning"	Voice comes on 1.5 sec. after warning light illuminates	Y		Headset	Pilot		

* - Radar Altimeter

TABLE 4. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCKS 01 & 05 (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
General Caution	Amber master caution light illuminates.	"Caution - caution"	Voice comes on 7 sec after caution light illuminates	Y	Pilot can inhibit by resetting master caution light within 7 sec after it comes on.	Headset	Pilot		

TABLE 5. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCK 10

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Landing Gear	Landing gear or trailing edge flap not down when airspeed is less than 170 kts, altitude is less than 10,000 ft, and descent rate is greater than 250 ft per minute.	Tone	250 ± 50 Hz repetition rate 5.0 1.0 Hz		Silencer, no volume control	Headset	Pilot		
Low Speed	AOA ≥ 15° while landing gear down or flaps extended.	Tone	250 ± 50 Hz steady		Silencer, no volume control	Headset	Pilot		Has priority over landing gear tone.
Low Speed/High Attitude Warning	Airspeed is too low for current attitude while landing gear is up.	Tone	250 ± 50 Hz steady		No volume control	Headset	Pilot		Applicable only when pitch is between 45° and 90°. Airspeed is too low if less than (Pitch) x 2.22.
Radar Warning Receiver (RWR) Threat Tone	1. In automatic mode - when RWR initially selects and locks onto highest priority threat. 2. In manual mode - pilot can sequentially select displayed threats in order of their priorities assigned by the RWR.	Tone	1600 - 5000 Hz depending on PRF of selected displayed threat	Y	Pilot selects RWR mode; volume control on comm panel	Headset	Pilot		

TABLE 5. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCK 10 (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
New Guy (RWR)	Whenever a new threat emitter is detected and displayed by the RWR and when an emitter changes modes.	Tone	1. When RWR is in automatic mode: 1000 Hz; 7 beeps in approx. 7.5 sec. 2. When RWR is in manual mode: PRF of selected threat; 3 beeps.	Y	Pilot selects RWR mode; volume control on comm panel	Headset	Pilot		
Threat Missile Launch (RWR)	When threat system turns on, and again when missile launch detected.	Tone	1000 Hz repetition rate 5 Hz for 3 sec	Y	Volume control on comm panel	Headset	Pilot		
Airborne Intercept Missile	Missile locked onto target.	Tone	400 - 2000 Hz		Volume and on/off control	Headset	Pilot		

TABLE 5. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Instrument Landing System (ILS)	ILS signal is received.	Morse Code of station	400 Hz (outer marker) 1300 Hz (middle marker) 3000 Hz (inner marker)		Volume control on ILS Panel	Headset	Pilot		
Tactical Air Navigation (TACAN) System	Ground station signal is received.	3 letter Morse Code station identification	1350 Hz at 30 sec intervals		Volume control on TACAN Panel	Headset	Pilot		
Low Altitude/ Terrain	Terrain following radar on and radar altitude less than 75% of pilot-selected clearance.	Tone	800 Hz	Y*	On/off switch; clearance set on multi-function display	Headset	Pilot		
General Warning	Red master warning light illuminated.	"Warning, warning - warning, warning"	Voice comes on 1.5 sec after warning light illuminates	Y		Headset	Pilot		

* - radar altimeter

TABLE 5. AUDITORY SIGNALS IN THE F-16, PRODUCTION BLOCK 10 (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
General Caution	Amber master caution light illuminated	"Caution, caution"	Voice comes on 7 sec after caution light illuminates	Y	Pilot can inhibit by resetting master caution light within 7 sec after it comes on.	Headset	Pilot		

TABLE 6. AUDITORY SIGNALS IN THE F-4D

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Stall Warning	1. Angle of Attack (AOA) $\geq 15^{o}$	Tone	400 Hz. Repetition rate=1.5 Hz at AOA=15 and increases to 20 Hz at AOA=18 .	Y	Volume	Headset	Pilot and copilot		
	2. $18 < AOA < 20^{o}$	Tone	900 Hz, steady. Increases in volume at optimal AOA for landing.	Y	Volume	Headset	Pilot and copilot		
	3. $AOA \geq 20^{o}$	Tone	1600 Hz. Repetition rate=1.5 Hz at AOA=20 and increases to 20 Hz at AOA=23 .	Y	Volume	Headset	Pilot and copilot		Accompanied by vibrator on rudder pedals.
Tactical Air Navigation System (TACAN)	Ground station signal is received.	3 letter Morse code station identification	1350 Hz. Repeats every 37 sec	Y	Volume	Headset	Pilot and copilot		Bearing and distance to station also displayed visually

TABLE 6. AUDITORY SIGNALS IN THE F-4D (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Radar Homing and Warning (RHAW)									
New Guy	When new threat radar is detected or the PRF of earlier detected threat changes	Tone	1000-5000 Hz depending on PRF of threat. 3 beeps in 1.5 sec	Y	Maximum volume to off.	Headsets	Pilot and copilot		Crew can silence all but the New Guy and Launch audios by momentarily pressing the hand-off button. Crew can also sequentially select displayed threat by pressing hand-off button until a diamond marker encloses threat of interest. PRF of threat will then be heard. Crew can also elect to have audio switch automatically to highest priority threat, or to remain on threat selected by crew.
Normal Audio	A threat radar is detected	Tone	1000-5000 Hz depending on PRF of threat. Steady.	Y	Maximum volume to off.	Headsets	Pilot and copilot		
Launch	Threat missile launch detected	Tone	1000 Hz 7 beeps in 1.5 sec	Y	Maximum volume to off.	Headsets	Pilot and copilot		
Very High Frequency Omni Range (VOR)	VOR on and turned to VOR station frequency	3 letter Morse code station identification or recorded voice	1020 Hz	Y	Volume	Headset	Pilot and copilot		
Instrument Landing System (ILS)	When ILS and Marker Beacon Receiver on	Tone	400 Hz (outer marker) 1300 Hz (middle) 3000 Hz (inner)		Volume, on/off	Headset	Pilot and copilot		

TABLE 6. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Identification, Friend or Foe (IFF) Mode 4	Mode 4 audio selected and being interrogated	Tone	300-2200 Hz depending on number of interrogators. Steady.	N[a]	On/off	Headset	Pilot and copilot		
Airborne Interrupt Missile (AIM-9)	Missile locked onto heat source.	Tone	400-1200 Hz depending on signal strength.[b] Steady.			Headset	Pilot and copilot		
AIM-7	Missile locked onto target (radar guided)	Tone				Headset	Pilot and copilot		
Ballistic Bombing System (ASQ 91)	Starts when "pickle" button is depressed. Stops when bomb is released.	Tone	1200 Hz. Steady.		On/off[c]	Headset	Pilot and copilot	Very loud, overrides other audio.	Also can produce a short beep to signal crew when to begin pull up. This feature is generally not used.
Canopy Unlocked	Both canopy controls in the "close" position for at least 12 sec., and conditions extant for forward or rear "canopy unlocked" light to be on.	"Canopy, canopy"	Voice	Y	Volume	Headset	Pilot and copilot		Power must be on in aircraft.
Low Altitude	Radar altitude below minimum	"Altitude, altitude"	Voice	Y	Volume	Headset	Pilot and copilot		Also heard when aircraft is leveled after a maneuver in which bank [illegible] 90 or pitch [illegible]

[a] Pilot can select either audio or visual, but not both.
[b] Newer systems are intermittent (chirp).
[c] If crew releases "pickle" button, bomb is not released.

TABLE 7. AUDITORY SIGNALS IN THE C-5

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Unsafe Landing Gear	Nose gear not down or main gear cross-wind collars not engaged while: 1. Flaps extended more than 80%. or 2. Airspeed less than 200 kts, air delivery system switch set on "safe", and any throttle retarded below min. cruise setting.	Horn	595 ± 50Hz 91 ± 4 dB @ 3 ft.	Y	Cancel	Overhead horn	Cockpit		Cancel capability for condition 2 only.
Ground Proximity Warning System (GPWS)	1. Descent rate is within outer warning envelope	"Sink rate"		N		Headset, dedicated speaker	Cockpit		For conditions 1-4 and 5-7, the warning envelope is divided into outer and inner regions; the inner region is the more severe condition. For conditions 1-2 the warning envelope is a function of radar altitude and descent rate. For 3-4 it is a function of radar altitude and closure rate, and for 6-7 is is a function of radar altitude and the ILS signal.
	2. Descent rate is within inner warning envelope	"Whoop, whoop, pull up"		Y					
	3. Terrain closure rate is within outer warning envelope.	"Terrain, terrain"		N					
	4. Terrain closure rate is within inner warning envelope.	"Whoop, whoop, pull up"		Y					

TABLE 7. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Ground Proximity Warning System (Cont'd)	5. Excessive altitude loss after take-off.	"Don't sink"		Y					In condition 7 the message is louder and faster than in condition 6.
	6. Deviation from glide slope is within outer warning envelope.	"Glide slope"		Y					
	7. Deviation from glide slope is within inner warning envelope.	"Glide slope"		Y					
	8. Radar altitude is below preset value.	"Minimums, Minimums"		N					Threshold value is controlled by a "bug" on the radar altimeter.
	9. Radar altitude is within warning envelope while Mach number is less than .35 and landing gear is up.	"Too low, gear"		N					For conditions 9-12, the warning envelope is a function of radar altitude and Mach number.
	10. Radar altitude is within warning envelope while Mach number is greater than .35 and landing gear is up.	"Too low, terrain"		N					

TABLE 7. AUDITORY SIGNALS IN THE C-5
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Ground Proximity Warning System (Cont'd)	11. Radar altitude is within warning envelope while Mach number is less than .28 and the flaps are up.	"Too low, flap"		N					
	12. Radar altitude is within warning envelope while Mach number is greater than .28 and the flaps are up.	"Too low, terrain"		N					
Stall Warning	Aircraft progresses into stall conditions in excess of conditions that activate stick shakers.	Horn tone			Disable	Headset, cockpit PA speakers	Cockpit		Stick shaker warning always precedes audible warning.
Preintercept Altitude Alert	Altitude approaches selected value.	Tone		Y	Inhibit	GPWS speaker and headset	Cockpit		Alert sounds at 1000 ft and 300 ft preintercept altitudes. May be used in climb or descent. A component of Fuel Saving Advisary System (FSAS).
Overshoot of Selected Altitude	1. Postintercept altitude deviates from selected value by 300 ft during climb or descent	Tone	1000 Hz. 1 sec on, 5 sec off.	Y		GPWS speaker and headset	Cockpit		

TABLE 7. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Overshoot of Selected Altitude (Cont'd)	2. Altitude deviates from selected cruise altitude by 300 ft.	Tone	1000 Hz 1 sec on, 5 sec off.	Y		GPWS, speaker, and headset	Cockpit		
Windshear Alert	Present wind is more than 15 kts greater than predicted runway wind or actual groundspeed is more than 15 kts greater than reference groundspeed, provided: 1. Landing data loaded. 2. Landing gear down. 3. Altitude is more than 200 ft above runway altitude. 4. Heading is $\pm 30^{\circ}$ runway heading.	Tone	1000 Hz .25 sec on, .25 sec off.	Y		GPWS, speaker, and headset	Cockpit		Audible warning inhibited by simultaneous GPWS warnings. Landing data must be loaded into FSAS before approach.

TABLE 7. AUDITORY SIGNALS IN THE C-5
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Fire Suppression System (FSS) Fire Warning	FSS sensors are activated while aircraft is on ground.	Horns	2700 ± 500 Hz 160 dB @ 3 ft.	Y		Warning horns	Bunk area Crew rest area Troop courier area Aft troop area		Horns do not sound if aircraft on jacks.
Auxiliary Power Unit (APU) Fire	Fire in either APU compartment while aircraft is on ground.	Horns	2700 ± 500 Hz 160 dB @ 3 ft.	Y		Warning horns	Bunk area Crew rest area Troop courier area Aft troop area		Horns do not sound if aircraft on jacks.
Oxygen Warning	Barometric pressure inside cabin indicates altitude of 13,230 ± 750 ft.	Horns	2700 ± 500 Hz 160 dB @ 3 ft.	Y	Cancel	Warning horns	Bunk area Crew rest area Troop courier area Aft troop area		System also automatically opens oxygen container doors, deploys oxygen masks, and turns on dome lights to max. brightness in troop, courier, and cargo compartments.
Crash Landing, Ditching, or Bailout Alert	Pilot wishes to instruct crew and passengers to prepare for crash landing, ditching, bailout, or ground evacuation	Horns	2700 ± 500 Hz 160 dB @ 3 ft.	Y		Warning horns	Bunk area Crew rest area Troop courier area Aft troop area		

TABLE 7. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Crash Landing, Ditching, or Bailout Alert *(Cont'd)*									Must be manually activated. The following code is to be used: One sustained blast for ground evacuation, ditching or crash landing immediately after takeoff, or imminent impact. Three short blasts for prepare for bailout and subsequent bailout. Six short blasts for prepare for ditching or crash landing.
Very High Frequency Omni Range (VOR)	When VOR on and tuned to a VOR station frequency	Morse code or recorded voice representing station ID and bearing	Morse code continuous 10 words/min.			Headset	Pilot		Crew can select Morse code or recorded voice.
Instrument Landing System (ILS) (Marker Beacon Receiver)	When ILS on and MKR BCN switch on	Morse code of station	400 Hz (outer marker) 1300 Hz (middle marker) 3000 Hz (inner marker)	Y	On/of switch for aural signal	Headset	Pilot		Visual indicators are colored lights: blue for outer marker, amber for middle marker, and white for inner marker.

TABLE 7. AUDITORY SIGNALS IN THE C-5
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Identification, Friend or Foe (IFF) Mode 4	Mode 4 audio selected and being interrogated	Tone	300 - 400 Hz	Y	On/off	Headset	Pilot		Not all aircraft are equipped with Mode 4. An annunciator warning light indicates loss of Mode 4 capability.
Tactical Air Navigation (TACAN) System	When TACAN on	Morse code	Continuous	Y	On/off, volume	Headset	Pilot		A GO/NO-GO light indicates the system condition. A three-digit channel display indicator displays selected channels from "01" to "126".
Automatic Direction Finding (ADF)	When ADF on	Radio broadcasts or course-oriented radio range signals		Y	On/off, volume	Headset	Pilot		The visual display is the selected frequency.

TABLE 8. AUDITORY SIGNALS IN THE C-141

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Under Spoiler Speed Warning	Spoilers are deployed at an inappropriate angle of attack (AOA).	Horn		Y					Stall prevention system assesses appropriateness of AOA as a function of airspeed.
Stall Warning	1. After 5 sec off stick shaker operation. 2. At a computed stall condition in excess of conditions that activate stick shakers. 3. At a computed AOA while flaps are extended beyond 25° and landing gear is down.	Horn		Y		Headset and overhead horn			Conditions 1 and 2 are applicable when landing gear and/or flaps are up. The computed AOA in condition 3 is a function of rate of change in AOA and yaw rate.
Landing Gear Warning	1. Any throttle is retarded to within 1 in. of "idle start" position while landing gear not down. 2. Wing flap lever is moved to "landing" position while landing gear not down.	Horn		Y	Cancel	Overhead horn	Cockpit		Cancel capability for conditions 1 only.

TABLE 8. AUDITORY SIGNALS IN THE C-141
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Maximum Speed Warning	Predetermined maximum airspeed or Mach number is exceeded.						Pilot, copilot, jumpseat, flight engineer		Signal is described as a high pitch squeal.
Ground Proximity Warning System (GPWS)	1. Rate of descent in excess of a threshold that varies with radar altitude.	1. "Whoop, whoop, pull up"		Y		GPWS loudspeaker and headsets	Pilot, copilot, scanner		
	2. Excessive closure rate to terrain while not in landing configuration.	2. "Whoop, whoop, pull up"		Y					
	3. Excessive closure rate to terrain while in landing configuration.	3. "Whoop, whoop, pull up"		Y					
	4. Excessive altitude loss after take-off or go-around.	4. "Whoop, whoop, pull up"		Y					
	5. Unsafe configuration while below 500 ft.	5. "Whoop, whoop, pull up"		Y	Inhibit				
	6. Glide slope deviation is within outer warning envelope.	6. "Glide slope"		Y	Inhibit				Condition 6 message is delivered at reduced volume.
	7. Glide slope deviation is within inner warning envelope.	7. "Glide slope"		Y	Inhibit				Condition 7 message is delivered at full volume.

TABLE 8. (Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Engine Fire Warning	A fire is detected in an engine.			Y		Speaker and headsets	Pilot, copilot, flight engineer, observer station		
Bail-Out Alarm	1. Manually activated by pilot. 2. Automatically activated by oxygen flow in the troop oxygen system. 3. Automatically activated by Auxiliary Power Unit (APU) fire warning if any door warning circuits are unlocked.	Horn				Warning horn	Cargo compartment		
Identification, Friend or Foe (IFF) Mode 4	Mode 4 audio selected and being interrogated	Tone. Radar identification of aircraft.	300-400 Hz	Y	Switches for: 1. On/off 2. Audio and light indicators, audio only or light only.	Headset	Pilot		

TABLE 8. AUDITORY SIGNALS IN THE C-141
(Cont'd)

SIGNAL NAME	ACTIVATING CONDITIONS	SIGNAL/MESSAGE	SIGNAL CHARACTERISTICS	ACCOMPANYING VISUAL (Y/N)	OPERATOR CONTROL CAPABILITY	SIGNAL PROVISION DEVICE	RECEIVING STATIONS	PILOT COMMENTS	EXPLANATORY NOTES
Very High Frequency Omni Range (VOR)	VOR/ILS on and VHF/NAV receiver tuned to a VOR frequency	Morse code or recorded voice representing Station ID and bearing	Morse code: continuous, 10 words/min.			Headset	Pilot		
Instrument Landing System (ILS)	VOR/ILS on, VHF/NAV receiver tuned to localizer frequency, and HDG switch in NAV position	Morse code of station	400 Hz (outer marker) 1300 Hz (middle marker) 3000 Hz (inner marker)	Y	On/off	Headset	Pilot		Visual indicators are blue for the outer marker, white for the middle marker, and amber for the inner marker.

The earlier production versions of the F-16 (see Table 4) have 17 physically distinct signals: 15 non-speech signals and 2 speech signals. Five of the non-speech signals have variable physical forms. The frequencies of the fixed-form non-speech signals range from 250 ± 50 to 3000 Hz. The upper limit of frequency for the variable-form signals is 5000 Hz. The interruption rates of the fixed-form signals range from steady to 5 Hz. The interruption rates of the variable-form AOA tone reach a maximum of 10 Hz when AOA reaches 18°. There are 6 activating conditions associated with flight configuration signals and 3 associated with aircraft status/malfunction signals. The flight configuration signals are the landing gear warning, the low speed warning (2 conditions), the 2 AOA signals (one a variable-form signal when AOA is between 12° and 18°, the other a fixed-form signal when AOA is greater than 18°), and the low altitude/terrain warning. The aircraft status/malfunction signals are the landing gear warning and 2 speech signals: general warning and general caution. These two speech signals are classified as aircraft status/malfunction signals because the conditions that activate the master warning and master caution lights (which in turn activate the audible messages after a time delay) are predominantly malfunctions or precautionary status indicators. Thus these versions of the F-16 tend to use speech for aircraft status/malfunction information and non-speech for flight configuration information. The signals not included in either category are the radar warning receiver (RWR) threat tone, RWR New Guy, RWR Launch warning, airborne intercept missile (AIM) tone, the three instrument landing system (ILS) tones, TACAN, and IFF mode 4 audio.

The newer versions of the F-16 (see Table 5) have 14 physically distinct signals: 12 non-speech signals and 2 speech signals. The information given above for the upper and lower bands of frequencies and interruption rates in the older F-16's are applicable to the newer F-16's. The classification of signals into the flight configuration and aircraft status/malfunction categories are also the same, with one exception: the 2 AOA signals in the older F-16's are omitted in the newer versions, leaving 4 activating conditions associated with flight configuration signals. It should be noted that one of the activating conditions for the low speed tone has been changed from a simple function of airspeed when the aircraft is in landing configuration to a function of airspeed and pitch, regardless of landing configuration (cf., Low Speed/High Attitude Warning in Table 5 with Low Speed Warning, Condition 1, in Table 4). There is also one less signal not included in either category: the IFF mode 4 audio has been omitted in the newer F-16's.

The F-4D (see Table 6) has 18 physically distinct signals: 15 non-speech signals and 3 speech signals. Five of the non-speech signals have variable physical forms. The frequencies for the fixed-form non-speech signals range from 400 to 3000 Hz. The variable-form signals extend the lower and upper bounds to 300-5000 Hz. The interruption rates for the non-speech signals vary from steady to 20 Hz. There are four flight configuration signals: the three stall warning tones (each with a unique activating condition that is a function of AOA) and the low altitude voice warning. There is only one aircraft status/malfunction signal: the unsafe canopy voice message. The signals not included in these categories are the three ILS tones, TACAN, IFF mode 4 audio, the AIM-7 and AIM-9 tones, VOR Morse code, VOR voice, ballistic bombing system signal, the radar homing and warning (RHAW) normal audio, RHAW New Guy, and RHAW launch warning.

The data for the C-5 are presented in Table 7. It should be noted that the information represents the system intended for inclusion in the C-5B, which is in production but not yet deployed, and currently intended for installation or already installed in the C-5A. Thus, there may be some C-5A's in deployment that have not been retrofitted with the system described below. This system has 27 physically distinct signals; 16 non-speech signals and 11 speech signals. The IFF mode 4 audio is the only signal with a variable physical form. Its frequency range is 300-400 Hz. The frequencies of the fixed-form signals range from 400 to 3000 Hz. Decibel ratings were available for the landing gear horn--91 ± 4 dB at 3 ft--and the warning horns located throughout the aircraft--160 dB at 3 ft. There are 18 activating conditions associated with flight configuration signals and 4 activating conditions associated with aircraft status/malfunction signals. The flight configuration signals are the landing gear warning (2 conditions), stall warning, preintercept altitude alert, altitude overshoot alert (2 conditions), and the 9 ground proximity warning system (GPWS) voice messages, 3 of which have 2 activating conditions each. The aircraft status/malfunction signals are the landing gear warning (potentially also a flight-configuration signal) and the warning horn system that is automatically activated under 3 conditions: fire in an auxiliary power unit (APU) during preflight, fire on board the aircraft while on the ground, and low cabin pressure (triggering the oxygen warning system). The signals not included in these categories are the windshear alert, VOR Morse code, VOR voice, the three ILS tones, IFF mode 4 audio, TACAN, the automatic direction finding (ADF) signal, and the bail out alert signals (which are manually activated by the pilot in accordance with the code given in Table 7).

The C-141 (see Table 8) has 14 physically distinct signals: 10 non-speech signals and 4 speech signals. Little information was available on the physical characteristics of the signals in the C-141. There are 14 activating conditions associated with flight configuration signals and 4 conditions associated with aircraft status/malfunction signals. The flight configuration signals are the landing gear warning (2 conditions), stall warning (3 conditions), spoiler warning, maximum speed warning, and the three GPWS voice messages (1 of which has 5 activating conditions). It should be noted that the landing gear warning and the spoiler warning are the same physical signal. The stall warning activates this horn as well, but also provides a signal through the headset. The aircraft status/malfunction signals are the landing gear warning, engine fire warning, and the bail out alarm horns which, as in the C-5, may be automatically activated by APU fire and by the oxygen warning system. Signals not included in these categories are the three ILS signals, VOR Morse code, VOR voice, and the manually operated bail out alarm.

Discussion

Since the auditory information systems are designed very differently in the tactical and transport aircraft studied, these two classes of aircraft will be discussed separately. For convenience, the non-speech signals in the tactical aircraft are summarized in Table 9.

The first result which is obvious from Table 9 is that the number of non-speech auditory signals in each of the tactical aircraft studied far exceeds the 4 recommended by MIL-STD-1472C. The earlier version of the F-16 has 15, while the later F-16, the F-15, and the F-4D have 12, 11, and 15, respectively.

There seems to be little standardization of auditory signals among the tactical aircraft studied. Although the landing gear tone is the same in both F-16 models and the F-15, that is where the similarity ends (the F-4 has no audible landing gear warning). In comparing the closely related stall, angle of attack (AOA), and high attitude warnings in the four aircraft, very little commonality is found. The F-4 uses three tones (400, 900, and 1600 Hz), depending on the magnitude of the AOA, the F-15 uses only a 1600-Hz tone, and one version of the F-16 uses a 250-Hz tone and the other uses a 800-Hz tone.

More serious, however, than lack of standardization among aircraft, is the similarity of signals within aircraft. The earlier F-16 uses 800-Hz tones (one interrupted, one steady) for both excessive AOA and low altitude. The former condition can be corrected by decreasing the aircraft pitch, while the same response could have disastrous consequences in the latter case. Also, in the F-15, a 900-Hz tone is used for two functions: departure from controlled flight, and over g. In both cases the tone is interrupted, though at different rates. Considering that the crew is likely to be under high physical and/or psychological stress in conditions where either of these signals is activated, there may well be a potential for confusion here, and it comes at a time when a quick response is necessary.

There is also some potential for confusion between signals which indicate a problem in the flight configuration of the aircraft as opposed to serving other functions, such as indicating aircraft status or malfunction. As mentioned earlier, inappropriate flight configuration, such as excessive angle of attack, are potentially, but not invariably, instances of pilot error. Because of similarities in frequency and repetition rate, the IFF tone in 3 of the 4 tactical aircraft could be mistaken for some of the flight configuration warnings. In the F-4, the IFF tone and the stall tone for an intermediate AOA are both steady and may occupy the same frequency range. Both the IFF tone and the AOA warning in the earlier F-16 model are interrupted and can be similar in frequency as well. In both aircraft the IFF and stall or AOA signals could occur unexpectedly during flight, unlike the ILS and weapon signals which result from procedures which are intentionally initiated by the crew. This fact makes them less predictable based on the pragmatic context of the moment and, therefore, probably more likely to be confused.

Another set of results for tactical aircraft is summarized in Table 2. This table shows the relationship between type of auditory signal (speech/non-speech) and the type of activating condition (flight configuration versus

TABLE 9. SUMMARY OF NON-SPEECH SIGNALS IN THE F-16, F-15, AND F-4D

Function	Type	Frequency (Hz)	Repetition Rate (Hz)
F-16 Production Blocks 01,05			
*Landing gear	Tone	250 ± 50	5 ± 1
*Low Speed	Tone	250 ± 50	Steady
	Tone	250 ± 50	Steady
*Angle of Attack	Tone	800	1-10
	Tone	800	Steady
*Low Altitude	Tone	800	
IFF	Tone	300-1000	Short bursts
	Tone	1600-5000	Steady
Threat	Tone	1000	7 beeps in 7.5 sec
	Tone	1000	5 Hz for 3 sec
Weapon	Tone	400-2000	Steady
	Tone	400	Steady
ILS	Tone	1300	Steady
	Tone	3000	Steady
TACAN	Morse Code	1350	3 letters at 30-sec intervals
F-16, Production Block 10			
*Landing gear	Tone	250 ± 50	5 ± 1
*Low speed/	Tone	250 ± 50	Steady
high attitude	Tone	250 ± 50	Steady
*Low altitude	Tone	800	
	Tone	1600-5000	Steady
Threat	Tone	1000	7 beeps in 7.5 sec
	Tone	1000	5 Hz for 3 sec
Weapon	Tone	400-2000	Steady
	Tone	400	Steady
ILS	Tone	1300	Steady
	Tone	3000	Steady
TACAN	Morse code	1350	3 letters at 30-sec intervals

* Signals indicating a dangerous flight configuration which may imply pilot error.

TABLE 9. SUMMARY OF NON-SPEECH SIGNALS IN THE F-16, F-15, and F-4D (Cont'd)

Function	Type	Frequency (Hz)	Repetition Rate (Hz)
		F-15	
*Landing gear	Tone	250 ± 50	5 ± 1
*Angle of Attack	Tone	1600 ± 160	1 and up
*Departure	Tone	900 ± 180	1
*Over g	Tone	900	4-10
IFF	Tone	300-3000	
Threat	Tone	1950	
	Tone	1950 modulated	
Bombing Cue	Tone	550 ± 110	
Weapon	Tone	Buzzy growl	
ILS	Morse code	1020	
TACAN	Morse code	1350	
		F-4D	
*Stall	Tone	400	1.5-20.
	Tone	900	Steady
	Tone	1600	1.5-20.
IFF	Tone	300-2200	Steady
Threat	Tone	1000-5000	3 beeps in 1.5 sec
	Tone	1000-5000	Steady
	Tone	1000	7 beeps in 1.5 sec
Weapon	Tone	400-1200	Steady
	Tone		
Bombing Cue	Tone	1200	Steady
ILS	Tone	400	Steady
	Tone	1300	Steady
	Tone	3000	Steady
VOR	Morse code	1020	3 letters
TACAN	Morse code	1350	3 letters at 37-sec intervals

* Signals indicating a dangerous flight configuration which may imply pilot error.

aircraft status/malfunction and "other"). As noted earlier, all four tactical aircraft tend to use non-speech signals for flight configuration (potential pilot error) conditions and speech for aircraft status/malfunction conditions. Non-speech auditory warnings are not, however, a reliable indicator of a potential pilot error condition in these aircraft, since non-speech signals are also used for "other" functions, including TACAN, IFF, weapons control, ILS and threat warnings.

Finally, it is notable that both the F-15 and F-16 use speech warnings for conditions which vary greatly in urgency or criticality. In the F-15, speech is used for both "100% of g limit" and "Bingo fuel". The F-16 uses voice for both general warnings and general cautions, in both cases accompanied by visual indicators.

Except for the ground proximity warning system (GPWS), the auditory warning systems for the transport aircraft studied are less differentiated than those in the tactical aircraft. The C-5A/B uses the same 2700-Hz horn for six different conditions (fire suppression system, APU fire, oxygen low, crash landing, ditching, and bail out). Both the alert for overshoot of selected altitude and the windshear alert use the same 1000-Hz tone, though with different repetition rates. The unsafe landing gear and stall warnings are both horn tones, but it is not known how much they differ.

Like the tactical aircraft, the two transports studied use non-speech signals in numbers far exceeding the recommended 4. In the C-5A/B there are 23 different conditions which can activate non-speech auditory signals, while in the C-141 there are 21 such conditions.

Referring again to Table 2, it is clear that speech warnings are a fairly reliable cue for potential pilot error situations in the two transports. However, in both aircraft the VOR can also produce recorded speech. No information was available which would indicate whether the VOR speech is easily distinguishable from the GPWS speech warnings. Although speech is used primarily for conditions in which there is a potential pilot error, both transports also use non-speech auditory signals for other conditions which fall in the potential pilot error class.

CONCLUSIONS AND RECOMMENDATIONS

Evaluation of Current Configurations

In comparing the human factors principles reviewed previously with the actual configurations of auditory signals in the five aircraft studied, it is clear that the configurations are deficient in several respects. Surprisingly, this is as true for the relatively new F-16 as it is for the older aircraft. It is also notable that the implementation of synthesized speech in the F-15 and F-16 for some warnings has not been accompanied by elimination of significant human factors deficiencies in the non-speech warnings. This state of affairs suggests that the new speech synthesis technology is being applied for the sake of being "up-to-date" technologically, with insufficient attention paid to the goal of improving aircrew performance through a better human-machine interface.

The major deficiencies in the configurations studied fall into three categories. First, auditory signals which serve common functions are not well standardized among aircraft, even within those aircraft which have similar combat roles. In the F-15, for example, the signal for low speed/high angle of attack (AOA) with landing gear down is a 1600-Hz tone interrupted at 1.0 Hz or greater depending on the AOA, while the F-16 uses a 250-Hz steady tone for essentially the same function.

Second, all of the aircraft studied use fairly large numbers of non-speech auditory signals. For example, the F-15 uses 11 different non-speech audio signals and the C-5A uses various horns to signal 12 different conditions. The large number of non-speech signals reduces the chances that the crew will remember the meaning of any given signal (32, 19). Moreover, in the aircraft studied, the non-speech signals are sufficiently similar that it is quite possible that the signals could be confused, particularly at times of high workload and stress. For example, the F-16, production blocks 01 and 05, use an 800-Hz tone to indicate both excessive AOA and low altitude/terrain. Confusion among these two signals could have disastrous consequences, since one condition can be corrected by increasing aircraft pitch and the other by decreasing pitch.

The distinctiveness of non-speech signals could be enhanced at relatively low cost and risk by adopting Patterson's (5) recommendations to vary the temporal characteristics over a wider range and to use complex tones with multiple harmonics. Other alternatives are: (a) to substitute speech for non-speech signals as Davis and Stockton (33) have recommended for the F-16, or (b) to back up non-speech auditory signals with visual indicators which provide further information/cues to the problem at hand. The latter is the solution currently used in most cases; it is least favored since it increases the crew's visual workload and delays the appropriate response.

A third type of deficiency in the configurations of signals studied is that the urgency of the condition is not reliably indicated by signal characteristics. For example, voice messages in the F-15 denote conditions which vary in urgency from "BINGO FUEL" TO "OVER G". Providing cues by which the urgency of the signalled condition can be quickly discerned could save precious time and resources in critical phases of flight, such as take off, landing, and bombing.

In their survey of commercial pilots, Veitengruber et al. (11) report that pilots want aural alerts to be prioritized, and they want the priority level to be indicated by the characteristics of the warning so that an immediate assessment of the urgency of the situation can be made. Given the high workload and stress characteristic of some tactical flight missions, such as close air support and air-to-air combat, this recommendation seems especially appropriate for tactical aircraft.

In addition to correcting these deficiencies, there are a number of problem areas in which further research and development could significantly enhance auditory information systems in military aircraft. In the following paragraphs, five such problem areas are discussed and recommendations for further research are made.

Signal Loudness, Annoyance and Disruption of Other Functions.

In view of findings by Patterson (5) and by Veitengruber et al. (11) that many of the auditory signals aboard commercial transport aircraft are unnecessarily loud, it is recommended that a similar study be undertaken for military aircraft. Patterson argues that many of the auditory signals in commercial aircraft are so loud as to produce annoyance and disruption of the crew's thought at critical moments. Such effects are of even greater concern for military, particularly tactical, aircraft where the margin for pilot error is often much smaller. Accurate data should be gathered on the power spectra of signals and noise in various flight configurations for USAF aircraft. The signal levels and spectra should be adjusted appropriately using the Auditory Filter Method described by Patterson and Milroy (20). Patterson's (5) other recommendations for reducing the annoying and disruptive effects of auditory signals should also be incorporated in the design or redesign of auditory displays whenever feasible. In addition to adjusting the power spectra of warning signals, Patterson's recommendations included: (a) using intermittent warnings, i.e., a high "off" time relative to "on" time, and (b) using a gradual signal onset to reduce annoyance.

Signal Distinctiveness and Resistance to Masking

As the number of non-speech auditory signals increases, it becomes increasingly unlikely that the crew will be able to recall the meaning of any given signal. One solution, of course, is to use speech signals instead. However, there are circumstances in which non-speech signals may be more desirable. First, certain non-speech signals may have a commonly recognized meaning as a result of long, consistent usage and should therefore be preserved. Second, it may be desirable to reserve speech for only the most urgent warnings. Third, speech may not be the signal of choice in situations where a great deal of voice communication is necessary, as was the case in the Vietnam conflict.

Patterson (5) makes two additional recommendations which bear directly on the distinctiveness and masking resistance of non-speech auditory signals. He recommends that signals be composed of four or more prominent frequency components in the range from 1000 to 4000 Hz. Multicomponent sounds are more difficult to mask, and maintain their perceptual character better under varying conditions of masking than do simpler sounds. Patterson also speculates that using regularly spaced components, i.e., harmonics, would provide added resistance to masking over sounds with non-harmonic components. He notes that the distribution of power across the harmonics could be used to indicate the urgency or criticality of the warning. Sounds with relatively more power in the lower harmonics could be assigned to warnings of lesser urgency, while sounds with more power in the higher harmonics could signal warnings of greater urgency.

Concurrent Auditory Signals

Another concern, mentioned previously in the section on Human Factors Considerations, is the effect of multiple concurrent auditory signals on the aircrew's performance. The problem has apparently received little study to date (but see Manaker, 8). This is undoubtedly due to the difficulty of obtaining the required data. One would first need to determine what combinations of auditory signals actually occur in the real operational context, and then measure the pilot's performance on multiple tasks under the same or simulated conditions. Based on pilots' subjective reports and the large number of signals which could occur, it seems likely that multiple auditory signals are encountered frequently enough to be of concern. For example, in air-to-air combat, the pilot could simultaneously be presented with communications from one or more speakers in the presence of jamming, electronic warfare signals, system malfunction signals, and a stall warning. Some options for reducing or eliminating effects of simultaneous signals include: automatic prioritization and sequential presentation of signals, maximizing signal distinctiveness; and varying the apparent direction from which competing signals originate.

Additional Applications for Auditory Information Systems

An area of research and development with a large potential payoff is the possibility of providing additional information via audition in order to relieve the pilot's visual workload. The best potential candidate functions to convert from the visual to the auditory modality are those which require, or at least are compatible with, verbal processing and speech output, as Wickens and his colleagues have shown (25).

Simpson and her colleagues have suggested a number of potential applications of speech to replace or supplement visual information. In a 1980 study, she used a flight simulator to assess the effectiveness of a synthesized voice approach callout system (SYNCALL) for commercial airliners (3). The SYNCALL system was programmed to produce both normal approach callouts (e.g., glide slope intercept, localizer intercept, altitude above field level) and deviation callouts (e.g., airspeed, descent rate), all of which are normally given by the pilot not flying. Except for a one-engine approach in which SYNCALL made inappropriate deviation callouts, approach performance was better with SYNCALL than when the pilot not flying made the calls. In a later article (34) Simpson suggests two other possible applications:

> The advent of a digital data link between ground stations and aircraft makes it feasible for the pilot to receive a synthesized voice readout of weather conditions at the destination, or to provide a variety of other data about the destination airport, the aircraft, or the relationship between the two.
>
> Onboard flight computers could not only assist the pilot in entering his flight plan, but also check the plan for internal consistency by using basic geometry.

Another set of visual functions which could be beneficially converted to audition are those in which the two modalities are naturally complementary. Oatman (35) points out two such instances: (a) when auditory information can be used to connect visual information with previous knowledge, and (b) when an auditory cue indicates th_ part of the visual display which the operator should single out for inspection. An example of the former is the audio presentation of the pulse repetition frequency of a threat while a symbol for the threat appears on the cathode-ray tube (CRT) of a radar warning receiver (RWR). A possible application representing the latter case cited by Oatman would be to use the apparent direction and pitch of a sound to cue the pilot as to the general direction of a target to be acquired visually. Two specific applications come to mind: (a) Aural presentation of azimuth information generated by an onboard radar to facilitate visual acquisition of other aircraft, and (b) Aural presentation of RWR information to facilitate visual acquisition of threat missiles, airborne interceptors, or threat sites. Current onboard radars and RWR's present directional information on visual displays. This information could easily be encoded as aural signals to the two ears with relative intensity and lag (between the ears) such as to convey the same directional information. The pitch of the sound could be used to indicate the general elevation of the target, if such information were available. In addition to reducing the pilot's workload, this kind of presentation would speed visual target acquisition by: (a) Eliminating eye movement and visual accommodation from a display inside the cockpit to the visual scene outside, and (b) Reduce the cognitive processing which the pilot must perform to coordinate position on the display with position in space. Previous research indicates that pilots of military aircraft spend a substantial percentage of their time moving their eyes as opposed to fixating on an object. During eye movement, the eye cannot acquire information, i.e., this is "dead" time. For example, in nap-of-the-earth flight, helicopter pilots spend from 25-30% of their time in eye movements rather than fixations (36). Eliminating even a portion of this dead time might produce substantial benefits in aircraft safety, survivability, and effectiveness.

Application of Synthesized Speech

The most important development in auditory information systems for military aircraft is clearly the continuing application of speech synthesis technology to new functions. Although numerous authors have offered general recommendations for the application of speech synthesis in aircraft, there is a need to distill from the various sources one coherent set of guidelines or a standard.

From the pragmatic standpoint, the designer of cockpit information systems should address four issues before deciding to use synthesized speech:

(a) What part of the information to be transferred to the aircrew should be provided aurally rather than visually or by other modalities?

(b) Of the information to be transferred aurally, what functions should be allocated to speech as opposed to non-speech signals?

(c) How should speech messages be worded?

(d) What are the characteristics of a speech message which promote optimal aircrew performance?

Considerable advice on the first of these issues is already available in the human factors research literature (see the Human Factors Considerations/Guidelines section of this report for Speech Signals). However, the answer as to when, and for how many functions, the auditory modality should be used will depend on the state of the art in auditory signal design. As our knowledge improves in such areas as how to reduce the sometimes annoying effects of aural signals and how to increase the intelligibility of synthetic speech, such signals will become more generally applicable. Thus any guidelines on this issue need to be updated as research proceeds on the latter issues.

As for the second issue, certain criteria can be suggested for deciding when a given caution or warning should be presented by means of speech rather than by a non-speech aural signal:

(a) Use speech for the most urgent warnings, in order to reduce the probability of a delayed response due to failure to recall the meaning of the warning.

(b) Use speech for those warnings and cautions likely to be least familiar to the crew (due to low frequency of occurrence and/or inadequate training or skills maintenance).

(c) Use speech for those warnings which the crew is least likely to anticipate based on the pragmatic context (e.g., flight configuration). Those signals which can occur in the widest variety of conditions should be the most difficult to recall the meaning of, other things being equal.

The requirements of the application will dictate which criteria are most appropriate, or which should be weighted most heavily. Further research is needed to study these and other possible criteria and to explore which criteria are most appropriate for each type of application.

The third issue, how to word speech messages, has been addressed by several authors (1, 22, 37, 38). Brown et al. (37) developed a methodology for determining the wording and relative priorities of speech messages and applied it to six types of Army helicopters. Their methodology considers five kinds of information:

(a) The tasks which the pilot must perform in each emergency condition.

(b) Pilot opinion as to the appropriateness of recommended speech warning messages and their relative priorities.

(c) Accident statistics reflecting the accident prevention capability of the speech warning system.

(d) Cockpit integration consideration (e.g., whether the speech warning was redundant with a visual display), effects of noise, and competing signals on the speech warning.

(e) A message content analysis which ensured that the signals were maximally informative, discriminable, and capable of eliciting quick responses.

The Brown et al. methodology provides a systematic way of designing speech warnings and merits application to other types of aircraft.

The last issue, concerning the characteristics of speech which promote optimal performance, is the most central. Further research is needed in at least three areas: (a) the qualities which define the attention-getting capability of speech messages, (b) the factors which maximize the distinctiveness of speech and minimize interference with communications, and (c) factors which contribute to the intelligibility of synthesized speech. As Werkowitz (23) notes, there is currently a trade-off between the distinctiveness and intelligibility of synthesized speech. Robot-like speech is relatively easy to distinguish from natural speech communications, but also less intelligible than more natural sounding synthetic speech.

Another issue which may come to the forefront as the number of speech messages in the cockpit increases is ease of comprehension. There is, of course, more to comprehension than intelligibility. One may understand the individual words in a message without understanding the message. Ease or difficulty of comprehension obviously should influence the third design issue noted earlier, the choice of words in a message. The psycholinguistic research literature is a rich source of ideas for improving comprehension. For example, the pragmatic context probably influences the speed of comprehension of speech warnings by providing cues to background knowledge which helps the crew interpret a message. For signals which are not closely related to the context, additional verbal cues to the same background knowledge would probably facilitate comprehension (c.f., Doll and Lapinski, 39; Johnson, et al., 40).

In conclusion, it is clear that a number of significant improvements in auditory information systems for military aircraft could be made on the basis of existing knowledge. In addition, there are many areas in which further research and development could considerably enhance such systems at relatively little cost and risk. If the numerical superiority of hostile forces is to be overcome by the superior effectiveness of our forces (i.e., the "force multiplier" concept), then such research should have a very high priority.

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

The majority of articles included in this bibliography are directly concerned with auditory caution/warning systems in aircraft. Many of these articles are reports of experiments, reviews of the literature, or evaluation of existing or proposed systems; their qualifications for inclusion are obvious. Other articles are included, however, that were judged to be directly relevant to current human factors problem areas in aircraft auditory systems. Articles concerned with basic research in audition were not included, nor were articles concerned with the engineering aspects of speech synthesis technology included. Articles that describe different approaches to speech synthesis and discuss advantages and disadvantages were included. Articles that report experimental findings or results of pilot opinion surveys are annotated in a bit more detail than are other articles such as literature reviews. The entries appear in alphabetical order. A topical index follows the annotations and may be useful for cross-referencing.

1. Bate, A. J. (1969). Cockpit warning system study (AMRL-TR-68-193). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

The relative merits of supplementing aircraft visual/annunciator panel malfunction warning systems with a general alerting tone or with a recorded voice message that identified specific malfunctions were assessed. It was found that the addition of the general alerting tone resulted in faster and less variable response times. The visual system not supplemented with any auditory signal was the poorest system tested in terms of response time. Performance on a concurrent simulated navigation task was equal for all systems tested.

2. Boucek, G. P., Jr., Veitengruber, J. E., & Smith, W. D. (1977). Aircraft alerting systems criteria study, Vol. II: Human factors guidelines for aircraft alerting systems. Seattle, WA: Boeing Commerical Airplane. (AD-A043 383)

Visual, auditory (speech and non-speech), and tactile methods of information display are reviewed. The vast body of findings related to the detection and identification of these types of signals is summarized. Guidelines and recommendations for the use of each type signal in future aircraft alerting and warning systems are made. The guidelines and recommendations are intended to maximize the probability of a correct response within a proper time period and to provide consistency in signal characteristics across situations.

3. Brown, J. E., Bertone, C. M., & Obermayer, R. W. (1968). Army aircraft voice-warning system study. Aberdeen Proving Ground, MD: U. S. Army Human Engineering Laboratories. (AD-667 924)

This report describes an analytical study that was intended to serve as a basis for the application of voice warning systems (VWS) for the Huey, Cobra, Chinook, Skycrane, and Mohawk helicopters. The following problems were studied: (a) the identification and selection of messages for maximum and minimum effectiveness, (b) the determination of priority sequences, and (c) the integration of the VWS into existing cockpits.

A survey of pilot opinion indicated pilots prefer the following:

1. Disable/mute control
2. Female rather than male voice
3. Duplication of VWS messages on the annunciator panel
4. Single messages rather than a series of diagnostic messages
5. Messages to go to all crewmembers
6. Inclusion of the chip detection warning even if the false alarm rate is 90%.

For twin engine helicopters the pilot preferred engine fire or failure messages to indicate which engine was on fire or had failed, and a separate message if both engines failed. The pilots emphatically did not want the VWS message to prescribe corrective action for any condition.

4. Buschow, K. L. (1966). Audible warning systems. C-5 Program Personnel Subsystem Quarterly Progress Report LGIUQ295-1-2 Appendix C. Marietta, GA: Lockheed-Georgia Company.

   The information on both speech and non-speech audible warning systems is reviewed with emphasis on when auditory signals should be used, desirable characteristics of these signals, and the method of presentation to the operator. Several design options are discussed. This document was prepared as part of the process of designing the audible warning system for the C-5A.

5. Butler, F., Manaker, E., & Obert-Thorn, W. (1981). Investigation of a voice synthesis system for the F-14 aircraft (Report No. ACT-81-001). Bethpage, NY: Grumman Aerospace Corporation. (AD-B058 705L) (This report is not available for release to the general public.)

   This study assessed the usefulness of a voice synthesis system (VSS) for the F-14A aircraft. A human factors evaluation was performed by generating a "realistic" combat scenario for the F-14A and identifying phases of the mission in which it is important for the pilot to remain outside the aircraft visually while it is also important for the pilot to receive information currently displayed via cockpit warning/caution lights. A baseline VSS system was proposed and essentially served to duplicate warning/caution lights with a voice message. Seven F-14 pilots evaluated the proposed system and were generally in approval. The report also reviews speech synthesis technology and documents relative characteristics of various speech synthesis chips and boards currently manufactured and/or marketed in the U.S.

6. Cooper, George E. (1977). A survey of the status of and philosophies relating to cockpit warning systems (NASA CR-152071). Saratoga, CA: NASA-Ames Research Center.

   A broad survey of industrial and military personnel cognizant of cockpit design revealed four "generally accepted" guidelines for auditory warning systems:

   1. "Auditory warnings should be limited to 4 or 5"
   2. "Continued loud sounds tend to incapacitate"
   3. "Voice warnings are desirable"
   4. "It is acceptable for all audio warnings to come from a single source and to be electronically generated"

   The survey also identified three guidelines "recommended by a few but overlooked by most":

1. "Audio warnings should be used for pilot error situations only"
2. "A radio override switch is needed to reduce interference by warning systems"
3. "Voice warnings should be advisory in nature".

7. Davis, G., & Stockton, G. (1981). F-16 voice message system study. Unpublished manuscript, General Dynamics/Ft. Worth Division, Ft. Worth, TX.

A proposed voice message system for the F-16 is described. The system delivers a total of 22 messages: 15 concerning conditions requiring immediate corrective action and 7 concerning conditions requiring pilot awareness. The messages are composed of synthesized speech with spectral characteristics simulating female voice. The system includes a switch-activated built-in test mode in which the entire repertoire of messages is delivered, allowing a preflight check of the system. A status display would provide legends indicating power failure, system failure, test mode, and normal operations. It was felt that the primary benefits of incorporating the system into the aircraft would occur at times in which it is important for the pilot to maintain visual surveillance outside the aircraft. Salient research findings in the literature are briefly reviewed.

8. Deatherage, B. H. (1972). Auditory and other sensory forms of information presentation. _In_ H. P. Van Cott & R. G. Kinkade (Eds.), _Human Engineering Guide to Equipment Design_ (pp. 123-160). New York: McGraw-Hill.

This chapter presents fundamental guidelines for the use of auditory displays. Among the topics discussed are auditory _vs_. visual displays; speech _vs_. non-speech in auditory displays; physical and psychophysical characteristics of sound; masking of auditory signals; and minimum, maximum, and optimum signal levels. The Theory of Signal Detectability and sensory systems other than vision and audition are also discussed.

9. Department of Defense (1970). _Military Standard 411D: Aircrew station signals_. Washington, DC: U. S. Government Printing Office.

This document contains the military standards for all aircrew station signals. The specifications for auditory warning signals (speech and non-speech) are presented in section 5.2 of this document and include specifications for standardized signals for bail-out, wheels-up, and angle of attack/stall warning signals.

10. Department of Defense (1981). _Military Standard 1472C: Human engineering design criterion for military systems, equipment, and facilities_. Washington, DC: U. S. Government Printing Office.

Section 5.3 of MIL-STD-1472C (pp. 51-62) contains the military standards for the use of auditory displays. Included in these standards are the requirements for both speech and non-speech auditory warning signals.

11. Edman, T. R. (1982). Human factors guidelines for the use of synthetic speech devices. Proceedings of the Human Factors Society--26th Annual Meeting--1982, 212-216.

The existing speech synthesis technologies were reviewed with respect to the naturalness, intelligibility, comprehensibility, and acceptability of the output. The criteria for use of speech messages presented by Woodson (1981) were reviewed along with the recommendations for the use of generated speech in military cockpits by Werkowitz (1981). Learning effects and other factors to be considered in applications of speech synthesis were also discussed.

12. Erlick, D. E., & Hunt, D. P. (1957). Evaluating audio warning displays for weapon systems. Wright-Patterson Air Force Base, OH: Aero Medical Laboratory. (AD-118 189)

This report presents a systematic plan for evaluating auditory warning systems with an emphasis on aircraft auditory warning systems. The major variables and problem areas to be considered in system design and evaluation are discussed. An effective auditory warning signal is defined as one that (a) is easily detectable, (b) holds attention, (c) is quickly identifiable, and (d) is "infinitely" retainable over time with regard to its meaning. The general advantages and disadvantages of auditory displays are discussed and particular attention is given to variables that affect accuracy of identification and retention of meaning.

13. F-15 performs Saudi interceptor role (1983, May 23). Aviation Week and Space Technology, pp. 72-75.

This article describes a variety of missions in which the Saudis use the F-15D. Among the features of the aircraft discussed in the article is the auditory display associated with g loads. The maximum g load is based on altitude, airspeed, and gross weight, and is calculated by an onboard computer. At 85% maximum g a 900 Hz tone, interrupted at a rate of 4 Hz, is heard through the headset. At 92% the interrupt rate increases to 10 Hz, and at 100% a voice warning, "Over g, over g", is heard. This system enables the pilot to make full use of the 9 g capabilities of the aircraft.

14. Harris, S. D., Owens, J. M., & North, R. A. (1979). Human performance in time-shared verbal and tracking tasks. Pensacola, FL: Naval Aerospace Medical Research Laboratory.

This research investigated the assumption that a speech synthesis/recognition system can provide the human operator an additional and parallel information processing channel. A visual/manual tracking task was used as the primary task and the four possible combinations of visual vs. auditory presentation and vocal vs. manual output were used in a concurrent arithmetic task. The results indicated that the visual presentation/vocal response combination provided the best joint task performance, but no combination resulted in equivalent single and dual task perform-

ance. It was therefore concluded that the auditory/voice channel does not constitute a completely parallel channel and that two variables--relative task priorities and specific resource requirements of each task--must be considered in predicting concurrent task performance.

15. Hart, S. G., & Simpson, C. A. (1976, May). Effects of linguistic redundancy on synthesized cockpit warning message comprehension and concurrent time estimation (NASA TMX 73, 170). 12th Annual Conference on Manual Control, pp. 309-321.

The intelligibility of synthesized aircraft warning messages was assessed with and without a background of competing weather broadcasts. It was found that the intelligibility of sentence-format messages was higher than two-word messages in both conditions. Secondary tasking involved verbal estimates of session length and production of an estimated 10-second interval. The tasks indicated that the sentence-format messages required less attention for comprehension that did two-word messages.

16. Hoeffel, J. C. (1965). Evaluation of A-4C/E aircraft low altitude aural warning system (VA-76 as modified by NAS Quonset Point) interim report no. 1. Washington, DC: Bureau of Naval Weapons. (AD-467 712)

A low altitude aural warning system was evaluated during low altitude navigation maneuvers. The primary deficiencies noted were that the warning tone was on continuously during ground operation, requiring that the volume be reduced while the aircraft is on the ground and then readjusted after takeoff, and that the accompanying light was difficult to detect in bright ambient light conditions. It was felt that the system was a significant improvement over the then-current visual-only alert and further testing was to be conducted.

17. Kemmerling, P., Geiselhart, R., Thorburn, D. E., & Cronburg, J. G. (1969). A comparison of voice and tone warning systems as a function of task loading (ASD-TR-69-104). Wright-Patterson Air Force Base, OH: Air Force Systems Command. (AD-702 459)

An F-111 flight simulator was used to compare tone and voice warning systems. Twelve Air Force pilots served as subjects. The subjects flew identical simulated bombing missions. A warning was presented at three points in the mission; the three points were judged as representing low, moderate, and high workload conditions. Measures of response times and visual scan patterns were taken for each warning presentation. The results revealed faster response times to voice warnings than to tone warnings for all three workload conditions. The visual scan pattern measurements revealed that subjects tended to cross-check the visual annunciator panel if the warning was a tone, but did not do so if the warning was voice.

18. Manaker, E. (1982). Pilot ability to understand synthetic voice and radio voice when received simultaneously. Bethpage, NY: Grumman Aerospace Corporation. (AD-A119 137)

This study addressed the problem of the simultaneous reception of a message over the radio and presentaion of a synthesized voice warning message (both presented through the pilot's headset). The methods of presentation contrasted were diotic (both messages presented to each ear), dichotic/diotic (one message presented to both ears, the other presented to only one ear), and dichotic (one message presented to one ear, the other message presented to the other ear). Results indicated that both the dichotic method and the dichotic/diotic method were superior to the diotic method in terms of the understandability of both messages. It was also found that the key variable in determining the understandability of radio messages overlapped by synthesized warning messages is the degree to which the radio call sign is obscured. Apparently the subjects could perceive the radio message, even when overlapped by a warning message, if they were sure the message was intended for them. Although the obscuring of the call sign by a warning message is a real-world possibility, the probability of such an occurrence was considered low, and it was concluded that the use of voice warning messages will not seriously hinder the reception of radio messages.

19. Munns, M. (1971, July). Ways to alarm pilots. Aerospace Medicine, 42, pp. 731-734.

This paper reviews the literature pertaining to aircraft warning signals (visual and auditory). It is recommended that designers consider the signal system as a whole in addition to the individual considerations for particular warning functions; possible situations of pilot overload or confusion might not be recognized otherwise. It was also noted that enhanced warning systems are not good substitutes for proper pilot training.

20. North, R., & Lea, W. (1982). Application of advanced speech technology in manned penetration bombers. Minneapolis, MN: Honeywell Systems & Research Center. (AD No. A119274).

A methodology was developed to identify the best uses for speech recognition and speech synthesis devices in aircraft. The methodology was applied to the B-52G/H aircraft. It was suggested that speech recognition would be most beneficial for retrieving procedural data presently contained in flight manuals. A number of beneficial uses for speech synthesis were identified.

21. Patterson, R. D. (1982). Guidelines for auditory warning systems on civil aircraft (CAA Paper 82017). London: Civil Aviation Authority.

Existing auditory warning systems aboard commercial airliners are reviewed with respect to overall sound level (loudness), temporal characteristics, and spectral characteristics. Briefly, most of the warnings were found to be too loud and to have onsets and offsets

that are too abrupt. The spectral characteristics were found to be acceptable. Basic human factors principles are discussed and the potentials of voice warnings are briefly explored.

22. Patterson, R.D., & Milroy, R. (1979). Existing and recommended levels for auditory warnings on civil aircraft. Cambridge, United Kingdom: Medical Research Council Applied Psychology Unit.

This report describes a procedure for estimating the appropriate sound level (loudness) of flight deck auditory warnings. The procedure is illustrated for two aircraft--the Boeing 727 and the BAC1-11. It was concluded that some of the warning sounds are far too loud.

23. Patterson, R. D., & Milroy, R. (1980). Auditory warnings on civil aircraft: The learning and retention of warnings. Cambridge, United Kingdom: Medical Research Council Applied Psychology Unit.

Two groups of 10 non-pilot subjects learned the meaning of ten aircraft auditory (non-speech) warning signals under serial or cumulative learning conditions. The subjects returned one week later for retest. Results indicated that upon retest most subjects correctly identified 8 or 9 of the 10 signals. An analysis of the errors made revealed that signals most likely to be confused were those with temporal similarity (mainly repetition rate) despite prominent spectral differences.

24. Pollack, I., Sumby, H., & Pickett, J. M. (1952). On the number of identifiable voices. Intra-Laboratory Report Number 8. Washington, DC: Human Resources Research Laboratories. (AD-844 643)

This article is a brief progress report for an investigation of the number of voices that may be discriminated by individuals listening to recorded voices. It was reported that under conditions of long speech samples with full frequency range, some listeners could identify up to 65 speakers. However, if the speech samples were limited to one monosyllabic word, discrimination was on the order of 2-7 speakers. The number of identifiable voices was found to vary as a function of length of speech passages, the extent of filtering of frequency ranges in the recordings, and the size of the class of possible voices.

25. Poulton, E. C. (1955). Simultaneous and alternate listening and speaking. Journal of the Acoustical Society of America, 27, 1204-1207.

Simultaneous listening and speaking was compared with alternate listening and speaking. Subjects listened to recorded speech passages over headphones. In the simultaneous condition the subject repeated the passage as he was listening to it; in the alternate condition the subject waited until the passage was completed before repeating it. The speed of presentation was varied from 1.5 to 4.5 words per second. It was found that the simultaneous condition resulted in more errors for all presentation rates. It was concluded that individuals have difficulty speaking while simultaneously listening. It was also noted that much of the speech produced in the training sessions for the simultaneous condition was meaningless drivel, but the subjects were unaware that their speech was unintelligible.

26. Randle, R. J., Jr., Larsen, W. E., & Williams, D. H. (1980). Some human factors issues in the development and evaluation of cockpit alerting and warning systems (NASA-RP-1055). Moffett Field, CA: NASA-Ames Research Center.

Major human factors issues in the evaluation of cockpit alerting and warning systems are discussed. Specific instances of problems with current systems are discussed and a general statement of the current problem is presented. A complete methodology for human factors evaluation in all phases of design, development, and testing is offered. Performance evaluation problems are explicitly discussed, and the respective roles of basic laboratory research and specific system evaluations are examined.

27. Simpson, C. A. (1975, November). Occupational experiences with a specific phraseology: Group differences in intelligibility for synthesized and human speech. Paper presented at the 19th Annual Meeting of the Acoustical Society of America, San Francisco, CA.

Two groups of subjects listened to sentences of two types - common phraseology and specialized phraseology appropriate for air traffic communications. One group was composed of commercial airline pilots; the other group was composed of police officers. Police officers were chosen under the assumption that they would be experienced in 2-way radio communication but unfamiliar with air traffic phraseology. The stimulus sentences were either recorded human voice or synthesized speech. It was found that the groups did not differ with respect to the intelligibility of common phraseology but that the aircraft pilots were better able to understand the specialized phraseology. The results were taken to support a model of speech comprehension in which the listener's familiarity with a particular type of phraseology served to reduce uncertainty in the speech decoding process.

28. Simpson, C. A. (1980, October). Synthesized voice approach callouts for air transport operations (NASA CR-3300). Menlo Park, CA: Psycho Linguistic Research Associates.

A flight simulator was used to assess the effectiveness of synthesized voice approach callouts during final approach and landing. The first phase of the project involved the observation of current callout procedures on 72 flights with landings at 24 airports. A synthesized voice callout system was then developed and incorporated into a flight simulator. Volunteer crews from commercial air carriers served as subjects in the second phase of the study and flew six different types of approaches, either using standard procedures or the experimental synthesized callout (SYNCALL)

system. Results indicated that performance on the airspeed and descent rate parameters was better using SYNCALL on One-Engine approaches. The correlation between SYNCALL and standard callouts (made by the pilot not flying) was examined by having the SYNCALL audio signal directed to tape instead of a speaker during the experimental conditions in which standard callouts were used. The reliability coefficients were comparable for all conditions except SYNCALL was more reliable than standard procedure callouts for making deviation approach callouts. Suggestions for improvement of SYNCALL were made.

29. Simpson, C. A. (1982, April 19). Speech I/O in the cockpit: Plane to pilot...pilot to plane. Design News, p. 159-168.

This article provides a general narrative of the author's research on synthesized speech in the aircraft cockpit, an overview of commercially available speech synthesis devices, and emphasizes the importance of human factors considerations in the implementation of synthesized speech in aircraft.

30. Simpson, C. A., Coler, C. R., Huff, E. M. (1982, March). Human factors of voice I/O for aircraft cockpit controls and displays. Proceedings of the Workshop on Standardization for Speech I/O Technology. Gaithersberg, MD: National Bureau of Standards.

This paper reviews the human factors questions surrounding the use of speech synthesis and speech recognition in the aircraft cockpit. The findings of several relevant studies conducted by NASA-Ames Research Center are briefly reviewed.

31. Simpson, C. A.,& Marchionda-Frost, K. (in press). Synthesized speech rate and pitch effects on intelligibility of warning messages for pilots. Proceedings of the Second Symposium on Aviation Psychology. Columbus, OH.

The intelligibility of synthesized warning messages was assessed at various rates and pitches. No significant differences in intelligibility were found using pitches (fundamental frequency of the voice) below, within, and above the highest amplitude octave band of the background noise. There was also no difference in intelligibility across presentation rates up to 178 wpm, although pilots indicated a preference for a more moderate rate of 156 wpm. Response time did decrease, however, as the rate increased. The elimination of redundant words in the message (to reduce the time required to complete message delivery) served to decrease intelligibility and increase response time.

32. Simpson, C. A., and Williams, D. H. (1975). Human factors research problems in electronic voice warning system design (NASA TMX 62, 464). 11th Annual Conference on Manual Control, pp. 94-106.

Basic human factors questions concerning the implementation of voice warning systems in aircraft are discussed, and relevant research findings are reviewed. The ground proximity warning system is used to illustrate several design options. Many of the questions raised in this report have been addressed in subsequent research by the authors and their colleagues.

33. Simpson, C. A., & Williams, D. H. (1980). Response time effects of alerting tone and semantic context for synthesized voice cockpit warnings. Human Factors, 22, 319-330.

Although current military standards and human factors guidelines recommend that a voice warning message be preceded by an alerting tone, there has been no experimental evidence supporting that recommendation. This study tested that recommendation and found that the alerting tone actually served to lengthen total response time, i.e., time from the onset of the warning until subject response. The addition of a word, however, did not increase system response time. The experiment used four current airline pilots as subjects and an S-2 fixed-base simulator outfitted with a Votrax VS-6 speech synthesizer and a specially configured 12-key response board as apparatus.

34. Smith, E. B. (1966). Military potential test of the AN/ASH-19 voice warning system and continuous in-flight performance recorder. Ft. Rucker, AL: United States Army Aviation Test Board. (AD-876 664).

The AN/ASH-19 Voice Warning System, a 1960's model using prerecorded tape, was evaluated in a number of helicopters. The controls of the device itself were found to be unacceptable from a human factors standpoint, but the operational characteristics of the system were found to be desirable. Specifically, it was felt that the system speeded response to fault conditions, provided messages that were, on the whole, intelligible and attention-getting, and freed the pilot's eyes for "outside" visual tasks during low-level tactical maneuvers, thereby enhancing aircrew/aircraft safety. It was recommended that the human factors problems with the controls on the device be remedied and the device be further evaluated for potential deployment.

35. Smith, W., & Crook, S. (1981, June 25). Phonemes, allophones, and LPC team to synthesize speech. Electronic Design, 121-127.

This article reviews the general technology used in speech synthesis and explains the basic approaches to speech synthesis, constructive synthesis, and analysis/synthesis. Several of the more common speech synthesis techniques are discussed with respect to technology, advantages, and disadvantages.

36. Society of Automotive Engineers, Inc. (1980). Flight deck visual, audible, and tactual signals (Aerospace Recommended Practice 450D). Warrendale, PA: Author.

This document contains the Aerospace Recommended Practice issued by the Society of Automotive Engineers pertaining to the design of alerting systems for aircraft. Briefly, the recommendations include a master aural attention-getting sound, that voice warnings are preferable to non-speech discrete aural alerts, and that all aural alerts be accompanied by an explanatory, alphanumeric visual display.

37. Townsend, T. H. (1978). Speech intelligibility through communication headsets for general aviation. Aviation, Space, & Environmental Medicine, 49, 466-469.

A word discrimination task was used to assess the intelligibility of speech heard over one of three communication headsets or an aircraft cockpit loudspeaker. Performance varied as a function of the degree of attenuation provided by the headset. The loudspeaker required an intensity of 106 dB SPL to equal the intelligibility provided by the headsets at intensities around 80 dB SPL.

38. Veitengruber, J. E., Boucek, G. P., Jr., & Smith, W. D. (1977). Aircraft alerting systems criteria study, Vol. I: Collation and analysis of aircraft alerting systems data. Seattle, WA: Boeing Commercial Airplane. (AD-A042 328)

The purpose of this study was to develop standards for aircraft alerting systems. Alerting methods currently used in aircraft were tabulated. A strategy for determining the priority of a given alert was developed. Current regulations and design specifications were reviewed. Data from a variety of sources were collected and plans for obtaining relevant missing data were formulated. Conclusions and preliminary recommendations are offered. These recommendations encompass visual, auditory (speech and non-speech), and tactile methods of presenting warning information.

39. Vogue, Victoria M. (1980). Acceleration forces on the human subject. Aviation, Space, & Environmental Medicine, 51, 970-980.

The technology of producing g forces and the notation conventions for designating the direction of g with respect to the body are reviewed. Physiological effects of g forces are discussed in detail. A paragraph on human factors considerations in exposure to g forces highlighted five findings:

1. Complex motor tasks are impaired at relatively low g levels.
2. Reaction time increases with g stress.
3. Reaction time to auditory signals remains superior to visual signals for all levels of g stress.
4. Visual functions are impaired at g levels well below physiological tolerance levels.
5. Alcohol decreases performance synergistically with increasing g loads.

40. Werkowitz, E. (1981, May). Ergonomic considerations for the cockpit applications of speech generation technology. Proceeding of the Voice-Interactive Systems: Applications and Payoffs Symposium. Naval Air Development Center.

This paper reviews the literature relevant to the integration of speech synthesis technology into the cockpit. Among the issues discussed are when auditory as opposed to visual displays should be used, and when speech as opposed to non-speech should be used in an auditory display. Experimental findings are discussed and recommendations concerning the future direction of research are made.

41. Wheale, J. L. (1980). Pilot opinion of flight deck voice warning systems. In D. J. Oboine & J. A. Levis (Eds.) Human Factors in Transport Research (Vol. 1, pp. 88-96). London: Academic Press.

A questionaire was used to assess pilot opinion of voice warning messages. The results indicated that pilots prefer voice warnings to be used to supplement existing visual and auditory signals. They felt that voice warnings should be cancellable, prefixed by an attention-getting sound, and limited in number to eight. They preferred a keyword format over a sentence format. They judged voice warning sytems to be informative, valuable, and alerting, but indicated that the use of such systems should be limited to immediate-action emergencies only. A lack of confidence in the sole use of voice warnings in emergencies was also indicated.

42. Wheale, J. L. (1981). The speed of response to synthesized voice messages. AGARD Conference Proceedings No. 311: Aural Communication in Aviation (pp. 7-1--7-11). 7 Rue Ancelle, 92200 Neuilly sur Seine, France.

The effectiveness of voice warning messages in aircraft was assessed using measures of response time. Four warning system arrangements were compared: (a) Red Alerts supplemented with audio (non-speech) warnings, (b) Red Alerts supplemented with voice messages, (c) Red Alerts supplemented with audio warnings and Amber Alerts supplemented with voice messages, and (d) Red Alerts supplemented with audio warnings and Amber Alerts and White Alerts supplemented with voice messages. The overall response times were not significantly different between arrangements. Within Red Alerts, however, response time to voice messages was significantly slower than response time to audio warnings. It was concluded that a choice among warning systems cannot be based on response times.

43. Wheale, J. L. (1982). Performance decrements associated with reaction to voice warning messages. AGARD Conference Proceedings No. 329: Advanced Avionics and the Military Aircraft Man/Machine Interface (pp. 18-1--18-12). 7 Rue Ancelle, 92200 Neuilly sur Seine, France.

This study evaluated the effectiveness of synthesized voice warning messages, using primary task performance and response time as dependent measures. Voice messages were compared with audio warnings (i.e., non-speech) and visual indicators. Performance of the primary task was equal across all conditions, but subjects responded to audio warnings quicker than voice or visual, and to voice quicker than visual.

44. Wheale, J. L. (1983). Evaluation of an experimental central warning system with a synthesized voice component. Aviation, Space, and Environmental Medicine, 54, 517-523.

A warning system consisting of Red Alerts supplemented with audio (non-speech) warnings, Amber Alerts supplemented with voice messages, and White Alerts with no auditory component was evaluated under varied conditions of workload. The effect of workload on response time was evident only in responses to White Alerts. Responses to Red Alerts/audio warnings were quicker than responses to Amber Alerts-/voice messages. Although warning type and urgency level were confounded in this study, previous experiments had demonstrated faster response times to audio warnings as compared to voice warnings with no confounding of urgency (see Wheale, 1981). The subjects, who were airline pilots, completed system evaluation questionnaires at the conclusion of the experiment and the results thereof are presented.

45. Wickens, C., Sandry, D., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. Human Factors, 25, 227-248.

Two experiments examined the compatibility of modes of input (auditory or visual), central processing (spatial or verbal) and output (speech or manual). It was found that the following combinations produced the best performance and least interference from secondary tasking:

Auditory input - verbal processing - speech output.
Visual input - spatial processing - manual output.

Resource competition effects in secondary tasking were also examined and compatibility was found to interact with resource competition, particularly as workload was increased.

46. Wickey, D. (1981, June 11). Synthesizer chip translates LPC to speech economically. Electronic Design,pp. 213-218.

This article reviews the technology used in the Texas Instruments single chip TMS 5220 voice synthesize processor. This processor can operate in a high quality LPC system or in a medium quality allophonic system, or in a system which combines the two approaches.

47. Williams, D. H., & Simpson, C. A. (1976). A systematic approach to advanced cockpit warning systems for air transport operations: Line pilot preferences. NASA Aircraft Safety and Operating Problems Conference (NASA SP 416, pp. 617-644). Moffett Field, CA: Nasa-Ames Research Center.

Fifty commercial airline pilots from eight airlines were given a structured questionnaire related to the design of future aircraft warning systems. Half the subjects were given a demonstration of new voice-warning and CRT display systems before they were given the questionnaire; the other half completed the questionnaire before

being given the demonstration. The results revealed few differences between the groups. It was found that the pilots preferred an audio system, particularly voice, over a visual system unless the false alarm rate was high. Pilots preferred a visual system for high false alarm rate systems and for low priority (urgency) messages. They also preferred, in general, to be able to cancel or mute the warning, although the preferred cancellation mode varied across warning methods. On most issues the data reflected much consistency and strong agreement among the pilots.

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APPENDIX B

STANDARDS AND GUIDELINES APPLICABLE TO AUDITORY INFORMATION SYSTEMS FOR AIRCRAFT

5.3 Audio Displays.

5.3.1 General.

5.3.1.1 Use. Audio displays should be provided when:

a. The information to be processed is short, simple, and transitory, requiring immediate or time-based response.

b. The common mode of visual display is restricted by overburdening; ambient light variability or limitation; operator mobility; degradation of vision by vibration, high g-forces, hypoxia, or other environmental considerations; or anticipated operator inattention.

c. The criticality of transmission response makes supplementary or redundant transmission desirable.

d. It is desirable to warn, alert, or cue the operator to subsequent additional response.

e. Custom or usage has created anticipation of an audio display.

f. Voice communication is necessary or desirable.

5.3.1.2 Signal Type. When an audio presentation is required, the optimum type of signal should be presented in accordance with Table V.

5.3.1.3 False Alarms. The design of audio display devices and circuits shall preclude false alarms.

5.3.1.4 Failure. The audio display device and circuit shall be designed to preclude warning signal failure in the event of system or equipment failure and vice versa.

5.3.1.5 Circuit Test. All audio displays shall be equipped with circuit test devices or other means of operability test.

5.3.1.6 Aircrew Stations. Audio signals for air crew stations shall conform to MIL-STD-411, where applicable.

5.3.1.8 Use with Several Visual Displays. One audio signal may be used in conjunction with several visual displays, provided that immediate discrimination is not critical to personnel safety or system performance.

5.3.2 Audio Warnings.

5.3.2.1 Warning Signals. Audio signals should be provided, as necessary, to warn personnel of impending danger, to alert an operator to a

TABLE V. FUNCTIONAL EVALUATION OF AUDIO SIGNALS

FUNCTION	TYPE OF SIGNAL		
	TONES (Periodic)	COMPLEX SOUNDS (Non-Periodic)	SPEECH
QUANTITATIVE INDICATION	**POOR** Maximum of 5 to 6 tones absolutely recognizable.	**POOR** Interpolation between signals inaccurate.	**GOOD** Minimum time and error in obtaining exact value in terms compatible with response.
QUALITATIVE INDICATION	**POOR-TO-FAIR** Difficult to judge approximate value and direction of deviation from null setting unless presented in close temporal sequence.	**POOR** Difficult to judge approximate deviation from desired value.	**GOOD** Information concerning displacement, direction, and rate presented in form compatible with required response.
STATUS INDICATION	**GOOD** Start and stop timing. Continuous information where rate of change of input is low.	**GOOD** Especially suitable for irregularly occurring signals (e.g., alarm signals).	**POOR** Inefficient; more easily masked; problem of repeatability.
TRACKING	**FAIR** Null position easily monitored; problem of signal-response compatibility.	**POOR** Required qualitative indications difficult to provide.	**GOOD** Meaning intrinsic in signal.
GENERAL	Good for automatic communication of limited information. Meaning must be learned. Easily generated.	Some sounds available with common meaning (e.g., fire bell). Easily generated.	Most effective for rapid (but not automatic) communication of complex, multidimensional information. Meaning intrinsic in signal and context when standardized. Minimum of new learning required.

critical change in system or equipment status, and to remind the operator of a critical action or actions that must be taken. NOTE: Certain audio signals have been standardized for aircraft use by joint service and international agreement. Stipulation of audio signals for future aircraft design should be in consonance with these agreements (see MIL-STD-411).

5.3.2.2 Nature of Signals. Audio warning signals should normally consist of two elements: an alerting signal and an identifying or action signal.

5.3.2.2.1 Two element Signal. When reaction time is critical and a two element signal is necessary, an alerting signal of 0.5 second duration shall be provided. All essential information shall be transmitted in the first 2.0 seconds of the identifying or action signals.

5.3.2.2.2 Single element Signal. When reaction time is critical, signals shall be of short duration. If a single element signal is permissible, all essential information shall be transmitted in the first 0.5 second.

5.3.2.3 Caution Signals. Caution signals shall be readily distinguishable from warning signals and shall be used to indicate conditions requiring awareness, but not necessarily immediate action.

5.3.2.4 Relation to Visual Displays. When used in conjunction with visual displays, audio warning devices shall be supplementary or supportive. The audio signal shall be used to alert and direct operator attention to the appropriate visual diaplay.

5.3.3 Characteristics of Audio Warning Signals.

5.3.3.1 Frequency.

5.3.3.1.1 Range. The frequency range shall be between 200 and 5,000 Hz and, if possible, between 500 and 3,000 Hz. When signals must travel over 300 m (985 ft), sounds with frequencies below 1,000 Hz should be used. Frequencies below 500 Hz should be used when signals must bend around obstacles or pass through partitions. The selected frequency band shall differ from the most intense background frequencies and shall be in accordance with other criteria in this section.

5.3.3.1.2 Spurious Signals. The frequency of a warning tone shall be different from that of the electric power employed in the system, to preclude the possibility that a minor equipment failure may generate a spurious signal.

5.3.3.2 Intensity.

5.3.3.2.1 Compatibility With Acoustical Environment. The intensity, duration and source location of audio alarms and signals shall be compatible with the acoustical environment of the intended receiver as well as the requirements of other personnel in the signal areas.

5.3.3.2.2 Discomfort. Audio warning signals should not be of such intensity as to cause discomfort or "ringing" in the ears as an aftereffect.

5.3.4 Signal Characteristics in Relation to Operational Conditions and Objectives.

5.3.4.1 Audibility. A signal-to-noise ratio of at least 20 dB shall be provided in at least one octave band between 200 and 5,000 Hz at the operating position of the intended reciever.

5.3.4.2 Alerting Capability -

5.3.4.2.1 Attention. Signals with high alerting capacity should be provided when the system or equipment imposes a requirement on the operator for concentration of attention. Such signals shall not, however, be so startling as to preclude appropriate responses or interfere with other functions by holding attention away from other critical signals.

5.3.4.2.2 Onset and Sound Pressure Level. The onset of critical alerting signals should be sudden, and a relatively high sound pressure level should be provided as specified in 5.3.4.1.

5.3.4.2.3 Dichotic Presentation. When earphones will be worn in the operational situation, a dichotic presentation should be used whenever feasible, alternating the signal from one ear to the other by means of a dual-channel headset.

5.3.4.2.4 Headset. When the operator is wearing earphones covering both ears during normal equipment operation, the audio warning signal shall be directed to the operator's headset as well as to the work area. Binaural headsets should not be used in any operational environment below 85 dB(A) when that environment may contain sounds that provide the operator with useful information when that information cannot be directed to the operator's headset. Such sounds may include voices, machine noise that indicates wear or malnfunction and other auditory indications of system performance/mission status.

5.3.4.3 Discriminability.

5.3.4.3.1 Use of Different Characteristics. When several different audio signals are to be used to alert an operator to different types of conditions, discriminable difference in intensity, pitch, or use of beats and harmonics shall be provided. If absolute discrimination is required, the number of signals to be identified shall not exceed four.

5.3.4.3.2 Coding. Where discrimination of warning signals from each other will be critical to personnel safety or system performance, audio signals shall be appropriately coded. Alarms that are perceptibly different shall correlate with different conditions requiring critically different operator responses (e.g., maintenance, emergency conditions, and health hazards). Such signals shall be sufficiently different to minimize the operator's search of visual displays.

5.3.4.3.3 Critical Signals. The first 0.5 second of an audio signal requiring fast reaction shall be discriminable from the first 0.5 second of any other signal that may occur. Familiar signals with established names or associations shall be selected. Speech should be used whenever feasible.

5.3.4.3.4 Action Segment. The identifying or action segment of an audio warning signal shall specify the precise emergency or condition requiring action.

5.3.4.3.5 Differentiation From Routine Signals. Audio alarms intended to bring the operator's attention to a malfunction or failure shall be differentiated from routine signals, such as bells, buzzers, and normal operation noises.

5.3.4.3.6 Prohibited Types of Signals. The following types of signals shall not be used as warning devices where possible confusion might exist because of the operational environment:

a. Modulated or interrupted tones that resemble navigation signals or coded radio transmissions.

b. Steady signals that resemble hisses, static, or sporadic radio signals.

c. Trains of impulses that resemble electrical interference whether regularly or irregularly spaced in time.

d. Simple warbles which may be confused with the type made by two carriers when one is being shifted in frequency (beat-frequency-oscillator effect).

e. Scrambled speech effects that may be confused with cross modulation signals from adjacent channels.

f. Signals that resemble random noise, periodic pulses, steady or frequency modulated simple tones, or any other signals generated by standard countermeasure devices (e.g., "bagpipes").

g. Signals similar to random noise generated by air conditioning or any other equipment.

5.3.4.4 Compatibility.

5.3.4.4.1 Existing Signals. The meaning of audio warning signals selected for a system should be consistent with warning signal meanings already established for that function.

5.3.4.4.2 Acoustic Environment. Established signals shall be used, provided they are compatible with the acoustic environment and the requirements specified herein for the voice communication system. Standard signals shall not be used to convey new meanings.

5.3.4.5 Masking.

5.3.4.5.1 Other Critical Channels. Audio warning signals shall not interfere with any other critical functions or warning signals, or mask any other critical audio signals.

5.3.4.5.2 Separate Channels. Where a warning signal delivered to a headset might mask another essential audio signal, separate channels may be provided to direct the warning signal to one ear and the other essential audio signal to the other ear. In such a situation and when required by operating conditions, this dichotic presentation may further provide for alternation of the two signals from ear to ear.

5.3.5 Verbal Warning Signals.

5.3.5.1 Nature of Signals. Verbal warning signals shall consist of:

a. An initial alerting signal (nonspeech) to attract attention and to designate the general problem.

b. A brief standardized speech signal (verbal message) which identifies the specific condition and suggests appropriate action.

5.3.5.2 Intensity. Verbal alarms for critical functions shall be at least 20 dB above the speech interference level at the operating position of the intended receiver.

5.3.5.3 Vocal Criteria.

5.3.5.3.1 Type of Voice. The voice used in recording verbal warning signals shall be distinctive and mature.

5.3.5.3.2 Delivery Style. Verbal warning signals shall be presented in a formal, impersonal manner.

5.3.5.4 Speech Processing. Verbal warning signals shall be processed only when necessary to increase or preserve intelligibility, such as by increasing the strength of consonant sounds relative to vowel strength. Where a signal must be relatively intense because of high ambient noise, peak-clipping (see 3.24) may be used to protect the listener against auditory overload.

5.3.5.5 Message Content. In selecting words to be used in audio warning signals, priority shall be given to intelligibility, aptness, and conciseness in that order.

5.3.5.6 Message Categories.

5.3.5.6.1 Critical Warning Signals. Critical warning signals shall be repeated with not more than a 3-second pause between messages until the condition is corrected or overridden by the crew.

5.3.5.6.2 Message Priorities. A message priority system shall be established and more critical messages shall override the presentation of any message occurring below it on the priority list. If two or more incidents or malfunctions occur simultaneously, the message having the higher priority shall be given first. The remaining messages shall follow in order of priority. In the event of a complete subsystem failure, the system shall integrate previous messages via electronic gathering and report the system rather than the component failure.

5.3.6 Controls for Audio Warning Devices.

5.3.6.1 Automatic or Manual Shut-off. When an audio signal is designed to persist as long as it contributes useful information, a shut-off switch controllable by the operator, the sensing mechanism, or both, shall be provided, depending on the operational situation and personnel safety factors.

5.3.6.2 Automatic Reset. Whether audio warning signals are designed to be terminated automatically, by manual control, or both, an automatic reset function shall be provided. The automatic reset function shall be controlled by the sensing mechanism which shall recycle the signal system to a specified condition as a function of time or the state of the signaling system.

5.3.6.3 Volume Control.

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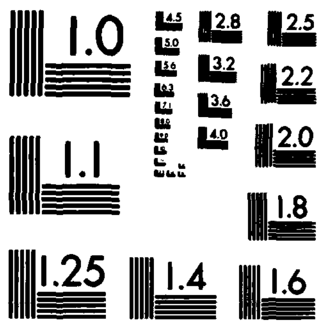

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

5.3.6.3.1 Automatic or Manual. The volume (loudness) of an audio warning signal shall be designed to be controlled by the operator, the sensing mechanism, or both, depending on the operational situation and personnel safety factors. Control movements shall be restricted to prevent reducing the volume to an inaudible level.

5.3.6.3.2 Ganging to Mode Switches. Volume controls may be ganged to mode switches to provide maximum output during mission phases in which intense noise may occur and to provide reduced volume at other times. Ganging shall not be accomplished if there is a possibility that intense noise may occur in an emergency situation during a mission phase in which the volume would be decreased below an audible level.

5.3.6.3.3 Caution Signal Controls. Audio caution signals shall be provided with manual reset and volume controls.

5.3.6.4 Duration. Audio warning signal duration shall be at least 0.5 second, and may continue until the appropriate response is made. Completion of a corrective action by the operator or by other means shall automatically terminate the signal.

5.3.6.5 Duration Limitations. In an emergency situation, signals that persist or increase progressively in level shall not be used if manual shut-off may interfere with the corrective action required.

5.3.7 Speech Transmission Equipment.

5.3.7.1 Frequency. Microphones and associated system-input devices shall be designed to respond optimally to that part of the speech spectrum most essential to intelligibility (i.e., 200 to 6,100 Hz). Where system engineering necessitates speech-transmission bandwidths narrower than 200 to 6,100 Hz, the minimum acceptable frequency range should be 250 to 4,000 Hz.

5.3.7.2 Dynamic Range. The dynamic range of a microphone used with a selected amplifier shall be great enough to admit variations in signal input of at least 50 dB.

5.3.7.3 Noise Cancelling Microphones. In very loud, low frequency noise environments (100 dB overall), noise cancelling microphones shall be used and shall be capable of effecting an improvement of not less than 10 dB peak-speech to root-mean-square-noise ratio as compared with non-noise-cancelling microphones of equivalent transmission characteristics.

5.3.7.4 Pre-emphasis. If necessary, speech system input devices should employ frequency pre-emphasis with a positive slope frequency characteristic no greater than 18 dB per octave from 140 to 1,500 to and no greater than 9 dB per octave over the frequency range 1,500 to 4,800 Hz, when no clipping is used.

5.3.7.5 Peak-clipping of Speech Signals. Where speech signals are to be transmitted over channels showing less than 15 dB peak-speech to root-mean-square-noise ratios, peak-clipping of 12 to 20 dB may be employed at system input and may be preceded by frequency pre-emphasis as specified in 5.3.7.4.

5.3.7.6 Noise Shields. When the talker is in an intense noise field, the microphone should be put in a noise shield. Noise shields should be designed to meet the following requirements:

a. A volume of at least 250 cu cm (15.25 cu in) to permit a pressure gradient microphone to function normally.

b. A good seal against the face with the pressure of the hand or the tension of straps.

c. A hole or combination of holes covering a total area of 65 sq mm (0.1 sq in) in the shield to prevent pressure buildup.

d. Prevention of a standing wave pattern by shape, or by use of sound absorbing material.

e. No impediment to voice effort, mouth or jaw movement or breathing.

5.3.8 Speech Reception Equipment.

5.3.8.1 Frequency Range. Headphones and loudspeakers shall be subject to the same frequency response restrictions as microphones and transmission equipment except that loudspeakers for use in multi-speaker installations and multiple channels fed into headphones (e.g., where several speech channels are to be monitored simultaneously) shall respond uniformly (±5 dB) over the range 100 to 4,800 Hz.

5.3.8.2 Loudspeakers for Multi-channel Monitoring.

5.3.8.2.1 Monitoring of Speakers. When several channels are to be monitored simultaneously by means of loudspeakers, the speakers shall be mounted at least 175 mrad (10°) apart in the horizontal plane frontal quadrant, ranging radially from π/4 rad (45°) left to π/4 rad (45°) right of the operator's normal forward facing position.

5.3.8.2.2 Filtering. When additional channel differentiation is required, apparent lateral separation shall be enhanced by applying low-pass filtering (frequency cutoff, F_c = 1,800 Hz) to signals fed to loudspeakers on one side of the central operator position. If there are three channels involved, one channel shall be left unfiltered, a high pass filter with 1,000 Hz cutoff shall be provided in the second channel, and a low-pass filter wth 2,500 Hz cutoff shall be provided in the third channel. A visual signal shall be provided to show which channel is in use.

5.3.8.3 Use of De-emphasis. When transmission equipment employs pre-emphasis and peak-clipping is not used, reception equipment shall employ frequency de-emphasis of characteristics complementary to those of pre-emphasis only if it improves intelligibility, i.e., de-emphasis shall be a negative-slope frequency response not greater than 9 dB per octave over the frequency range 140 to 4,800 Hz.

5.3.8.4 Headsets. If listeners will be working in high ambient noise (85 dB(A) or above), binaural rather than monaural headsets shall be provided. Unless operational requirements dictate otherwise, binaural headsets shall be wired so that the sound reaches the two ears in opposing phases. Their attenuation qualities should be capable of reducing the ambient noise level to less than 85 dB(A). Provisions should be incorporated to furnish the same protection to those who wear glasses.

5.3.9 Operator Comfort and Convenience.

5.3.9.1 Comfort. Communication equipment to be worn by an operator (e.g., headphones and telephone headsets) shall be designed to preclude operator discomfort. Metal parts of the headset shall not come in contact with the user's skin.

5.3.9.2 Hands-free Operation. Operator microphones, headphones, and telephone headsets shall be designed to permit hands-free operation under normal working conditons.

5.3.9.3 Accessibility of Handsets. Where communication requirements necessitate the use of several telephone handsets, the accessibility of their standby locations shall be determined by operational priority, i.e., the most frequently or urgently needed handset shall be the most accessible. Color-coding may also be employed where operating personnel will have visual contact with handsets under the working conditions.

5.3.10 Operating Controls for Voice Communication Equipment.

5.3.10.1 Volume Controls. Accessible volume or gain controls shall be provided for each communication receiving channel (e.g., loudspeakers or headphones) with sufficient electrical power to drive sound pressure level to at least 110 dB overall when using two earphones, and shall have pressure operated gain control switches to compensate for altitude in unpressurized compartments. The minimum setting of the volume control shall be limited to an audible level, i.e., it shall not be possible to inadvertently disable the system with the volume control. While separation of power (on-off) and volume control adjustment functions into separate controls is preferred, should conditions justify their combination, a noticeable detent position shall be provided between the OFF position and the lower end of the continuous range of volume adjustment. When combined power and volume controls are used, the OFF position shall be labeled.

5.3.10.2 Squelch Control. Where communication channels are to be continuously monitored, each channel shall be provided with a signal-activated switching device (squelch control) to suppress channel noise during no-signal periods. A manually operated, on-off switch, to de-activate the squelch when receiving weak signals, shall be provided.

5.3.10.3 Foot-operated Controls. When normal working conditions will permit the operator to remain seated at the working position and access to "talk-listen" or "send-receive" control switches is required for normal operation or if console operation requires the use of both hands, foot-operated controls shall be provided. Hand-operated controls for the same functions shall be provided for emergency use and for use when the operator may need to move from one position to another.

5.3.11 Speaker/Side Tone. The speaker's verbal input shall be in phase with its reproduction as heard on the headset. This side tone should not be filtered or modified before it is received in the headset.

5.3.12 Speech Intelligibility.

5.3.12.1 General. When information concerning the speech intelligibility of a system is required, three recommended methods are available, with the appropriate selection being dependent upon the requirements of the test:

a. The ANSI standard method of measurement of phonetically balanced (PB) monosyllabic word intelligibility, S3.2-1960, should be used when a high degree of test sensitivity and accuracy is required.

b. The modified rhyme test (MRT) (see Human Engineering Guide to Equipment Design) should be used if the test requirements are not as stringent or if time and training do not permit the use of the ANSI method.

c. The articulation index (AI) calculations should be used for estimations, comparisons and predictions of system intelligibility based upon ANSI S3.5-1969.

5.3.12.2 Criteria. The intelligibility criteria shown in Table VI shall be used for voice communication. The efficiency of communications needed and the type material to be transmitted shall determine which of the three communication requirements of Table VI is to be selected.

TABLE VI. INTELLIGIBILITY CRITERIA FOR VOICE COMMUNICATIONS SYSTEMS

COMMUNICATION REQUIREMENT	SCORE		
	PB	MRT	AI
Exceptionally high intelligibility; separate syllables understood	90%	97%	0.7
Normally acceptable intelligibility; about 98% of sentences correctly heard; single digits understood	75%	91%	0.5
Minimally acceptable intelligibility; limited standardized phrases understood; about 90% sentences correctly heard (not acceptable for operational equipment)	43%	75%	0.3

5.2 <u>Auditory warning signals</u> - Auditory warning signals, if used, shall conform to the requirements specified herein.

5.2.1 <u>Master warning signals</u> - A non-verbal audio master warning signal shall produce an output with the following frequency and interruption rates:

(a) Fundamental audio output frequency shall sweep from 700 Hz to 1,700 Hz in 0.85 second.
(b) Interruption interval 0.12 second.
(c) The cycle shall be repeated until the signal generator is de-energized.

5.2.2 <u>Bail-out signal</u> - The audio bail-out signal for use in troop carriers, cargo transport, and all other multi-crew aircraft shall be a bell. The bell shall strike at a continuous rate of 5 ± 1 beats per second and shall be audible during flight to all aircrew members and passengers.

5.2.3 <u>Wheels-up signal</u> - When a non-verbal audio wheels-up signal is used, it shall have the following tone and conform to the requirements of MIL-S-9320:

Frequency 250 ± 50 Hz, fundamental tone interrupted at 5.0 ± 1.0 Hz with a 50 ± 10 percent on-off cycle.

5.2.4 <u>Audio angle of attack/airspeed/stall warning signal</u> - When a non-verbal audio signal is used for presenting angle of attack/airspeed/stall warning information, referenced to a selected angle of attack/airspeed/stall speed, it shall be as noted in Table IV. The discrete position at which the chopped signal commences on either side of the "correct" signal will be readily adjustable.

Table IV. AUDIO ANGLE OF ATTACK/AIR SPEED/STALL WARNING SIGNAL

ANGLE OF ATTACK	AIR SPEED	TONE SIGNAL
Low	Fast	1,600 tone interrupted at a rate of 1 to 10 Hz, the rate increasing linearly with decreasing angle of attack/increasing air speed.
Safe low	Safe fast	900 Hz steady tone, plus 1,600 Hz tone interrupted at a rate of zero to 1 Hz, the rate increasing linearly with decreasing angle of attack/increasing air speed.
Correct	Correct	900 Hz steady tone.

TABLE IV (Cont'd)

ANGLE OF ATTACK	AIR SPEED	TONE SIGNAL
Safe high	Safe low	900 Hz steady tone, plus 400 Hz tone interrupted at a rate of zero to 1 Hz, the rate increasing linearly with increasing angle of attack/decreasing air speed.
High	Slow	400 Hz tone interrupted at a rate of 1 Hz to 10 Hz, the rate increasing linearly with increasing angle of attack/decreasing air speed (stall warning).

5.2.5 Verbal auditory warning signals - Verbal warning signals shall be audible signals in verbal form indicating the existence of a hazardous or imminent catastrophic condition requiring immediate action and shall only be used to complement red warning or other critical visual signals. The verbal warning signals shall be presented at levels which will insure operator reception under noise conditions in the specific aircraft. There shall be provision for overriding and resetting the signals. The signal, when activated, shall always start at the beginning of the message and shall continue to be presented until either:

(a) *The causative condition is corrected.*
(b) A warning of higher priority is presented.
(c) The signal is silenced by manual actuation of the override switch.

The structure for verbal warnings shall be:

(d) General heading - i.e., the system or service involved
(e) Specific subsystem or location
(f) Nature of emergency

Example:	ENGINE	No. 1	HOT
	(d)	(e)	(f)

PART III. PARTIAL MIL-S-9320C

3.6 Performance.

3.6.1 Frequency and interruption rate of the warning signal. The frequency and interruption rates shall be:

(a) Fundamental audio output frequency 250 ± 50 Hertz (Hz).
(b) Interruption rate 5 ± 1 Hz.

3.6.1.1 Output audio cycle. When interrupted at the specified rate, the on-off cycle of the audio output shall be 50 percent on, 50 percent off, with a 5 percent tolerance in the on-off cycle.

3.6.1.2 Harmonic content. The warning signal, when energized with 28 volts DC and loaded as specified in 3.6.2.2, shall have an output signal containing both odd and even harmonics. The voltage readings or harmonics 2 through 11 shall total 120 to 220 percent of the fundamental voltage reading. The voltage readings of the odd harmonics shall total a minimum of 75 percent of the total harmonic count, excluding the fundamental.

PART IV. PARTIAL MIL-G-38047A

3.5 Performance.

3.5.1 Frequency and interruption rate. The frequency and interruption rates shall be as follows:

(a) Fundamental audio output frequency shall sweep from 700 to 1,700 cycles per second (cps) in 0.85 second.
(b) Interruption interval--0.12 second.

The cycle shall be repeated until the generator is de-energized.

3.5.1.1 Audio output circuit. A tone of the specified frequencies shall be provided between connector terminals C and ground when the signal is energized. The decible (dB) level of this tone shall be 20 ± 2 dB. Between pin D and ground the dB level shall be 15 ± 2.0 dB.

PART V. PARTIAL MIL-S-6904B

1. Scope.

1.1 Scope - This specification covers the requirements for aircraft emergency crew warning signals for operation on 28VDC circuits aboard aircraft.

SPECIFICATIONS

Military

MIL-E-5272	Environmental Testing, Aeronautical and Associated Equipment, Genera' Specification for
MIL-S-6904/1	Signal, Emergency Warning (Bell)
MIL-S-6904/2	Signal, Emergency Warning (Horn)
MIL-S-6904/3	Signal, Emergency Warning (Horn with a Projector)

- -

3.5.6 Sound intensity - The signal shall provide a sound intensity of at least 100 decibels as indicated on a standard sound meter at a distance of 3 feet under conditions encountered in a soundproof room (see 4.6) and as specified on the applicable specification sheet (see 3.5.7).

PART VI. PARTIAL MIL-S-6904/1

Sound Intensity - The signal assembly shall provide a sound intensity of not less than 100 decibels as measured from a distance of 3 feet from the edge of the gong nearest the mounting flange, when operated at 24VDC under conditions encountered in a soundproof room.

Sound Frequency - The signal assembly shall provide sound at frequencies within ± 100 cps of those shown below with an amplitude within ± 5 decibels of that shown below, when measured at a distance of 3 feet from the edge of the gong nearest the mounting flange:

Frequency (Cycles Per Second)	Noise Level Decibels
1200	85
3000	92
5200	80
7700	92

Altitude - The signal shall operate at a pressure altitude from sea level to 50,000 feet.

PART VII. PARTIAL MIL-S-6904/2

Sound Intensity - The signal shall provide a sound intensity of at least 100 decibels as indicated on a standard sound meter at a distance of 3 feet when operated on 29 volt direct current under conditions encountered in a soundproof room.

Frequency - The signal shall have an armature stroke frequency of 650 cps ± 50 cps, with predominant sound output (output of diaphragm) of 2,700 cps ± 500 cps. Measurements shall be made with a General Radio 736A Wave Analyzer, or equivalent.

PART VIII. PARTIAL AvP970 Vol. 1

12 Warning Cautionary and Advisory Signals.

12.1 General.

12.1.1 All Crew Stations - Three distinct categories of signal (see para 12.1.3) shall be used to inform crew members of the conditions which exist relating to the operation of the aeroplane and/or its equipment. Both audio and visual means may be used, as specified by the Aeroplane Project Director for transmitting these signals.

12.1.2 Pilot's Station - The pilot shall be provided with a warning system in accordance with the requirements of Chapter 112, para 13.1.

12.1.3 Definitions - The three categories of signal are defined as follows:

(i) Warning Signal.

(a) A signal indicating the existence of an imminent catastrophic condition requiring immediate action or a limitation to the flight envelope of the aeroplane.
(b) A master warning signal may be used to indicate operation of any one of a number of warning signals.

(ii) Caution Signal.

(a) A signal indicating the existence of a hazardous or impending hazardous condition requiring attention but not necessarily immediate action.
(b) A master caution signal may be used to indicate operation of any one of a number of caution signals.

(iii) Advisory Signal.

A signal used to indicate aircraft configuration, a condition of performance, the operation of essential equipment, or to attract attention for routine purposes.

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12.3 AUDITORY SIGNALS

12.3.1 Auditory signals can be of a verbal or non-verbal form (see Leaflet 110/2), the preference being dependent on the type of warning required. The number of non-verbal signals should be minimized. when auditory signals are used as warning signals they must operate in conjunction with a visual signalling device. Auditory signals should be clearly audible under all flight conditions, including where necessary, when helmets or ear defenders are not worn (see para 12.3.2(i)). There shall be provision for overriding and recalling the signals. The signals, when activated, shall be presented until either:

(i) The causative condition is corrected; or

(ii) A signal of higher priority is present; or

(iii) The signal is silenced by the override switch (under this condition the system is still armed for all other functions).

12.3.2 Auditory signals used for warning purposes shall conform with the following requirements:

(i) <u>Standard Warning System</u> (see Chapter 112, para 13.2.2) - The warning signal shall be a lyre bird-like sound in accordance with the requirements of Specification EL1960.

(ii) <u>Auditory Angle of Attack/Airspeed Signal</u> - The auditory signal to be used for presenting angle of attack/airspeed information refernced to a selected angle of attack/airspeed shall be as follows:

ANGLE OF ATTACK	AIR SPEED	TONE SIGNAL
Low	Fast	1,600 c/s tone interrupted at a rate of 1 to 10 c/s the rate increasing linearly with decreasing angle of attack/increasing air speed.
Safe low	Safe fast	900 c/s steady tone, plus 1,600 c/s tone interrupted at a rate of zero to 1 c/s the rate increasing linearly with decreasing angle of attack/increasing air speed.
Correct	Correct	900 c/s steady tone.
Safe high	Safe low	900 c/s steady tone, plus 400 c/s tone interrupted at a rate of zero to 1 c/s, the rate increasing linearly with increasing angle of attack/decreasing air speed.
High	Slow	400 c/s tone interrupted at a rate of 1 c/s to 10 c/s, the rate increasing linearly with increasing angle of attack/decreasing air speed (stall warning).

The discrete position at which the chopped signal commences on either side of the "correct" signal shall be readily adjustable.

PART IX. PARTIAL AIR STD 10/30H

8. It is agreed that warning, cautionary and advisory signals will be defined as follows:

a. Warning Signal.

(1) A signal indicating the existence of an imminent catastrophic condition requiring immediate action or a limitation to the flight envelope of the aircraft.
(2) A Master Warning Signal may be used to indicate operation of any one of a number of warning signals.

b. Caution Signal.

(1) A signal showing the existence of a hazardous or impending hazardous condition requiring attention but not necessarily immediate action.
(2) A Master Caution Signal may be employed to indicate operation of any one of a number of caution signals.

c. Advisory Signal.

A signal used to indicate aircraft configuration, a condition of performance, the operation of essential equipment, or to attract attention for routine purposes.

- -

16. It is agreed that if audio-signals are used, they shall conform with the following specifications:

a. Master Warning Signal - A non-verbal audio master warning signal shall produce an output as shown in Figure 1 and have the signal tolerances and sweep rates specified thereon.

b. Bail-Out Signal - The audio bail-out signal for use in troop carriers, cargo transport, etc., aircraft shall be a bell. The bell shall strike at a rate of 5 beats per second ± 1 beat and shall be audible during flight throughout the compartment.

c. Wheels-Up Signal - The audio wheels-up signal shall have the following tone: 250 ± 50 Hz. Interrupted at 5 ± 1 Hz with a 50 ± 10 percent on-off cycle.

d. Audio Angle of Attack/Airspeed Signal. The audio signal for presenting angle of attack/airspeed information referenced to a selected angle of attack/airspeed is as follows:

ANGLE OF ATTACK	AIR SPEED	TONE SIGNAL
Low	Fast	1,600 tone interrupted at a rate of 1 to 10 Hz, the rate increasing linearly with decreasing angle of attack/increasing airspeed.
Safe low	Safe fast	900 Hz steady tone, plus 1,600 Hz tone interrupted at a rate of zero to 1 Hz, the rate increasing linearly with decreasing angle of attack/increasing airspeed.
Correct	Correct	900 Hz steady tone.
Safe high	Safe low	900 Hz steady tone, plus 400 Hz tone interrupted at a rate of zero to 1 Hz, the rate increasing linearly with increasing angle of attack/decreasing airspeed.
High	Slow	400 Hz tone interrupted at a rate of 1 Hz to 10 Hz, the rate increasing linearly with increasing angle of attack/decreasing airspeed.

The discrete position at which the chopped signal commences on either side of the "correct" signal will be readily adjustable.

e. Verbal Auditory Warning Signals - Verbal Warning Signals are audible signals in verbal form indicating the existence of a hazardous or imminent catastrophic condition requiring immediate action and may only be used to complement other forms of warning signals. Verbal warning signals are to be presented at the operator's ear at a significantly higher level above the ambient noise. There shall be provision for overriding and resetting the signals. The signal when activated shall be presented until either:

(1) The causative condition is corrected, or
(2) A warning of higher priority is presented, or
(3) The signal is silenced by the override switch.

It is agreed that the structure for verbal warning is as follows:

(4) General Heading - i.e., the system or service involved.
(5) Specific subsystem or location.
(6) Nature of the emergency.

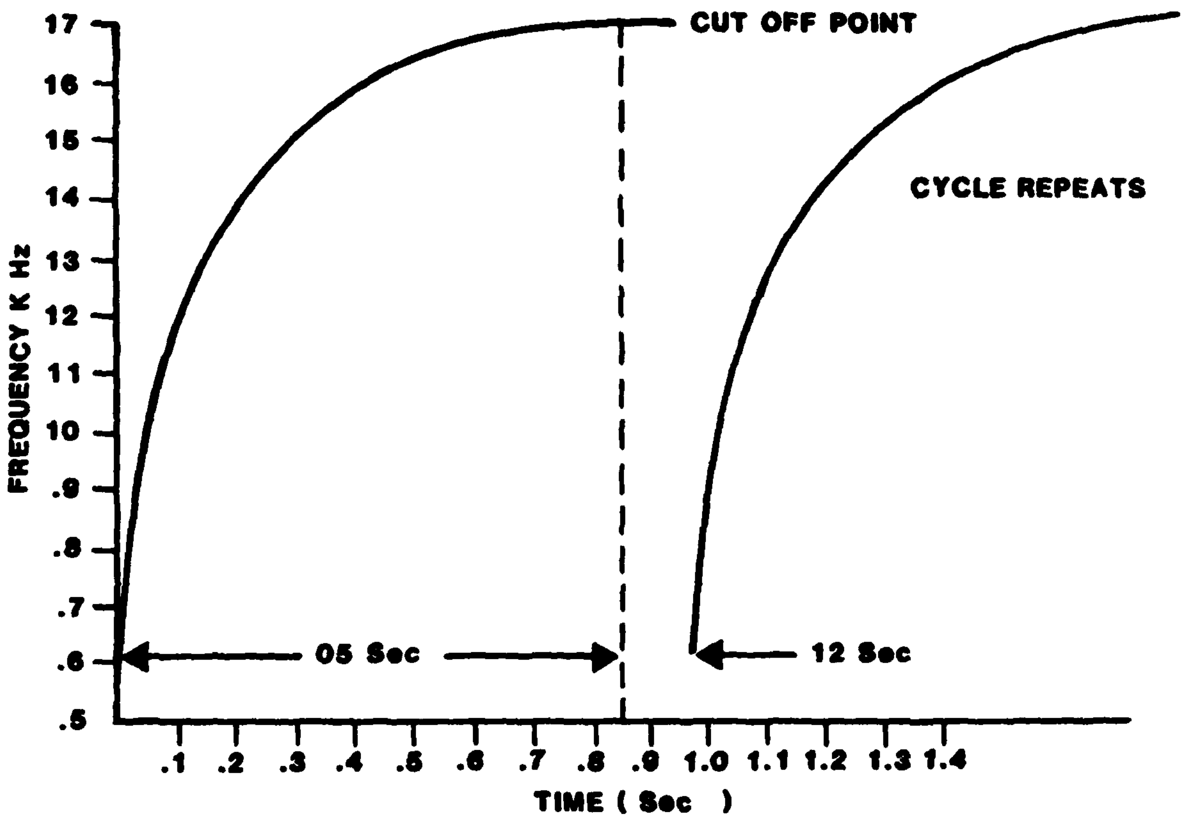

Figure 1. Master audio warning frequency characteristics.

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TYPES OF SIGNALS

3. The warning, cautionary and advisory signals may be visual, auditory or tactile. These signals are defined below:

a. Warning Signal.

(1) A signal indicating the existence of an imminent catastrophic condition requiring immediate action or a limitation to the flight envelope of the aircraft.

(2) A master warning signal may be used to indicate operation of any one of a number of warning signals.

b. Caution Signal.

(1) A signal indicating the existence of a hazardous or impending hazardous condition requiring attention but not necessarily immediate action.

(2) A master caution signal may be used to indicate operation of any one of a number of caution signals.

c. Advisory Signal. A signal used to indicate aircraft configuration, a condition of performance, the operation of essential equipment, or to attract attention for routine purposes.

FROM AMENDMENT 7, 1 MARCH 1983

Auditory Signals.

8. Auditory signals can be of a verbal or non-verbal form. However, the number of non-verbal signals should be minimized. When auditory signals are used as warning signals they will operate in conjunction with a visual signalling device. Auditory signals are to be presented at the operator's ear at a significantly higher level above the ambient noise. There shall be provision for overriding and recalling the signals. The signal, when activated, shall be presented until either:

(1) The causative condition is corrected; or
(2) A signal of higher priority is presented; or
(3) The signal is silenced by the override switch (under this condition the system is still armed for all other functions).

9. Verbal warning signals shall be as brief as possible and include the following items, if necessary:

(1) General Heading, i.e., the system or service involved.
(2) Specific subsystem or location.
(3) Nature of the emergency.

APPENDIX C
DATA COLLECTION SHEETS

AUDITORY INFORMATION SYSTEMS RESEARCH
GEORGIA TECH/USAFSAM

Aircraft: ________________

Non-speech Auditory Signals:

1. ________________________________
2. ________________________________
3. ________________________________
4. ________________________________
5. ________________________________
6. ________________________________

Speech Signals:

1. ________________________________
2. ________________________________
3. ________________________________
4. ________________________________
5. ________________________________
6. ________________________________

Aircraft Mission/Role: ________________________________

____

____

____

Comments: ________________________________

____

____

____

____

____

AUDITORY INFORMATION SYSTEMS RESEARCH
GEORGIA TECH/USAFSAM

NON-SPEECH SIGNALS

1. Signal Name: ____________________ 2. Type: ____________________
(e.g., horn, bell, chime, buzzer, siren, voice)

3. Activation Conditions:

____
____
____
____
____
____
____
____
____
____
____
____
____
____
____
____
____

4. Criticality (circle one answer)

1 - Immediate action required by crew.
2 - Immediate action required once aircraft is stable.
3 - Action required as soon as time is available.
4 - Action required later in the flight.
5 - No action required, signal for information only.

5. ***Signal Characteristics:***

		Duration	___________
Pitch	___________	**Repetition Rate**	___________
Rate	___________	**Stations**	___________
Volume	___________	**Device**	___________
AVC?	___ yes ___ no	**Frequency**	___________

6. **Operator Control (Yes/No):**

Enable Required	___________	**Volume**	___________
Cancel	___________	**Inhibit**	___________

7. **Information Provided:__ Alert, __ Alert+Condition, __ Alert+Condition Advisory +**
Only Advisory Recommended Action

8. **Accompanying Visual Display: _____ yes _____ no**

If yes, specify type and general location: ______________________

____

____

9. **Pilot's Rating of Occurrence:**

	Flight Configuration				
	Taxi	Take-off	Landing	Cruise	Others (specify)
Overall Freq. of Occurrence:					
False Alarm Rate:					

Describe frequency of occurrence: ______________________________

____

Describe false alarm rate: ____________________________________

____

10. **Does the signal override, mask, or interfere with other signals or communications? _______ yes _______ no.**

If yes, please explain: ____

____

____

11. **Are other signals confused with this signal? _______ yes _______ no.**

If yes, which signals? ____

____

12. **Other than under normal operational conditions, when is this signal heard?**

_______ Training, _______ Preflight, _______ Inflight Test, _______ Other

When?: ____

____

13. **Signal is repeated under following conditions:** ______________________

____

____

____

AUDITORY INFORMATION SYSTEMS RESEARCH
GEORGIA TECH/USAFSAM

SPEECH SIGNALS

1. **Signal Name:** ____________________

2. **Message:** ________________________
____

3. **Activation Conditions:** ________________________________
____
____
____
____
____
____
____
____
____
____
____
____
____
____
____

4. **Criticality (circle one answer):**

    1. **Immediate action required by crew.**
    2. **Immediate action required once aircraft is stable.**
    3. **Action required as soon as time is available.**
    4. **Action required later in the flight.**
    5. **No action required, signal for information only.**

5. Type of voice: ___ Female, ___ Male, ___ other (specify)__________

6. Signal characteristics:

		Duration	________
Pitch	________	Repetition rate	________
Rate	________	Stations	________
Volume	________	Device	________
AVC?	___ yes, ___ no	Frequency	________

7. Information Provided: ___ Alert, Only ___ Alert + Condition, Advisory ___ Alert + Condition Advisor Recommended Actio

8. Operator Control (Yes/No):

Enable Required	________	Volume	________
Cancel	________	Inhibit	________

9. Message is repeated under the following conditions:

____

____

10. Accompanying Visual Display? _____ yes, _____ no.

If yes, specify type and general location: ____________

____

____

11. **Does the signal override, mask, or interfere with other signals or communications? _______ yes _______ no.**

If yes, please explain:______________________

____

____

12. **Are other signals confused with this signal? _______ yes _______ no.**

If yes, which signals? ______________________

13. **Other than under normal operational conditions, when is this signal heard?**

_______ Training, _______ Preflight, _______ Inflight Test, _______ Other

When?: ____

____

14. **Pilot's Rating of Occurrence:**

Flight Configuration

	Taxi	Take-off	Landing	Cruise	Others (specify)
Overall frequency of occurance:					
False alarm rate:					

Describe frequency of occurance: ____

____

Describe false alarm rate: ____

____

LIST OF ABBREVIATIONS AND ACRONYMS

ADF	Automatic Directional Finder
AFWAL	Air Force Wright Aeronautical Laboratories
AIM	Airborne Intercept Missile
AMAD	Air Frame Mounted Accessory Driver
AMRL	Aerospace Medical Research Laboratory
AOA	Angle of Attack
APU	Auxiliary Power Unit
ASD	Aeronautical Systems Division
ATC	Air Traffic Control
CRT	Cathode Ray Tube
C/W	Caution/Warning
FPM	Feet per Minute
FTIT	Fan Turbine Inlet Temperature
GPWS	Ground Proximity Warning System
HUD	Head-Up Display
IFF	Identification Friend or Foe
ILS	Instrument Landing System
KIAS	Knots Indicated Air Speed
KTS	Knots
LPC	Linear Predictive Coding
MOA	Military Operating Area
MIL STD	Military Standard
PNF	Pilot Not Flying
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
RHAW	Radar Homing and Warning
ROM	Read-Only Memory
RWR	Radar Warning Receiver
SPO	System Project Office
SYNCALL	Synthesized Speech Approach Call-Out System
TACAN	Tactical Electronic Navigation
TEF	Trailing Edge Flap
TEWS	Tactical Electronic Warfare System
VOR	Very High Frequency Omni Range (radio aid to navigation)
WRCS	Weapons Release Computer System
WPM	Words per Minute

END

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