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13

Aircraft Alerting Systems Criteria Study

Volume II

Human Factors Guidelines for Aircraft Alerting Systems

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FINAL REPORT

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16. Abstract

Human factors literature that describes pilot response characteristics when confronted with aircraft warning, caution, and advisory signals was reviewed. The review covered visual, aural (sounds and voice), tactile, and bimodal alerts. Data obtained therefrom were categorized into (1) non-aircraft-related test results, (2) aircraft-related test results, and (3) military standards/design guidelines so as to establish the applicability of the data and to identify technical areas in which more human factors data relevant to aircraft-alerting systems may be required. Summaries of the literature for (1) factors that affect signal detection, and (2) factors that affect time from detection to response are provided. The results of the review were used to establish preliminary design guidelines for alerting systems in future commercial transport aircraft.

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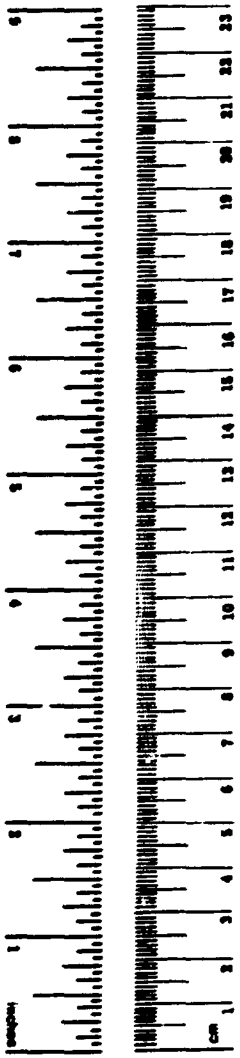
METRIC CONVERSION FACTORS

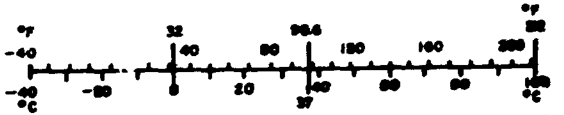
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

FOREWORD

This final technical report covers work performed under the third phase of FAA contract DOT-FA7WA-3233, "Collation and Analysis of Aircraft Alerting Systems Data." The study was initiated to establish an alerting philosophy for aircraft cockpit alerting systems. As a supplementary effort the "Human Factors Guidelines for Aircraft Alerting Systems" was compiled by G. P. Boucek, Jr.

The contract sponsor was FAA Systems Research and Development Service (FASSRDS) and performed by the Boeing Commercial Airplane Company. Technical guidance for the contract was provided by Mr. John Hendrickson, ARD-743, the contract monitor.

The full study effort covered the period January 1976 through Novemver 1976. The performing organization was Systems Technology—Crew Systems, of the Boeing Commercial Airplane Company, Seattle, Washington. W.D. Smith was program manager, J.E. Veitengruber was principal investigator, and G.P. Boucek was the signal/response analyst.

The work contained in the report is an update and extension of the work previously accomplished under the same contract number, modification 1, by Dr. A. G. Osgood.

SYNOPSIS

The objectives of the study were: (1) investigate the types of signals that can be used to transfer information in a cockpit environment, (2) determine the factors that affect the detection of these signals, (3) determine the factors that affect the time from signal detection to a correct action, and (4) formulate guidelines for maximizing the effectiveness of Aircraft Alerting Systems.

A state-of-the-art literature review was made to determine the impact of human factors considerations on signaling systems. A total of 850 references were reviewed with 180 of them being cited in the report.

Guidelines and recommendations were made for alerting systems such that (1) the signals convey enough information to maximize the probability of correct response within a time period that is commensurate with the priority of the alert, and (2) the characteristics of all signals are consistent from one situation to another and minimize interference from previous training.

Visual, aural (both verbal and nonverbal), and tactile signals are reviewed and recommendations are made for each.

CONTENTS

FIGURES

FIGURES (Cont)

TABLES

ABBREVIATIONS & SYMBOLS

ACFT	Aircraft
ADI	Attitude Director Indicator
AG	Attention Getter
ALT	Altitude
AMB	Amber
A/P	Autopilot
APU	Auxiliary Power Unit
ATM	Air Turbine Motor
A/T	Autothrottle
ASS ALT	Assigned Attitude
BLK	Black
BLU	Blue
BRT	Bright
CADC	Central Air Data Computer
CAS	Collision Avoidance System
CONT	Continued
CONFIG	Configuration
CSD	Constant Speed Drive (Electrical Generator)
CWS	Control Wheel Steering
dB	Decibels
DME	Distance Measuring Equipment
EGT	Exhaust Gas Temperature
EMER	Emergency
ENG	Engine
EVAC	Evacuation
FAR	Federal Aviation Regulation
FE	Flight Engineer
FL	Flashing
FLT INST	Flight Instrument
ft-L	Foot Lamberts
GRD PROX	Ground Proximity
GRN	Green
HORIZ	Horizontal
HSI	Horizontal Situation Indicator
Hz	Hertz
IAM	Independent Altitude Monitor
IATA	International Air Transport Association
IDG	Integrated Drive Generator (Electrical)
ILS	Instrument Landing System
INS	Inertial Navigation System
LDG	Landing
LTS	Lights
MDA	Minimum Descent Altitude
ORN	Orange
PRESS	Pressure
QUAN	Quantity

ABBREVIATIONS & SYMBOLS (Cont)

RA	Radio Altitude
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers, Inc.
SAS	Stability Augmentation System
SELCAL	Selective Call System (Company Communication)
STAB	Stabilizer
SYST	System
VOR	Very High Frequency Omnidirectional Radio Range
WHT	White
YEL	Yellow

1.0 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The continuing advancement of high-performance aircraft has brought with it not only an increasing degree of complexity in the physical operating systems but also an ever-increasing demand on the capabilities of the pilot. If this trend continues at its present pace, just the task of monitoring and interpreting the warning, caution, and advisory signals alone could soon be equal to that of piloting the aircraft. Because the variety of lights, bells, sirens, buzzers, chimes, etc., used for signaling is so large, the operator, who is already beginning to be saturated, may not be able to distinguish the fine differences among the various signals. Considerable effort has been focused on the determination and implementation of improved methods for presenting warning, cautionary, and advisory information to pilots.

Reviewing various signal inputs and the multiplicity of information conveyed by them is sufficient to reveal a fundamental problem—the problem of prioritizing information presentation. There have been many schemes for assigning importance and thus attention-getting qualities to signaling devices. However, in general these schemes have all been dependent in one way or another on the time in which a pilot must act. Therefore, the questions of signal priority and event criticality come down to the question of the amount of time a pilot has between when a problem is detected and when any further action on the pilot's part can do nothing to alter the outcome dictated by the problem. There is a time period that is the shortest interval possible permitting a successful correction of, or compensation for, the problem and avoiding damage to the aircraft and/or passengers. If the time between detection and outcome is less than this critical time period, then a warning signal serves no purpose because the situation cannot be changed. If, on the other hand, the interval is longer than the critical time period, a warning device correctly acquired and interpreted can enable the pilot to correct the problem. The time between detection of the problem by the aircraft's sensors and the critical time can be used to create a priority system. This system may be developed either subjectively or objectively. The former would use experienced personnel to define the signal categories. The amount of time used to develop categories and the placement of signals would be based on a consensus of the subjective judgment of these experts. The appeal of this method is greatly aesthetic, however, because the reliability and consistency of this type of judgment is highly suspect.

A more costly and longer procedure would be to quantitize all the time-related parameters, calculate the exact amount of time needed for each type of problem, and construct the priority scheme based on these calculations. This system would be quite cumbersome and may be too situation-specific to be useful in designating signal guidelines. A perfect crew response also is assumed once the signal is presented.

Finally, prioritization could be based on probability models of both the aircraft system and crew responses. This scheme would combine the probabilities of such things as system failure; injury potential if no corrective action taken within a specified time; crew not detecting the signal within a specified time, etc. Using this prioritization method, the combination of these probabilities must be less than some predetermined value. Since failure probabilities are relatively fixed, the final overall figure may be adjusted by changing the probabilities associated with the signal detection and the crew responses. Thus, times and detection probabilities may be associated with different signals and responses, and a priority scheme developed.

Whichever system is employed, it will be found that the priority of a signal is based primarily on a time continuum with the highest priority signals requiring the quickest actions and the lowest priority signals requiring no action by the pilot at all. Thus, signal guidelines must also be directed toward those properties of a signal that have an affect on the time required to detect and interpret it.

1.2 SCOPE OF EFFORT

The specific objectives for this study were to:

1. Investigate the type of signals that can be used to transfer information in a cockpit environment
2. Determine the factors that affect the detection of these signals
3. Determine the factors that affect the time from signal detection to a correct action
4. Formulate guidelines for maximizing the effectiveness of a signaling system

To accomplish these objectives, an extensive review of the literature relevant to aircraft caution, warning, and advisory systems was conducted. A major portion of the data pertaining to the detection of signals is found in the literature on the human senses. Neither time nor space permits a full coverage of human sensory behavior and its relationship to information displays. However, attempts have been made to present this type of coverage and the reader, if he wishes, may find these in the works of Stevens (1951) and Van Cott et al. (1972). The literature that was reviewed was limited to the relevant signal characteristics and related areas of concern. The general topics that were included are shown in table 1.

In these areas a search of the available literature produced abstracts of 850 possible references. This list was reviewed and 285 documents were obtained and their relevance determined. Finally, 180 references were cited in the final report. The data were divided into two major categories with respect to relevance. The first category consisted of data collected in a simulated or real aircraft situation. These data are directly relevant to the design of caution and warning systems. The second category of data covers directly relevant subject areas, but the material was collected in a manner that makes its direct applicability questionable.

For example, the measure most often used in the latter class of study was simple reaction time (RT). This measure is the time it takes an observer to detect a signal and make a simple reaction (press a button) to it when that is the only task he is required to do. These time measurements are not contaminated by other variables (i.e., workload, distraction movement, etc.) and are therefore the optimum (shortest possible) responding unit. Response time, on the other hand, as used in the former class of experiments, is a measure of the time to respond to a signal when that is not the only thing the observer is doing. In fact, the response is actually a secondary task that is accomplished simultaneously with the primary task (flying the aircraft). Reaction time can given an indication as to the direction of the results for response time, but it is not necessarily a direct measurement.

Appendix A presents some of the studies that fall into these two categories, along with their major findings. Also presented are the applicable military standards so that the appropriate comparison can be made. Appendix B provides the reader with the annotated bibliography that resulted from the literature search.

Table 1 Areas of Concern of the Literature Search

1. Visual Signals
   - Size
   - Brightness
   - Contrast
   - Format
   - Color
   - Location
   - Workload
   - Vigilance
   - Pilot Age
   - Legend Characteristics
2. Auditory Signals
   - Frequency
   - Intensity
   - Location
   - Ambient Noise
   - Disruptions
   - Number of Signals
   - False Signals
   - Workload
   - Vigilance
   - Ear Dominance
3. Bimodal Presentation (Auditory—Visual)
   - Interstimulus Interval
   - Format
   - Intensity
   - Workload
   - Vigilance
4. Tactile Signals
   - Detectability
   - Effectiveness
   - Number of Signals
   - Intensity
   - Frequency
   - Disruptiveness

1.3 SUMMARY

In the operation of an aircraft the variety and rate of information are at times so great as to saturate the pilot's attention. Therefore, every cockpit must employ high attention-getting signals to inform the pilot of the aircraft's status. The signals employed must possess sufficient perceptual insistence to command the involuntary attention of the pilot. They must ensure a response time that is commensurate with the priority of the signal and must convey enough information to maximize the probability of the correct response within a reasonable time period. Finally, the characteristics of all signals should be consistent from one situation to another to provide for a minimum of interference from previous training. For a detailed breakdown of the recommended guidelines see section 5.0.

1.3.1 VISUAL SIGNALS

High-priority visual signals should be bright red flashing lights as close as possible to the operator's line of sight. They should subtend at least 1° visual angle and should present the operators as much lighted surface as possible (lighted background and opaque legends). They should be easily interpretive and carry as much information as possible.

For lower priority signals where response time is longer, the color may be amber, blue, or green and the other parameters may be less rigidly adhered to.

1.3.2 AURAL SIGNALS

Verbal warning signals should be used in the highest priority situations. They should be preceded by an alerting tone, word, or phrase. The structure should be lengthy enough to provide redundant cues and the language and phraseology should be familiar to the pilot. Intensity should be at least 15 dB above the background, and the warning system should have the ability to attenuate other voice systems while the warning is activated.

Two types of aural alerting systems are discussed. Aural nonverbal warnings should be intermittent tones at least 15 dB louder than the background and containing multiple frequencies in the 250- to 4000-Hz range. If possible, they should be separated from background interference and presented to the "dominant" ear. In reference to intensity, exposure/time constraints must be followed on all levels of signal priority. When presented with a visual signal, the auditory signal should come first.

1.3.3 TACTILE SIGNALS

Tactile signals are not recommended because of their possible disruptive effect. The exception to this recommendation is where this type of signal is currently being used, e.g., stick shaker. If they are to be used, however, they should be of such amplitude as to be detected by the part of the body stimulated and should be delivered by a vibrating apparatus that will always be in contact with the body.

2.0 CHOICE OF SIGNALS TO BE USED FOR ALERTING SIGNALS

The crews of aircraft could receive system information via any of a number of sense modalities. At present, two sense modalities–vision and audition–are relied upon almost exclusively to transmit information to aircraft crews. Occasionally, visual and auditory stimuli are used together for alerts or warnings. A number of authors have suggested that the sense of touch might also be used for conveying information. Other sense modalities (e.g., smell, taste, orientation) are generally considered to be of negligible value for alert or warning signals because they are expensive to produce effectively and have limited practical use.

The choice of a specific type of signal for any alerting task should depend not only on the nature of the signal itself, but also on the function that the signal is to perform, the duties of the pilot, and other signals in the cockpit. Attention must be paid to such things as the disruptive effect of a false signal, the workload being incurred by each of the senses at the time the signal is most likely to occur, the frequency of signal activation, and the amount of ambient (background) noise, both visual and auditory, present in the cockpit and conflicting with the signal presentation. Finally, since any scheme for the selection of alerting signals must be based on the criticality of the information to be presented, the single most important characteristic of any signal is the time required to correctly detect, interpret, and respond to it. The total information or signaling system should be designed, selecting signals that help the pilot quickly recognize the physical phenomena occurring within the complex flight situation, and perform the required response in the most expedient fashion. The effectiveness of the resulting system can then be defined in terms of the time from signal onset to the completion of the correct response. It must also be remembered that the "correct" response to some low-priority signals will simply be recognition and notation of the problem and no further pilot action.

3.0 FACTORS THAT AFFECT SIGNAL DETECTION

There are basically two types of factors that have an effect on the detection of a given signal:

- Physical characteristics of the signal to be detected
- Properties of the environment in which the signal is presented

In practice, it is generally the interaction between these two types of factors that determines the attention-getting quality of a signal. These factors will be covered in detail in the following sections, with special emphasis on the speed and accuracy of the responses and the relevance of the different characteristics to a signal prioritization scheme.

3.1 STIMULUS CHARACTERISTICS THAT AFFECT THE DETECTION OF ALERTING SIGNALS

The effectiveness of any stimulus used as an alerting signal is dependent upon that stimulus being detected by the person who is to be alerted. Therefore, a review was made of the properties of visual, auditory, and tactile stimuli that affect their detection by humans. It should be noted that the time for detection of a stimulus is inferred from empirical measures of the time required for an observer to react to the stimulus.

Van Cott and Kincade (1972) point out that response time to weak or unexpected signals may be much longer than times recorded in situations where the reaction to the stimulus is the only task being performed. When an operator is attending to another task, his response to a warning signal not directly associated with that task is extremely variable and frequently long. Therefore, the data from simple reaction time studies must be treated with extreme caution because of the wide variety of factors that may affect response time in a "real" situation.

3.1.1 FACTORS THAT AFFECT DETECTION OF VISUAL SIGNALS

The primary signal characteristics that affect the detection of a visual signal are:

- Location of the signal
- Size of the signal
- Brightness of the signal
- Steady state or intermittent nature of the signal
- Color of the signal

3.1.1.1 Affect of Location on Detection of Visual Signals

- VISUAL SIGNALS ARE MAXIMALLY DETECTABLE WHEN THEY ARE LOCATED DIRECTLY IN THE NORMAL LINE OF SIGHT.

- **HIGHEST PRIORITY SIGNALS SHOULD BE LOCATED NO MORE THAN ±15° FROM THE NORMAL LINE OF SIGHT.**

Standard design references and military standards state that primary visual signals should be located inside a circle with a radius of 15° from the user's line of sight (fig. 1) and secondary signals 30° (Van Cott and Kincade, 1972; McCormick, 1970; and MIL-STD-411D).

Although some confusion exists as to the function of signal location on its detectability, it is fairly obvious that a visual signal presented at the place where the observer is looking will be more effective than one that appears out of the visual field. However, the definitive of "where the observer is looking" seems to be in doubt.

Rich, Crook, Sulzer, and Hill (1971) presented stationary red targets that subtended 4 minutes (0.032 inch at a distance of 28 inches) of visual angle to pilots in a Cessna cockpit flight simulator during a simulated flight. When the targets were presented directly in the pilot's line of sight, 83% of the targets were detected. As the visual angle between the pilot's line of sight and the target increased, the probability of detection decreased. When the targets were 30° and 40° from the pilot's line of sight, only about 35% of the targets were detected.

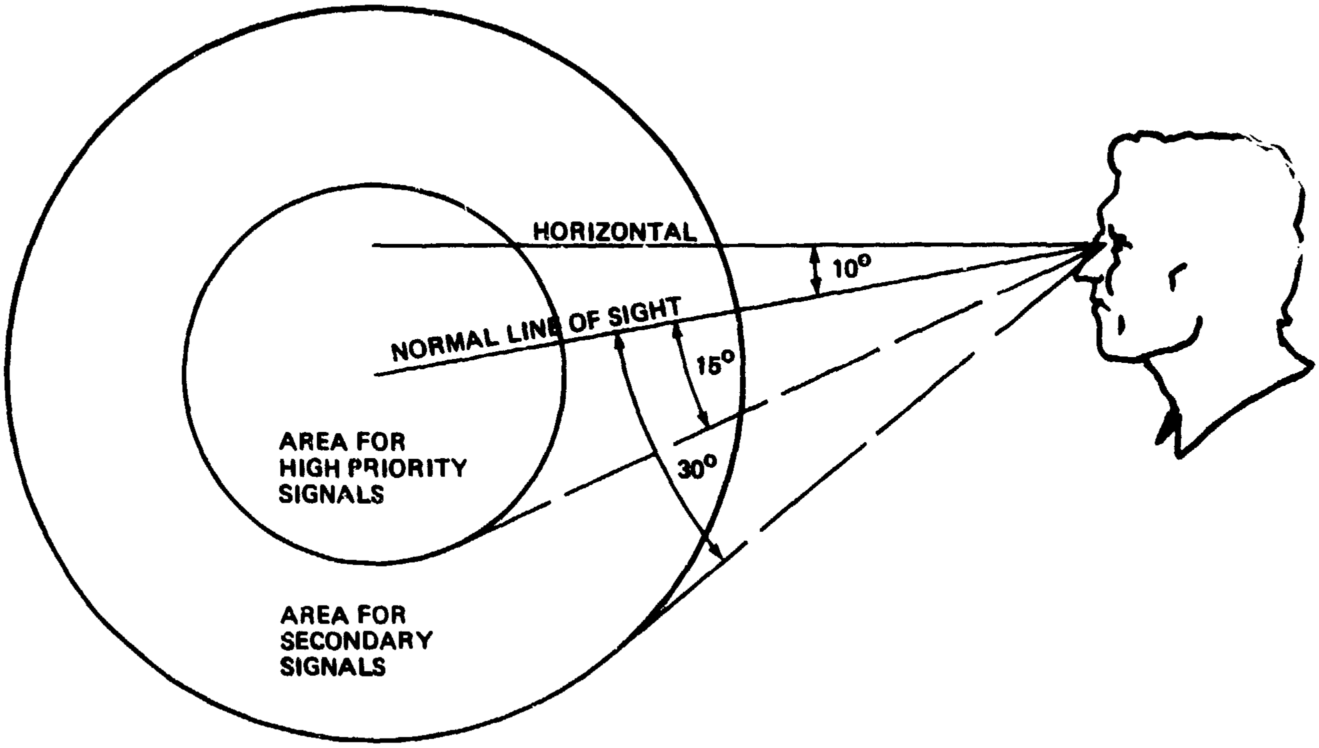


Figure 1 Preferred Placement of Visual Signals

Haines (1975) presented stationary signals to observers positioned in a darkened room such that the signals could appear at 10° intervals out to 90°. A simple reaction time task was performed in which the observer depressed a button when the signal was detected. To make the reaction times useful, the data were plotted as zones of equal reaction time (iso-RT zones). Figures 2 through 6 illustrate the iso-RT zone for white, blue, yellow, green and red signals, respectively. The heavy solid line surrounding the plots indicates the outer limits of the binocular field of view.

These times were obtained in an extremely controlled environment where the observer had no distractions and his only task was to detect the signal. The reader must expect that responses to signal lights "real time" in an aircraft cockpit will be longer. The reaction time data, therefore, should be variability without the warning tone, the approximate doubling of the median response time, and at the 96.5° location, over 25% of the signals were missed.

In most practical situations, a pilot is not waiting for a signal. Normally he is attending to other tasks and the signal must intrude on his attention. In this context, signal location may have a major effect on the detection time. Sharp (1967 and 1968) presented stationary light signals to observers while they were performing a moderately difficult tracking task. Two sets of data from two different studies are shown in figure 7. The data covering the angles from 0° to 75° represent the response time to a combined visual and auditory signal, while those from 57.5° to 96.5° represent the response time to a visual signal alone. The most important features of these data are: the increase in variability without the warning tone, the approximate doubling of the media response time, and at the 96.5° location, over 25% of the signals were missed.

More often, it is the "no response" to a signal that is more important than a time delay. The no-response for the Haines experiment (1975) averaged 1% to 5% of the signal presentation, regardless of their color, as long as they appeared within 30° of the line of sight. Beyond 30°, the no-response for red signals increased rapidly, hitting 100% at the periphery of the field.

The data from these and other experiments indicate that the military standard requirements and design guidelines are reasonable. THEREFORE, HIGHEST PRIORITY SIGNALS SHOULD BE LOCATED AS CLOSE TO THE PILOT'S LINE OF SIGHT AS POSSIBLE, BUT NO GREATER THAN 15° AWAY. OTHER SIGNALS MAY DEVIATE FROM THE LINE OF SIGHT TO THE EXTENT THAT THEIR SPECIFIC REACTION TIME AND CRITICALITY WILL ALLOW. IF THE PILOT'S DIRECTION OF GAZE IS LIKELY TO BE IN A DIFFERENT DIRECTION FOR EXTENDED PERIODS OF TIME, HIGH PRIORITY SIGNALS SHOULD BE LOCATED WHERE HE IS LIKELY TO BE LOOKING.

3.1.1.2 Affect of Size on Detection of Visual Signals

- HIGH-PRIORITY VISUAL SIGNALS SHOULD SUBTEND AT LEAST 1° VISUAL ANGLE.
- LOWER PRIORITY VISUAL SIGNALS SHOULD SUBTEND AT LEAST 0.5° VISUAL ANGLE.

The detectability of a stimulus is positively related to the size of the stimulus for visual stimuli that subtend a visual angle of 1° or less. However, no reliable effect of size has been demonstrated for larger visual stimuli.

Blackwell (1946) attempted to determine the smallest signal that could be detected under different

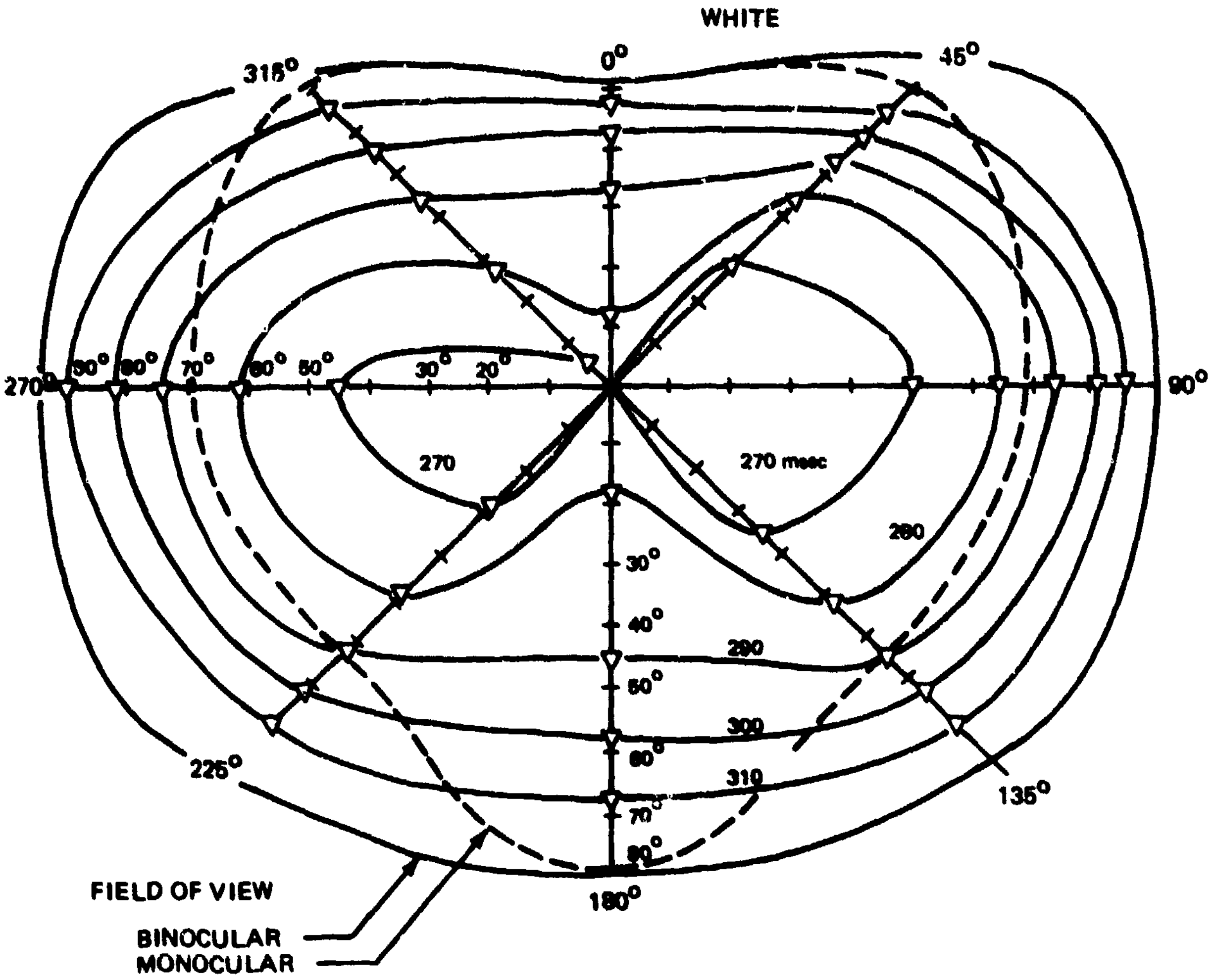


Figure 2 Retinal ISO RT Zones for White (Haines 1975)

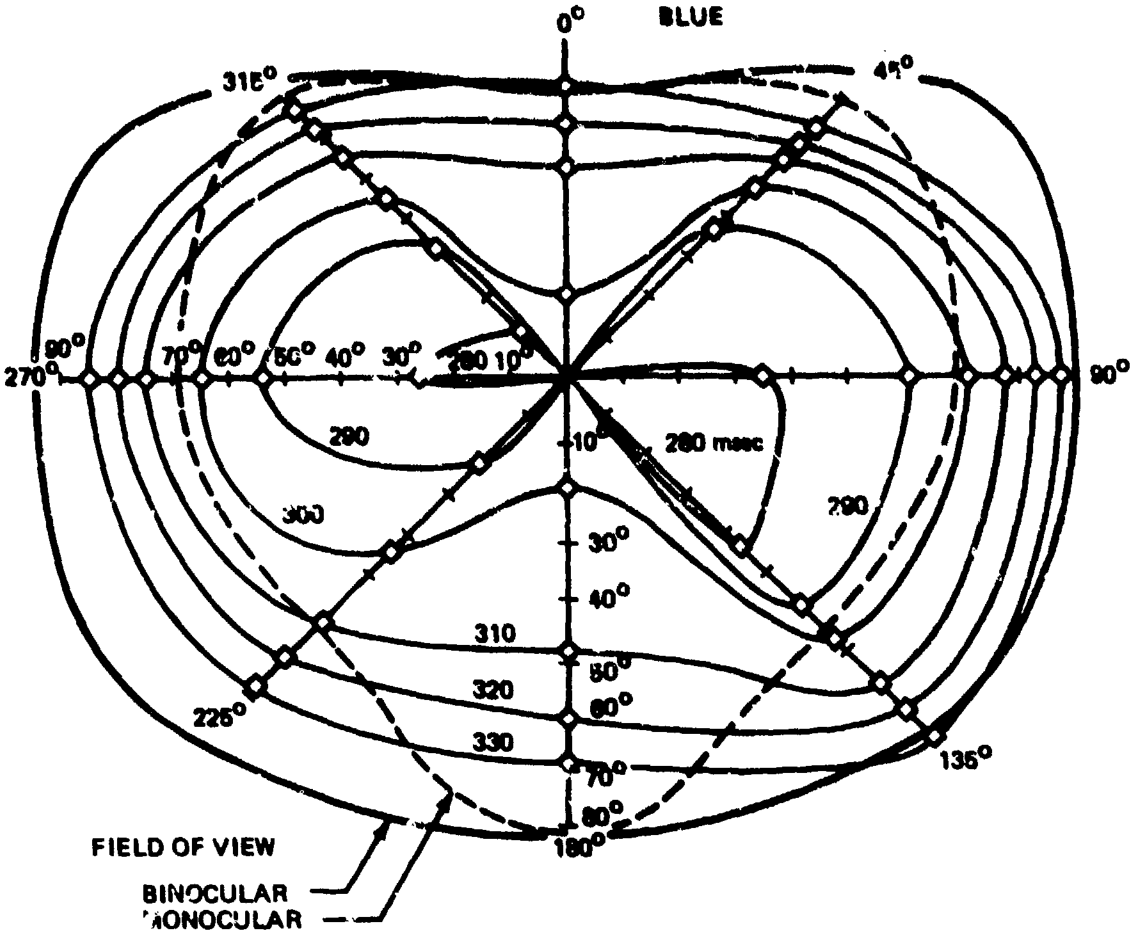


Figure 3 Retinal ISO RT Zones for Blue (Haines 1975)

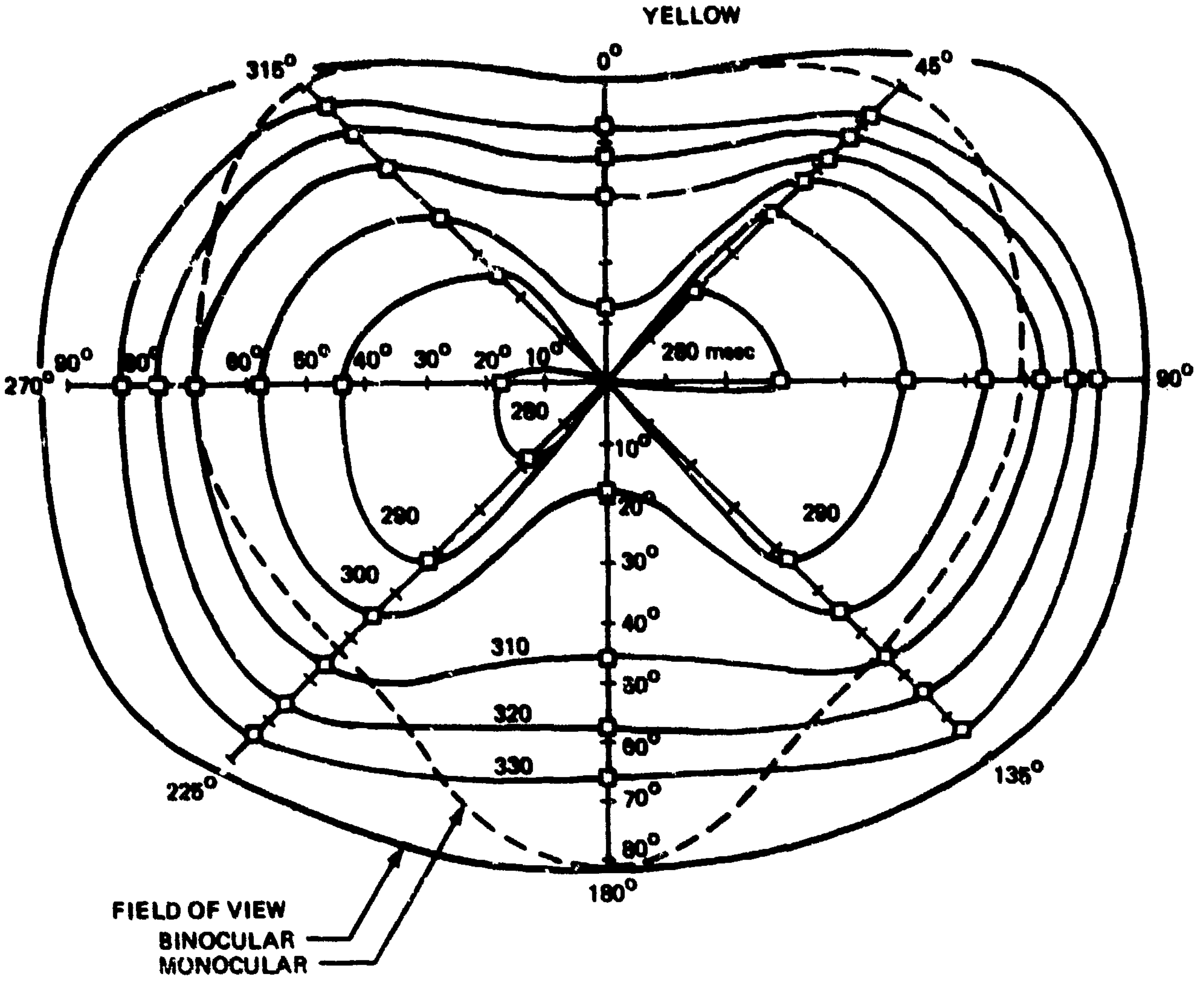


Figure 4 Retinal ISO RT Zones for Yellow (Haines 1975)

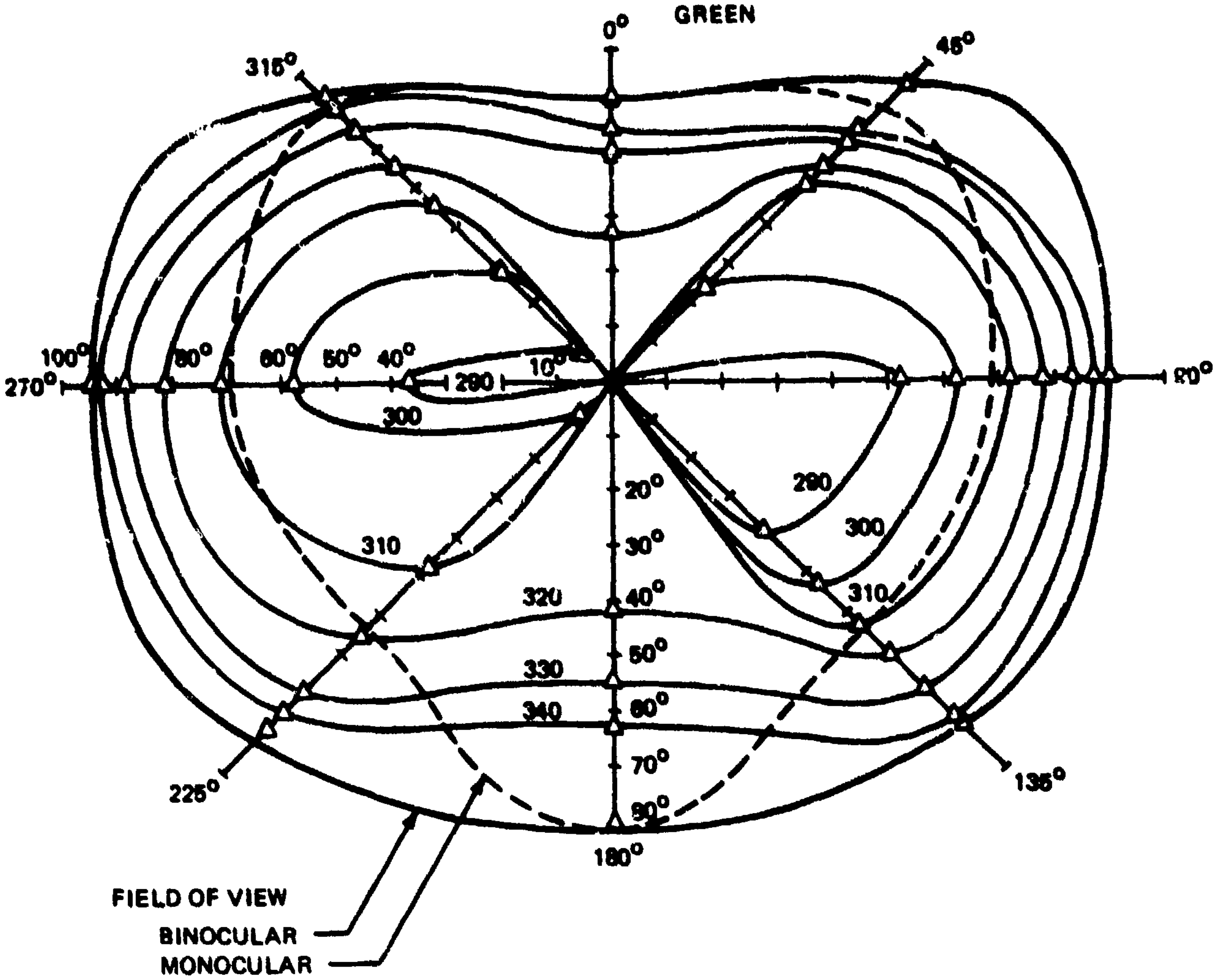


Figure 5 Retinal ISO RT Zones for Green (Haines 1975)

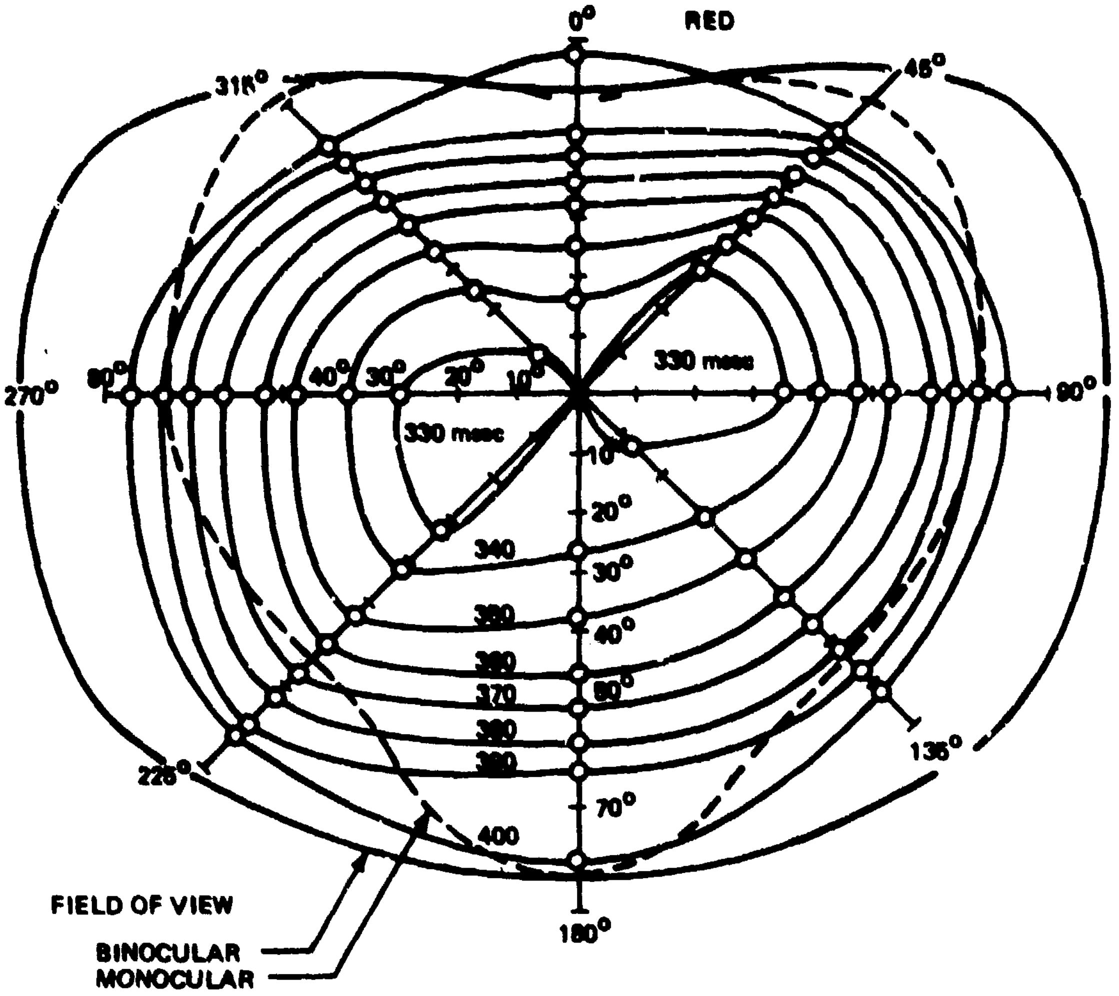


Figure 6 Retinal ISO RT Zones for Red (Haines 1975)

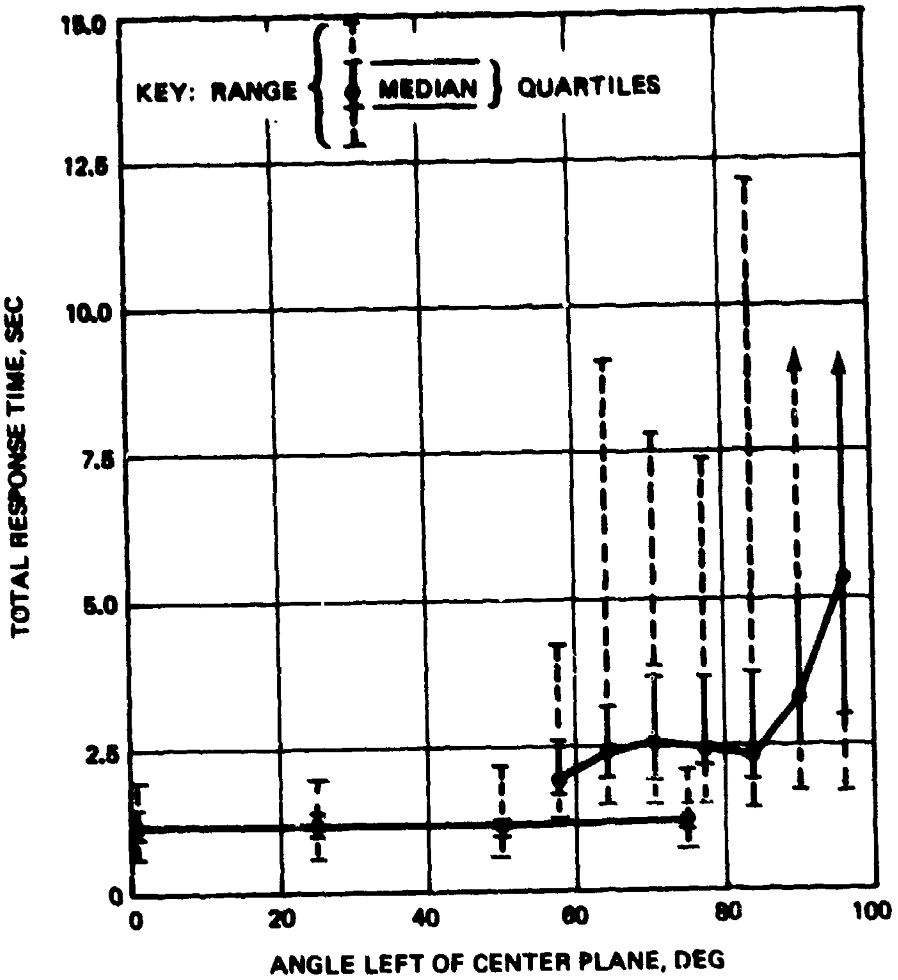


Figure 7 Total Response Time to Warning Lights While Tracking (Sharp, 1967, and 1968)

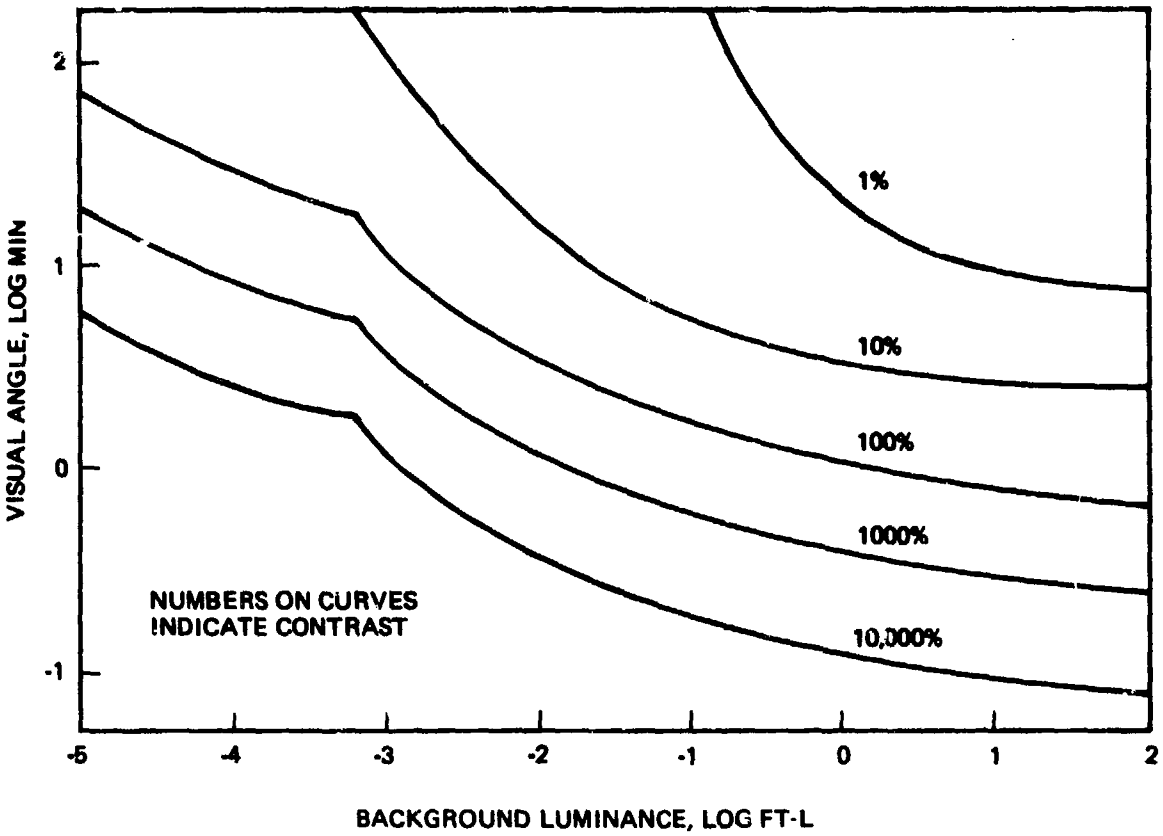


Figure 8 Minimum Perceptibility, or Spot Detection, for Circular Targets as a Function of Contrast and Background Luminance (Blackwell, 1946)

contrasts and background luminance. His findings are presented in figure 8. The formula used for contrast was the absolute value of the signal brightness minus the background brightness divided by the background brightness times 100, i.e.,

$$\text{Contrast} = \frac{B_S - B_B}{B_B} \times 100$$

The thresholds used in the figure are for 99% probability of detection.

Merriman (1969) investigated the effects of size on the attention-intrusion ability of border-lit red warning lights. His stimuli consisted of red transilluminated borders around an 0.25° high by 1.4° wide opaque black strip. Six different widths of red borders were used as warning lights (see table 1). The subjects had to detect and respond to the red warning lights while monitoring another set of lights. Even though the data from this study can be presented in a number of ways, the most appropriate measure to use is the visual angle of the border because this eliminates viewing distance from consideration. When talking about the signal size, the two extremes (table 2) are the actual visual angle subtended by the border and the total square degrees of visual angle of the entire lighted area (a square that has sides 1 degree of visual angle in length has an area of 1 square degree of visual angle). The former measurement should give the smallest signal size possible for detection and the latter the largest. Practically, the true figure should lie somewhere between.

Table 2 Border Measurements for the Meriman Study 1969

Border Width (inches)	**0.031**	**0.063**	**0.125**	**0.188**	**0.250**	**0.313**
Border Visual Angle (deg)	**0.06**	**0.13**	**0.26**	**0.39**	**0.51**	**0.64**
Lighted Area (deg^2)	**0.23**	**0.51**	**1.15**	**1.92**	**3.88**	**2.74**

Deviation for the six warning lights is shown in figure 9. The areas given for the warning lights are the total square degrees of visual angle. As can be seen, the mean response times and the standard deviation decreased as the area of the red warning light was increased from 0.28 to 2.74 deg^2. An additional increase in the size of the warning light from 2.74 to 3.88 deg^2 had no observable effect on detection time. The increases in mean response times and standard deviations for decreasingly small signal lights was largely ascribed to a tendency for the smaller signal lights to occasionally go undetected for extended periods of time.

Sheehan (1972) measured the response times to alphanumeric legends presented on a simulator of an A-7E head-up display. Subjects had to detect and respond to one of three different visual warnings (FIRE, SAM HI, or HYD PRESS) while performing a two-dimensional visual tracking task. The visual warnings were projected on the head-up display in one of three different sizes of alphanumeric characters. The subjects had to push buttons to indicate which of the three messages had been presented.

The character heights in degrees of visual angle and the respective reaction times were as follows: 0.5^o, 1.97 second; 1^o, 1.00 second; and 2^o, 0.98 second. As shown in figure 10, increasing the height of the characters from 0.5^o to 1^o reduced the mean response time by about one-half. However, an additional increase in height from 1^o to 2^o did not have a detectable effect on the response time. It should be noted that the response times recorded by Sheehan included the time for detection of a message as well as the time to decide which message had been presented and to make the correct response.

In summary, not much is gained when a visual signal is increased in size over 1^o visual angle and there is some evidence that 0.5^o is an adequate minimum. THEREFORE, FOR DETECTION, HIGH-PRIORITY SIGNALS AND ALPHANUMERIC LEGENDS SHOULD BE NO SMALLER THAN 1^o VISUAL ANGLE; LESSER SIGNALS SHOULD BE NO SMALLER THAN 0.5^o.

3.1.1.3 Affect of Brightness on Detection of Visual Signals

- HIGHEST PRIORITY SIGNALS SHOULD BE AT LEAST TWICE AS BRIGHT AS OTHER DISPLAYS.
- LOWER PRIORITY SIGNALS SHOULD BE AT LEAST 10% BRIGHTER THAN OTHER DISPLAYS.
- MILITARY STANDARDS REQUIRE A MINIMUM OF 150 ft-L FOR HIGH-PRIORITY SIGNALS AND 15 ft-L FOR LOW.

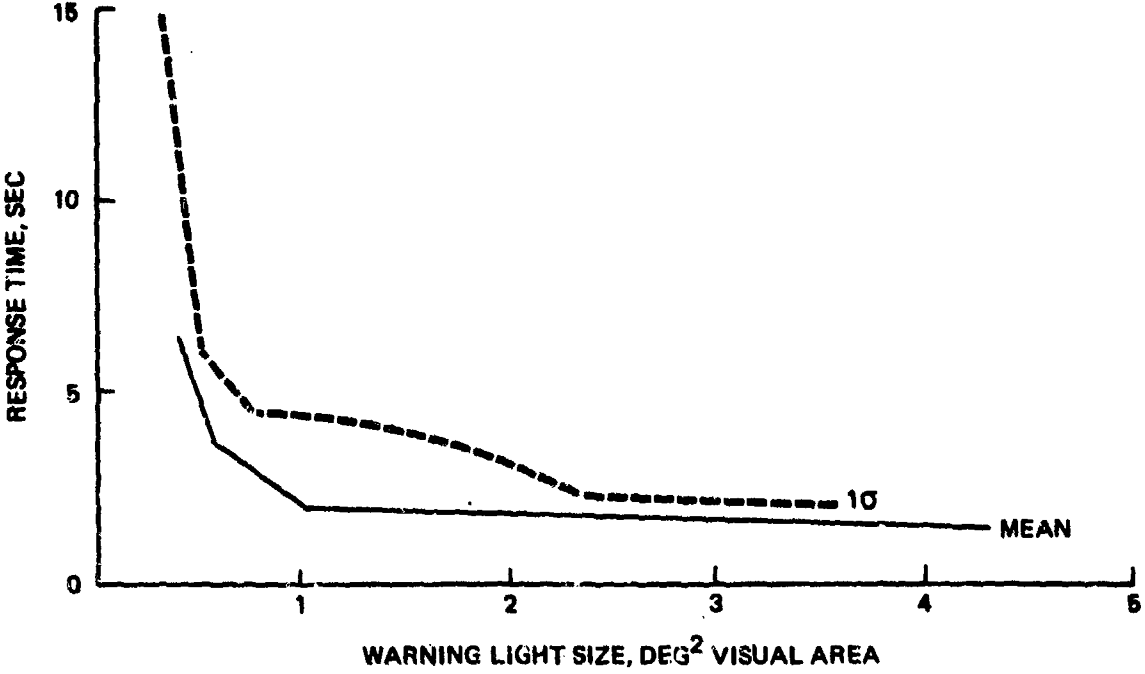


Figure 9   Effect of Warning Light Size on Reaction Time

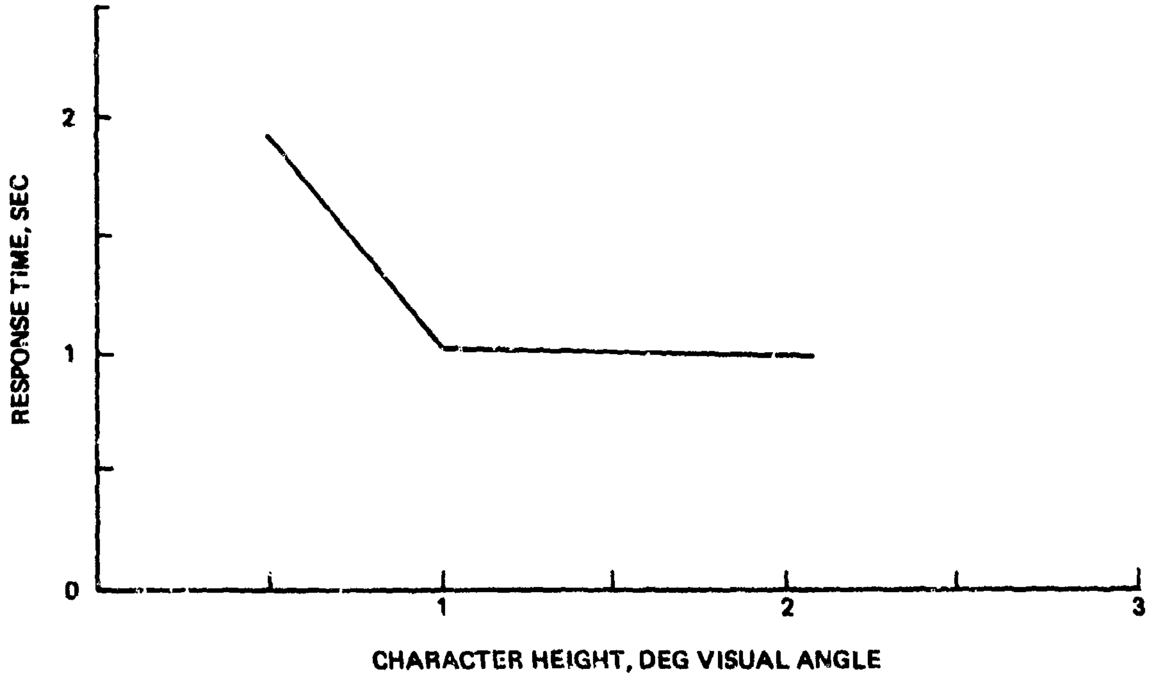


Figure 10   Effect of Character Height on Reaction Time

The affect of signal brightness on detection is directly related to the amount of ambient lighting and the amount of light reflected by the display panel. The design recommendations and Military Standards give various approaches to the problem.

Van Cott and Kincade (1972) recommend that visual signals should be bright enought to stand out clearly against the panel on which they appear under all expected lighting conditions, but they should not be so bright as to blind the operator. In work stations that are darkened at night, provision should be made for dimming the warning lights when other lights are dimmed.

Similarly, Meister and Sullivan (1969, p. 90), state that the intensity of the high-priority signal should be at least twice as bright as the immediate background. The background should be dark in contrast to the display and should be in a dull finish.

Even though the criticality of the signal must dictate the intensity of any signal, the range of intensities must be dictated by the detection threshold on one end and disruption of normal activities on the other. White and Schneyer (1960) recommend a minimum of 100 ft-L for high-priority and master caution signals and 5 to 10 ft-L for all other signal lights. MIL-STD-411D operationally defines this range for practical application with a range of signal priorities. THE BRIGHTNESS OF ANY REAR-LIGHTED SIGNAL SHALL BE AT LEAST 10% GREATER THAN THE BRIGHTNESS OF THE AREA AROUND THE SIGNAL. HIGH-PRIORITY SIGNALS REQUIRE A RECOMMENDED MINIMUM OF 150 ft-L FOR HIGH AMBIENT SITUATIONS AND 15 ±3 ft-L IN LOW AMBIENT LIGHT. THE RECOMMENDED MINIMUM BRIGHTNESS FOR SECONDARY SIGNALS ARE 15 ±3 ft-L. Using any recommendation, care must be taken in choosing the signal values. Even though it would take a signal of 10^5 ft-L to produce actual discomfort, a direct look at a signal of as little as 4 ft-L will cause a loss in dark adaptation for a full minute (Stevens, 1951). In general, early studies (Davis, 1947; Luckiesk, 1944; Steinman, 1944; and Steinman and Venias, 1944) agree that as signal intensity increases, simple reaction time will decrease. There is little doubt that the relationship is a nonlinear one, and has been described more or less successfully with exponential, hyperbolic, and parabolic functions.

Raab and Fehrer (1962) studied the affect of flash luminance on simple reaction time using circular signals that subtended 1° 10 minutes of visual angle and was viewed binocularly in a darkened room. Figure 11 shows a reduction in reaction time to a 2-msec flash out to 3000 ft-L. The larger reductions of time occur up to 30 ft-L, after which the reductions may be attributed to startle responses. Kohfeld (1971) found that when using a white signal with a 23° visual angle, the simple reaction time of the observers decreased rapidly between 0.0001 and 0.1 ft-L and not as rapidly between 0.1 and 1000 ft-L (fig. 12).

Pollack (1968) tested five luminance levels (400, 20, 1, 0.5 and 0.0025 mL) for six different colors to determine whether signal intensity had an effect on reaction time. Her results concur with the previous studies. Therefore, the findings of these studies support the standards that have been set.

No data were discovered that provide aircraft-related quantitative data on the optimum ratio of signal brightness relative to the background. Nor are there any data collected in an applied cockpit situation that indicate how dim a signal can be before detection is impaired or how bright lights can be and still not blind the pilot. However, it is recommended that the highest priority signals be twice as bright as other displays and that other signals be at least 10% brighter.

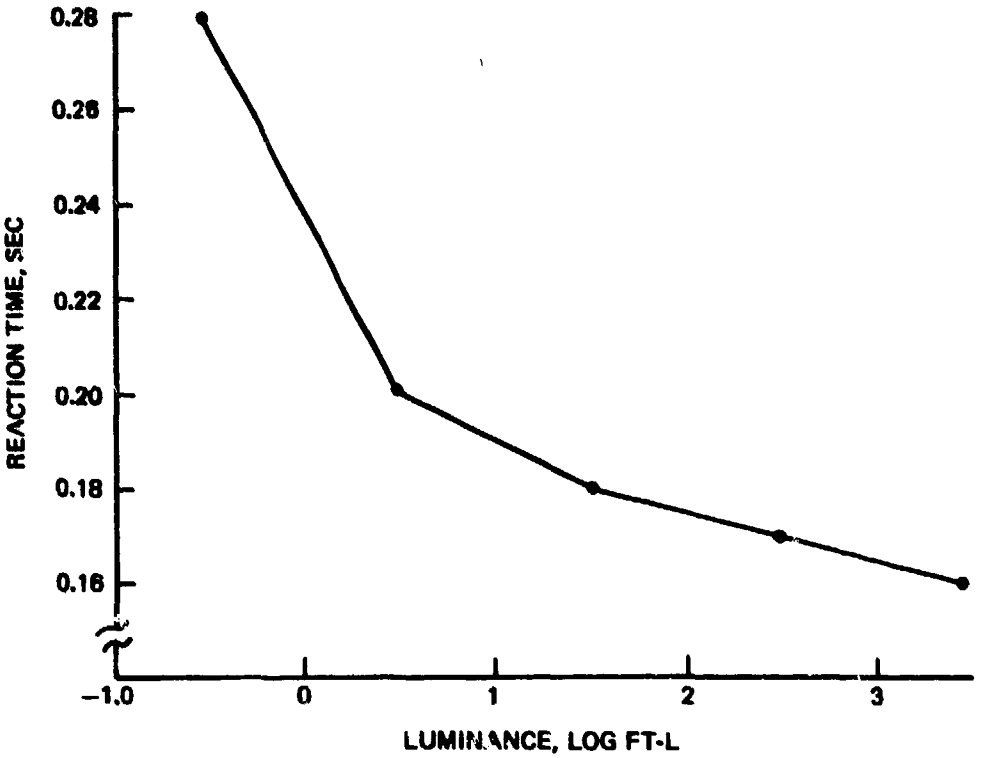


Figure 11 Simple Reaction Time as a Function of Signal Luminance in Ft-L (Raab and Fehrer 1962)

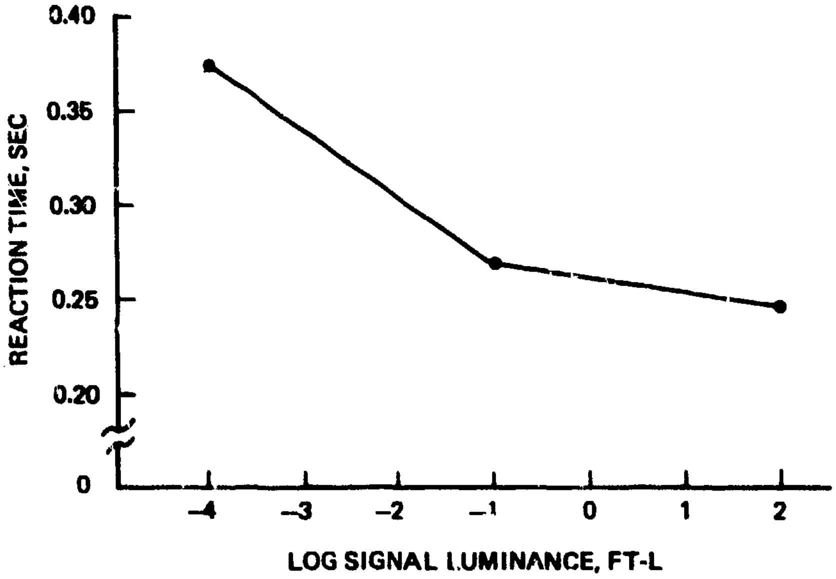


Figure 12 Simple Reaction Time as a Function of Signal Luminance (Kohfeld 1971)

3.1.1.4 Affect of Whether Visual Signals Are Steady State or Intermittent on Detection

- FLASHING LIGHTS ARE DETECTED QUICKEST WHEN ALL OTHER SIGNALS ARE STEADY STATE.

A visual stimulus can be either steady state (constant brightness) or flashing (alternately on and off). Numerous experiments have been conducted on the detectability of steady and flashing lights. However, the obtained results have been highly dependent on the procedures used by the researchers. For example, Gerathewohl (1953) reported that the mean reaction times to flashing lights were shorter than to steady lights of the same brightness. Gerathewohl always had one distracting background light on when the target stimuli were presented. The results of this study are presented in figure 13. As can be seen from the results, the flashing signals remain more effective than the steady signals until the signal intensity less the background intensity is approximately 10 times as great as the background intensity. (Contrast = 1000 using formula in sec. 3.1.1.2.)

Crawford (1962 and 1963) found that the effectiveness of steady or flashing signal lights was affected by the background conditions. Crawford's 1962 subjects were required to detect and indicate the location of signal lights. As shown in figure 14, when the background was blank, either a flashing or a steady signal light was detected in approximately 0.8 second. When the background was all steady lights, flashing signal lights were detected faster than steady signal lights. The mean detection times for signal lights were roughly proportional to the inverse of the log of the number of steady background lights. When 21 steady background lights were present, the mean reaction times were 2.0 seconds for steady signal lights and 1.3 seconds for flashing signal lights. In contrast, the mean reaction times with 21 flashing background lights were 2.1 seconds for steady signal lights and 2.6 seconds for flashing signal lights. IT SHOULD BE NOTED THAT MEAN DETECTION TIMES FOR EITHER STEADY OR FLASHING SIGNAL LIGHTS WERE LONGER IN THE PRESENCE OF FLASHING BACKGROUND LIGHTS THAN STEADY BACKGROUND LIGHTS.

In his 1963 experiments, Crawford had subjects detect either steady or flashing signal lights against a background of 10 distractor lights. The number of background lights that were flashing varied from 1 to 10. The results of the 1963 experiment were similar to the results for the 1962 experiment.

To take the development problem a step further, it would be useful for the designer to have a method by which he can determine which type of flashing signal is optimum for a situation. Edwards (1971) states that if conspicuity of a flashing signal is defined to be the effectiveness of the signal for the purpose of information transfer, it would seem that by making a choice between two flashing signals (or signals that differ on any characteristic), a reasonable approximation to a conspicuity measure could be obtained. To this end he used paired comparison techniques in which an observer had to select the most attention-getting signal from a pair. The most consistent comparisons were recorded when the observers were instructed to look midway between the two signals. By using probability theory, Edwards was able to construct graphically contours of equal attention-attracting power. This technique, although it still has some difficulties with experimental controls, could be modified and incorporated into a more realistic situation to give reliable information on the conspicuity of visual signals.

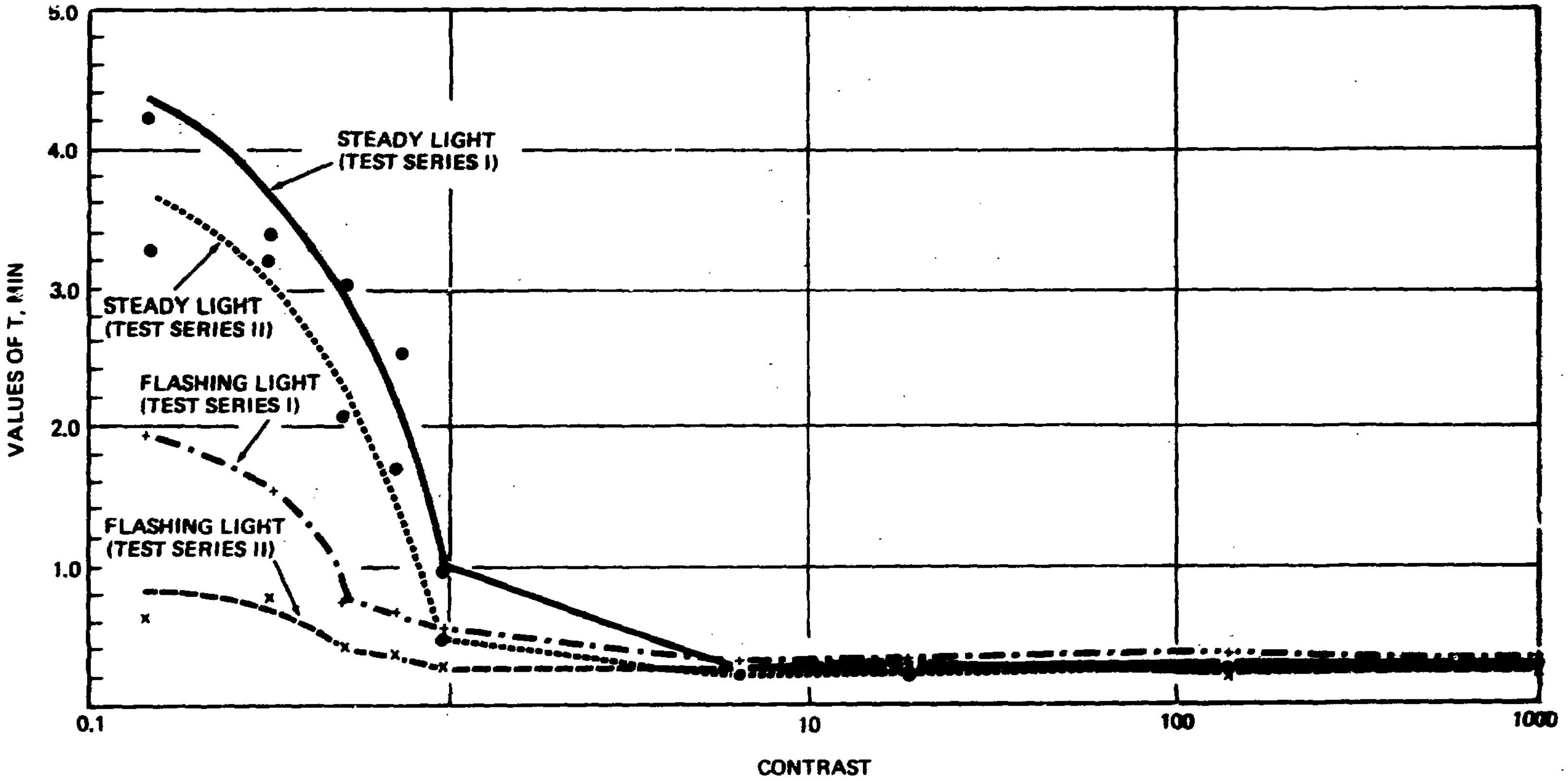


Figure 13 Relationship Between Contrast and Total Response Time (T) (Gerathewhol 1953)

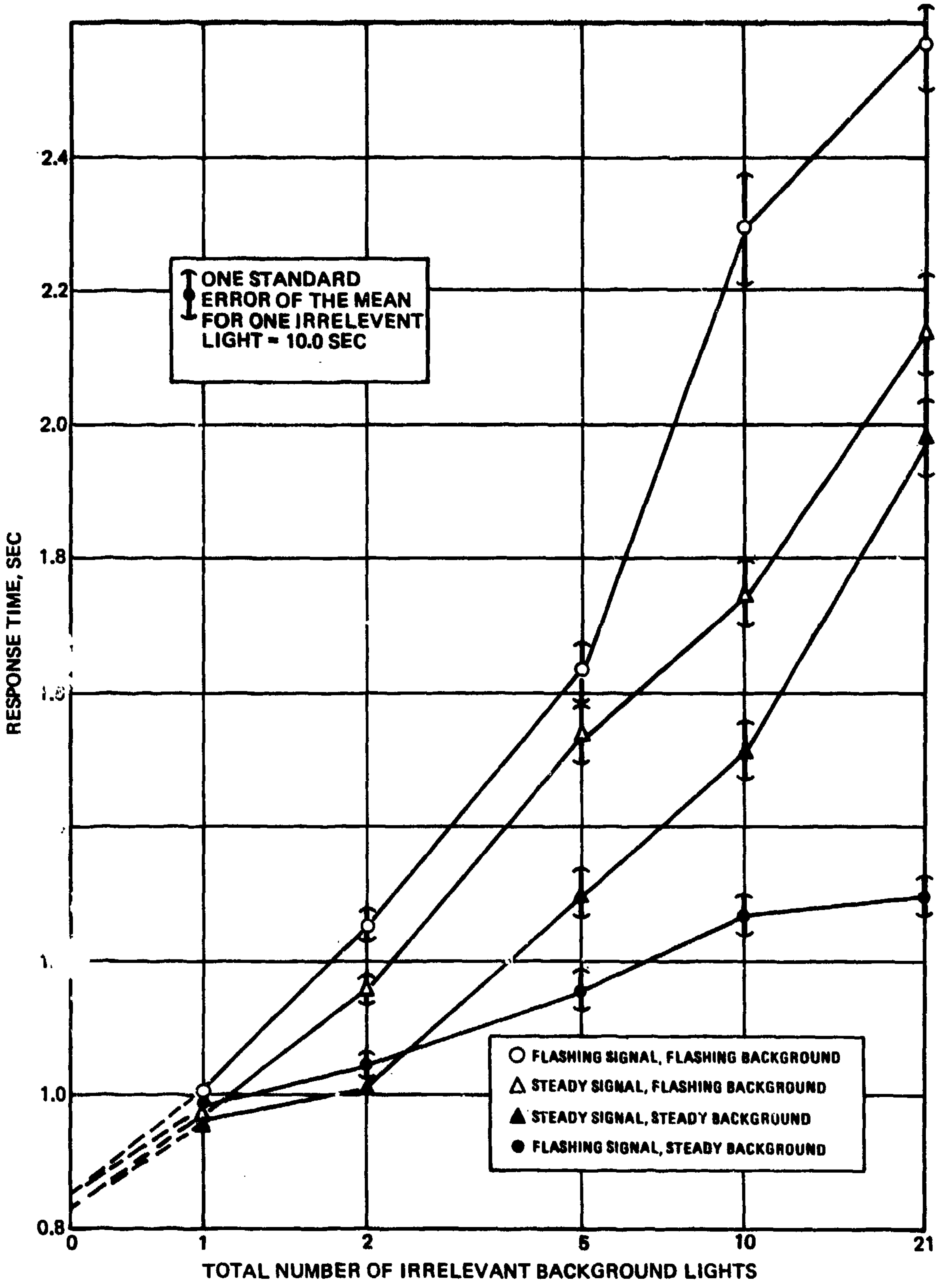


Figure 14 Effects of Irrelevent Background Lights on Response Time (Crawford 1962)

In summary, THE RELATIVE DETECTABILITY OF FLASHING AND STEADY SIGNAL LIGHTS IS DEPENDENT UPON WHETHER BACKGROUND LIGHTS ARE FLASHING OR STEADY. HOWEVER, THE FASTEST MEAN DETECTION TIMES ARE OBTAINED FOR FLASHING SIGNAL LIGHTS AGAINST A STEADY BACKGROUND. AN IDEAL VISUAL WARNING SYSTEM WOULD HAVE THE WARNING LIGHT FLASH AND HAVE ALL BACKGROUND LIGHTS EITHER BECOME STEADY STATE OR GO OFF UNTIL THE WARNING LIGHT IS DETECTED.

3.1.1.5 Affect of Color on Detection of Visual Signals

- COLOR HAS LITTLE EFFECT ON RESPONSE TIME FOR SIGNALS OF MODERATE TO HIGH INTENSITY WHEN PRESENTED ON DARK BACKGROUNDS.

- STANDARD COLOR CONVENTIONS SHOULD BE FOLLOWED:
  RED–HIGHEST PRIORITY
  AMBER–CAUTION
  GREEN OR BLUE–NORMAL OR SAFE.

Numerous studies have been conducted to determine the effect of color on visual detection performance (Weingarten, 1972; Hill, 1947; Pollack, 1968; Reynolds, White, and Hilgendorf, 1972; Haines, 1975). In general, these studies have shown color to have little effect, if any, on reaction time to visual signals if the intensities of the signals are above 0.002 ft-L (Pollack, 1968). When differences were found, the effect attributable to color is confusing. Some studies (Pollack, 1968, Haines, 1974 and 1975) showed red signals produced the slowest reaction time while others (Coates, 1972; Weingarten, 1972) showed it to be the fastest. Weingarten (1972) measured the relative detection times of red and green signal lights against achromatic backgrounds. He found that when the background was the same luminance as the signal light, the red lights were detected 20 to 25 msec faster than the green lights. However, when the signal lights differed in luminance from the background, no statistically significant differences between the detection times of the red and green lights were found. The importance of this conflict to the present study is suspected because the differences that are being discussed are in the order of 0.02 second. Therefore it can be concluded that response times to colored signals of moderate to high intensity are equal across colors for dark (essentially noncolored) backgrounds.

Reynolds et al. (1972) measured the speed of detection of red, green, yellow, and white lights against copper, tan, blue, and green backgrounds. The results (fig. 15) indicate that the overall ordering of stimulus colors as measured by the speed of responding was from fastest to slowest: red, 1.8 seconds; green, 2.0 seconds; yellow, 2.3 seconds; and white, 2.7 seconds.

Finally, Hill (1947) studied the interaction of the background luminance and color on detection thresholds. He found that the thresholds for red, white, yellow, and green signals were nearly equal over a range of background luminance from 10^{-6} to 10^{4} ft-L.

As it has been previously shown, Haines (1975) studied the reaction time for colored signals in the whole visual field (figs. 2 through 6). However, as has been pointed out, it is the no-response or missed signals that may be more critical. Figure 16 (from Haines, 1975) shows the percentage of no-response to blue, yellow, and green signals. A previous study by Haines (1973) also included red signals. The red signals behaved the same as the other colors up to 30° either side of center. Beyond

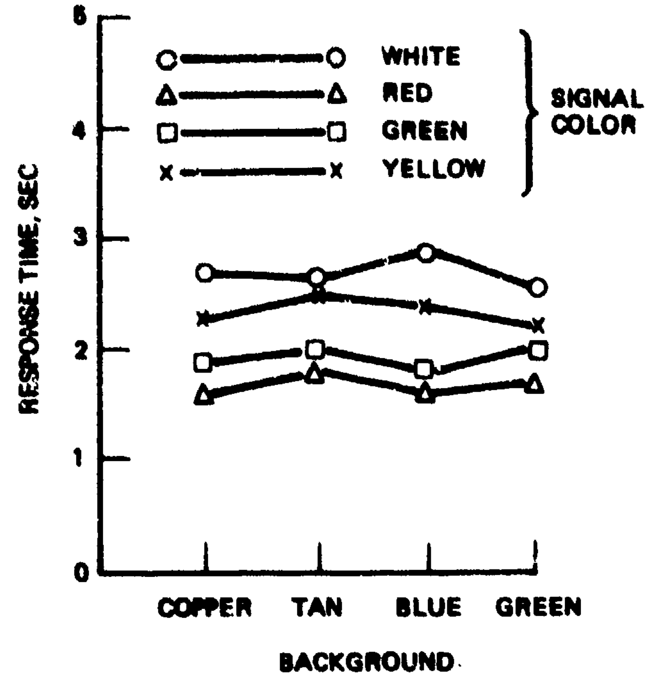


Figure 15 Interaction Between Signal Color and Background Color (Reynolds, et. al. 1972)

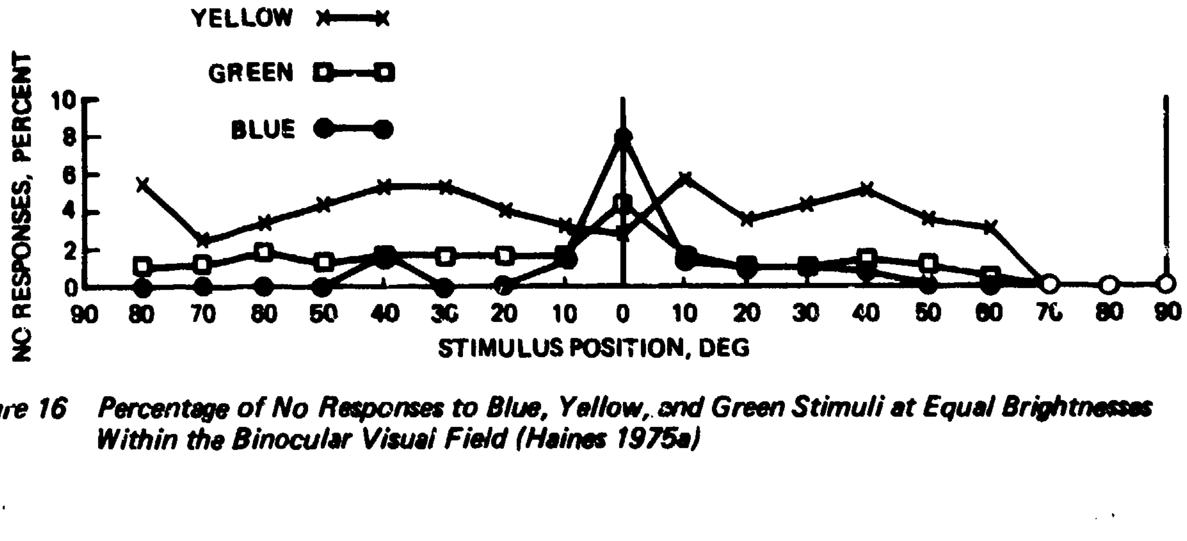


Figure 16 Percentage of No Responses to Blue, Yellow, and Green Stimuli at Equal Brightnesses Within the Binocular Visual Field (Haines 1975a)

this point, the misses for the red signals increased rapidly, hitting 100% in the periphery of the field. Reynolds (1972) analyzed the effect of background on errors in naming the signal color. These data appear in figure 17.

Since the results of the above experiment indicate that red signals are usually detected relatively as fast or faster than visual signals of any other color and the current conventions dictate red signals for high-priority situations, concurrence with the Federal Airworthiness Regulation 25.1322 and continued use of the following color codes for cockpit signal lights are recommended:

Red	– Highest priority warnings
Amber	– Caution
Green or blue	– Normal or safe operation

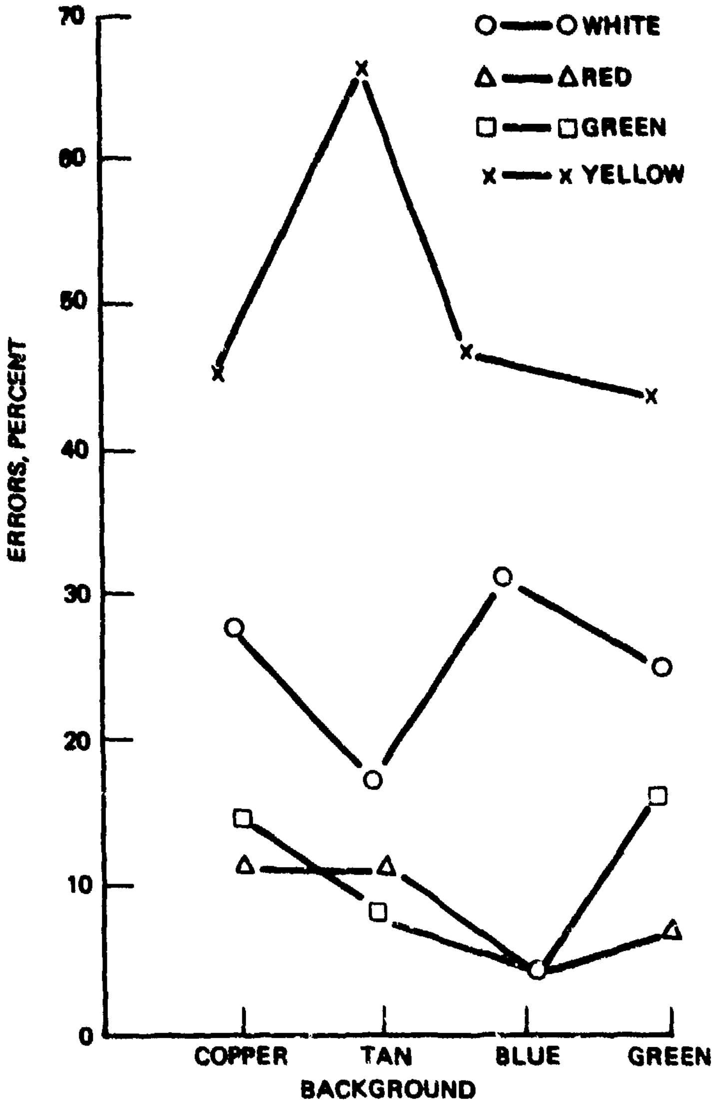


Figure 17 Interaction Between Signal Colors and Background Color on Color Naming Errors (Reynolds 1972)

3.1.2 STIMULUS FACTORS THAT AFFECT DETECTION OF AUDITORY SIGNALS

The detection of auditory signals is affected by properties of the signal stimulus characteristics of the individual listener and the listening environment. This section deals mainly with the effect of the properties of the signal on detectability. A more complete discussion of the effects of the listening environment is presented in a later section. A substantially more comprehensive review of research on auditory perception than can be presented in this paper is Van Cott's and Kincade's *Human Engineering Guide to Equipment Design* (1972).

The primary properties of an auditory signal stimulus that effect detection are:

- Frequency of the signal
- Intensity of the signal
- Location of the signal
- Steady state or intermittent nature of the signal
- Content or message of the signal

3.1.2.1 Affect of Frequency on Detection of Sound Signals

- AURAL SIGNALS SHOULD HAVE FREQUENCY BETWEEN 250 AND 4000 Hz.
- AURAL SIGNALS SHOULD BE COMPOSED OF MORE THAN ONE FREQUENCY.

Young humans can detect sounds with frequencies ranging from around 20 Hz to about 20 000 Hz. As shown in figure 18, maximum sensitivity is generally in the range of from 2000 to 4000 Hz (Fletcher and Munson, 1933). MIDFREQUENCY SOUNDS (2000 to 4000 Hz) TEND TO SOUND LOUDER THAN EITHER LOWER OR HIGHER FREQUENCY SOUNDS OF THE SAME ENERGY. Frequency has a strong effect on perceived loudness at low sound amplitudes. The effect of frequency on perceived loudness decreases as sound amplitude increases. Therefore, one of the important roles of frequency in selecting an auditory signaling device is to permit one signal to be perceived louder and overcome more noise in the midrange of frequency and intensity while using a smaller amount of energy.

Another aspect of signal frequency that has an impact on the detection of auditory signal is that aging in the male causes a progressive loss of hearing in the higher frequencies (fig. 19).

In addition to these losses, injuries occasionally produce insensitivities or deafness to particular frequencies. For these reasons, IT IS IMPORTANT THAT NO SIGNALING DEVICE USE A SINGLE FREQUENCY, BUT RATHER THEY SHOULD BE A COMBINATION OF SOUNDS. Further, since age causes loss in higher frequencies and the perceived loudness is greatest in the 4000-Hz area, SOUNDS WITH FREQUENCIES OF 250 TO 4000 Hz WOULD BE MOST LIKELY TO BE DETECTED BY MOST PEOPLE.

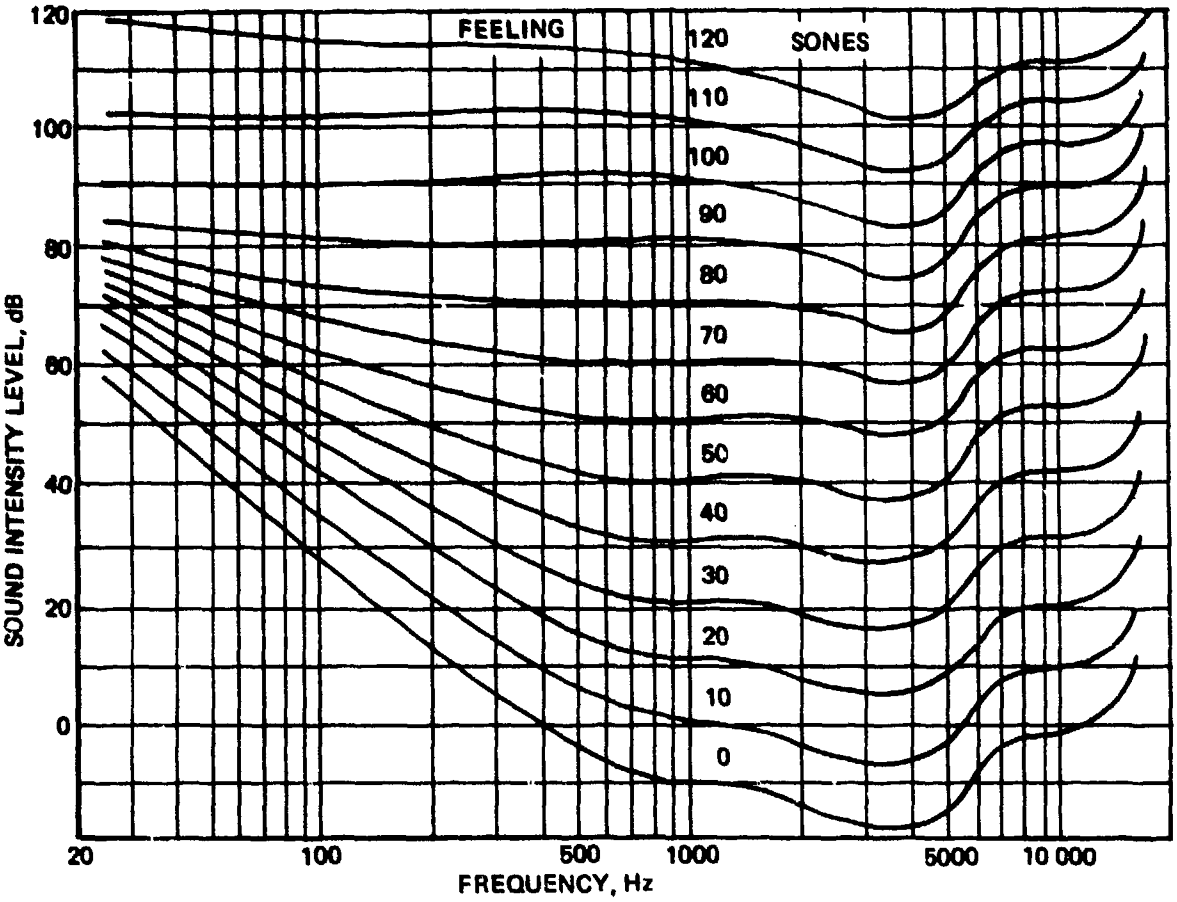
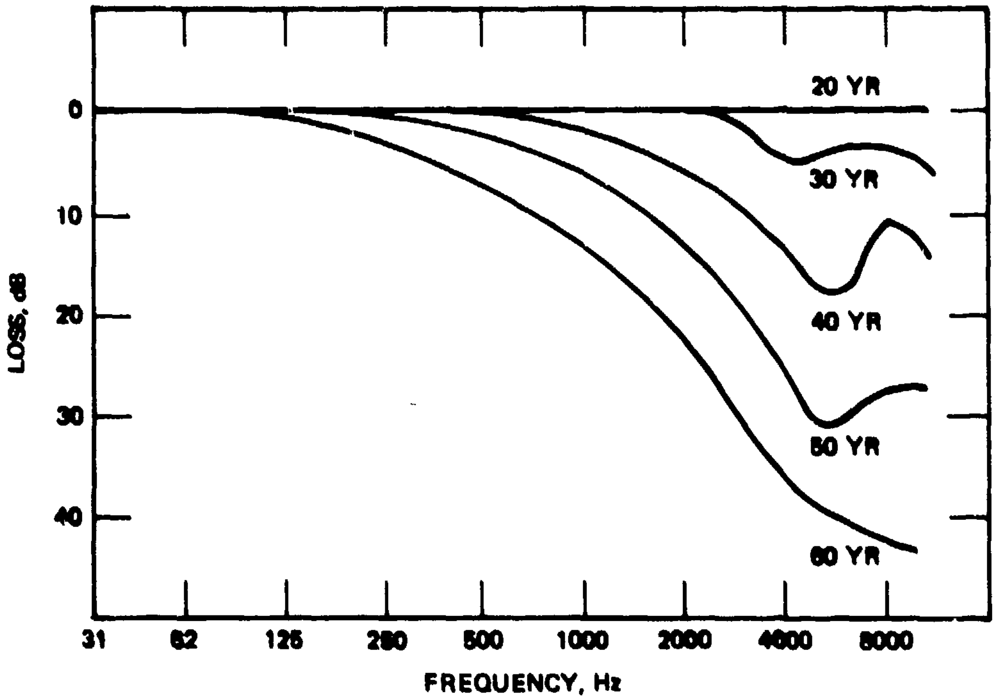


Figure 18 Curves of Sounds of the Same Perceived Loudness (Fletcher and Munson 1933)



NOTE: THE AUDIOGRAM AT 20 YEARS OF AGE IS TAKEN AS A BASIS OF COMPARISON. (FROM MORGAN, 1943, AFTER BUNCH, 1929.)

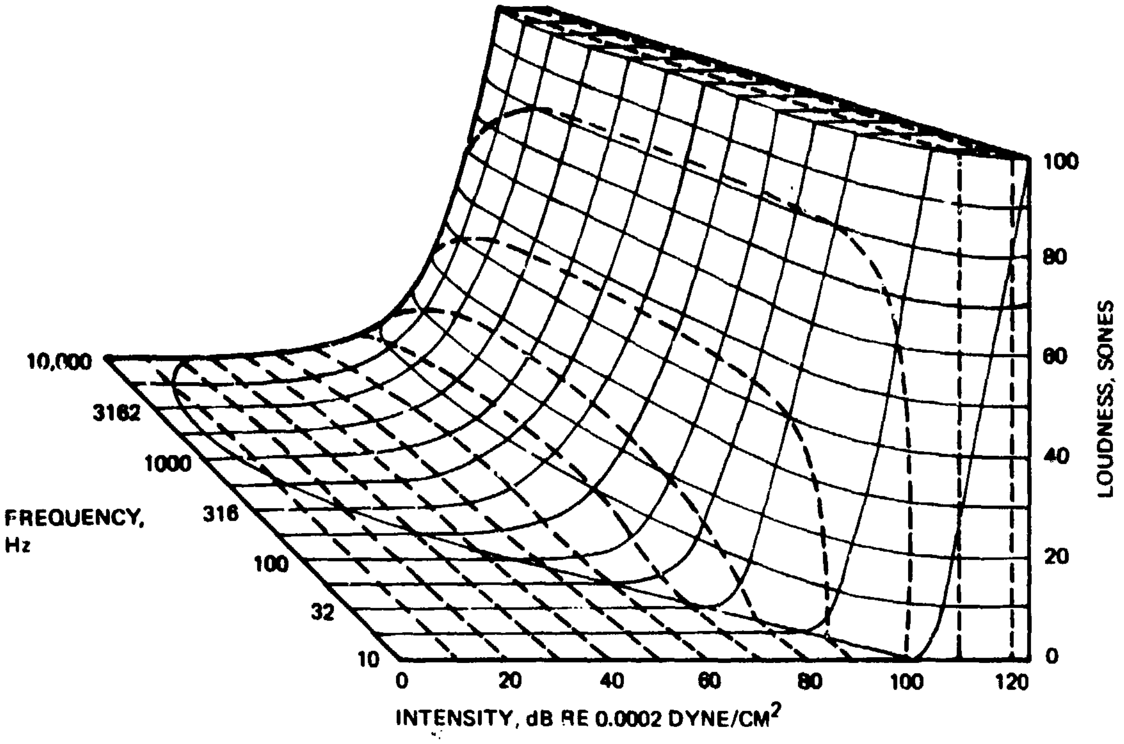
Figure 19 Progressive Loss of Sensitivity at High Frequencies With Increasing Age

3.1.2.2 Affect of Intensity on Detection of Sound Signals

- AURAL SIGNALS SHOULD EXCEED MASKED THRESHOLD BY AT LEAST 15 dB.
- OPTIMUM SIGNAL LEVEL IS HALFWAY BETWEEN MASKED THRESHOLD AND 110 dB.
- PAIN IS EXPERIENCED AT 135 dB FOR UNPROTECTED EARS.
- CONSIDERATION MUST BE GIVEN TO THE HUMAN TIME/EXPOSURE LIMITS.

The distinction between intensity and loudness has not always been observed. The intensity of a sound is a physical measure of the energy level of the sound transmitted per unit of time through a unit of area. Loudness, on the other hand, is an attribute of the sound as heard and reacted to by a listener. It is a subjective response and depends primarily on the sound pressure level (intensity), but it also depends on the frequency and spectrum of the sound. The relationship between these two dimensions of sound and frequency is shown in figure 20.

As a general rule, a more intense sound is more likely to be detected than a quieter sound of the same frequency. However, the detectability of any particular sound is primarily dependent on background noise. For any given background condition, there is an intensity of a signal sound that will



NOTE: SUBJECTIVE LOUDNESS IN SONES IS REPRESENTED VERTICALLY ABOVE THE INTENSITY-FREQUENCY PLANE. THE HEAVY CURVES COURSING FROM FRONT TO REAR IN THE DIAGRAM ARE EQUAL-LOUDNESS CONTOURS FOR PURE TONES. (STEVENS AND DAVIS, 1938)

Figure 20 Three-Dimensional Surface Showing Loudness as a Function of Intensity and Frequency

be detected 50% of the time by a particular individual. This level of intensity is referred to as the *threshold intensity*. An increase of as little as 3 dB in the intensity of the signal above the 50% detected level can result in nearly 100% detection by that individual.

Since auditory alerts will be used in an environment where the background noise is constantly changing not only in amplitude but also in frequency, it is important to determine what aspects of the background noise require adjustments in signal intensity.

Noise mixed with a signal tends to raise the detection threshold above the "threshold in quiet." This effect is referred to as *masking*. For cockpit applications of aural alerting signals, the effects of masking should be evaluated for three types of ambient noise:

Noise Type	Distinguishing Characteristics
Pure tone	Bandwidth = nominal frequency ±0 Hz
Narrow-band noise	Bandwidth = nominal frequency ±45 Hz
Wide-band noise	Bandwidth = wide spectrum

The masking effect of each of these types of ambient noise on aural alerts is discussed in the following paragraphs.

Quantitative relationships between the frequency of the masking tone and the amount of masking of auditory signals of various frequencies as applied to pure tones are shown in figure 21 (A, B, and C). In figure 21A, the frequency of the auditory signals (masked tones) are given on the abscissa of each graph. The ordinate presents the *masking level*, i.e., the amount *above* the threshold-in-quiet level that the auditory signal must be elevated in the presence of the masking tone. The number on each curve represents the intensity of the masking tone, measured as the amount above the threshold-in-quiet level. The lowest curve in figure 21B gives the threshold-in-quiet values.

For an example application of these curves, assume the ambient noise consists of a 400-Hz pure masking tone presented at 95 dB and determine the levels required of 200-, 400-, and 800-Hz auditory signals to achieve 50% detectability. The threshold-in-quiet levels of these signals are 30, 15 and 6 dB, respectively (derived from figure 21B); the 80-dB curve on the B = 400 Hz graph in figure 21A must be used to determine the intensity required of these alerting signals (95 dB Tone - 15 dB Threshold = 80 dB). Interpolation of these curves provides the following results:

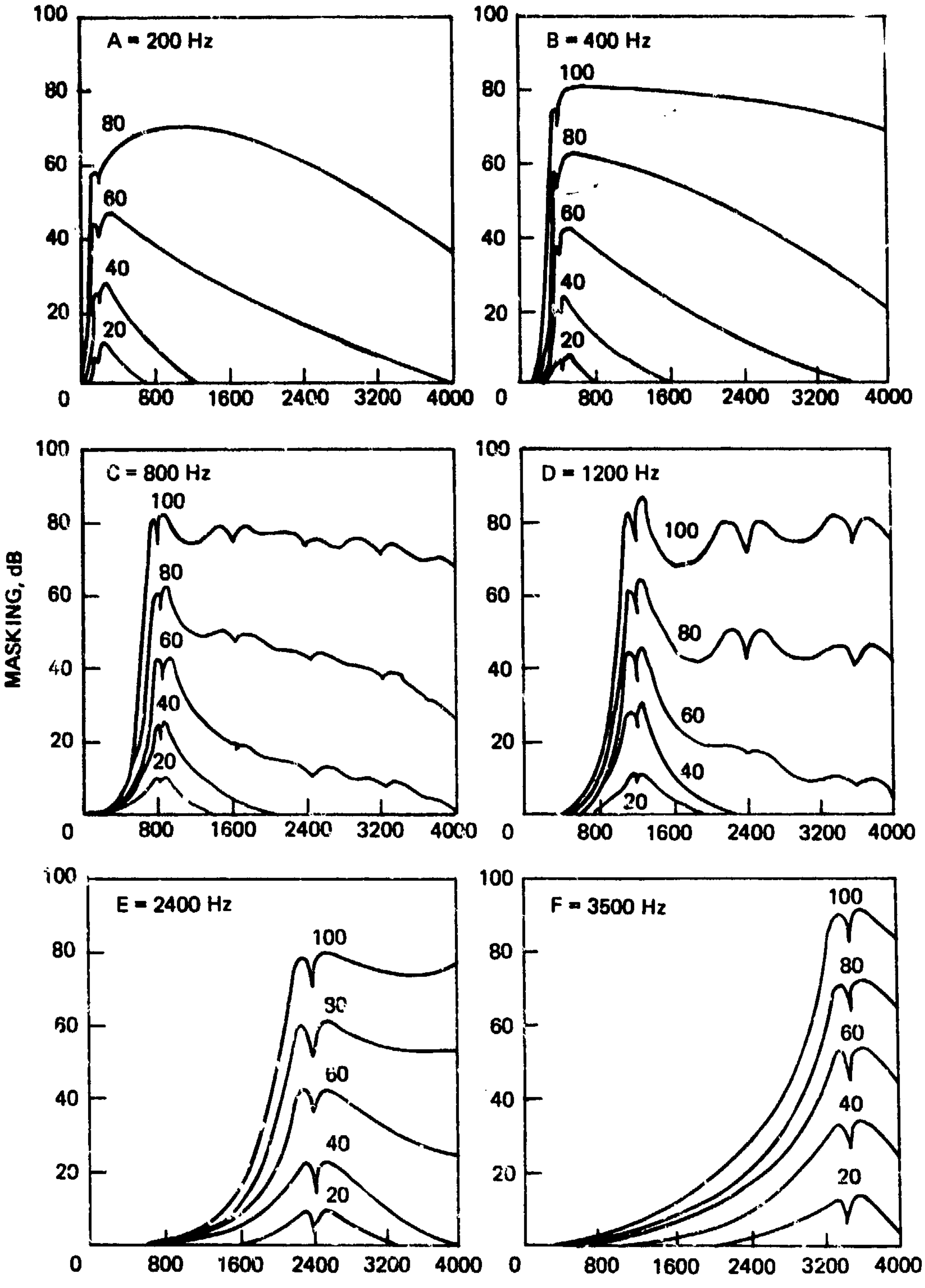
Auditory signal frequency, Hz	DELTA intensity required, dB	Total* intensity required, dB
200	15	45
400	55	70
800	62	68

*Total intensity = DELTA intensity + threshold in quiet

Note that maximum masking of a pure tone occurs when the background sound is of the same frequency range as the signal. Substantial masking also occurs when the auditory signal is composed of higher frequencies than the ambient noise. Lower frequency alerting signals are significantly less subject to masking.

The masking effects of narrow-band ambient noise is similar to the effects described above for a pure-tone environment. The primary difference occurs in the shape of the curves (fig. 21). For pure-tone ambient noise, small dips occur in these curves where the alerting signal frequency equals the ambient noise frequency. These dips are due to beats produced by two pure tones of slightly different frequencies. For narrow-band ambient noise, these beats do not occur and the masking curves smooth out.

Thus far only the effects of pure-tone and narrow-band ambient noise on auditory signals have been discussed. For cockpit applications, wide-band noise effects must also be considered. Morgan et al. (1963) state that the masking effects of wide-band ambient noise are considerably different than the masking effects of narrow-band and pure-tone ambient noise. The effects of wide-band noise extend beyond the spectrum of the noise itself. The masking effect of wide-band noise that has the same intensity throughout the spectrum (white noise) is approximately linear with respect to the increase in intensity of the noise. This is apparent from the regular spacing of the threshold contours in figure 21C. These are true thresholds—not DELTA thresholds as used in the pure-tone discussion. For wide-band noise that does not have uniform intensity over the frequency spectrum, the ear has the ability to filter or reject the part of the noise that is outside a certain range around the



NOTE: Number at top of each graph is frequency of masking tone.
Number on each curve is level above threshold of masking tone.

Figure 21A Masking of One Tone by Another Tone (Wegel and Lane 1924)

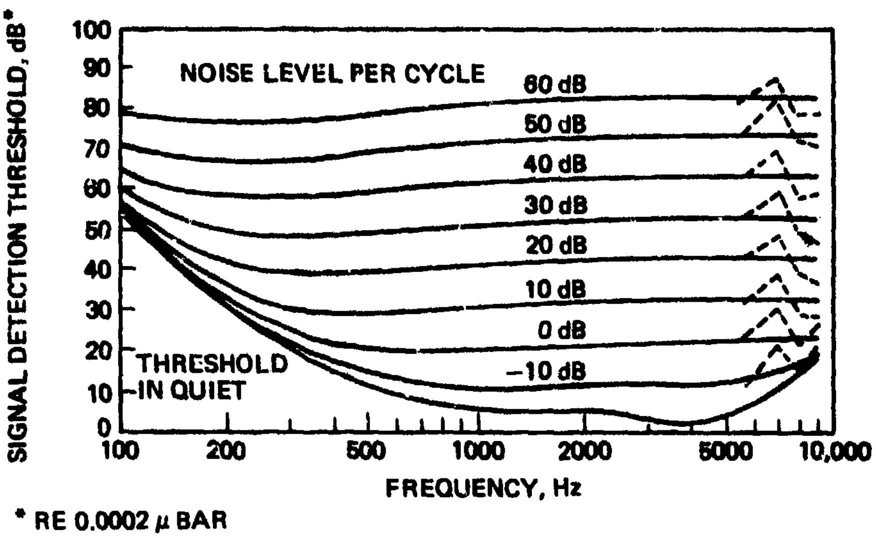


Figure 21B Masking Effect of White Noise on a Pure Tone (Hawkins and Stevens 1950)

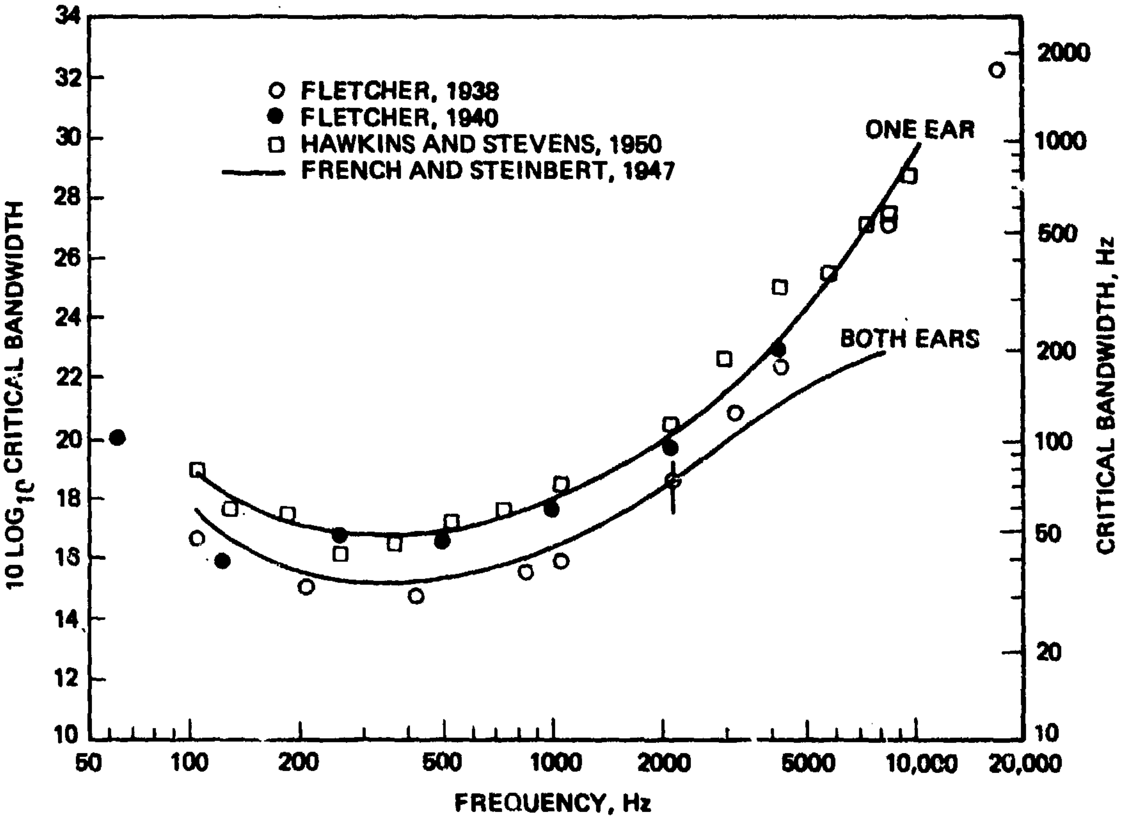


Figure 21C Critical Bandwidth of Masking in Wide Band Noise (Fletcher 1953) signal, thus eliminating some of the noise and making the signal more audible. The width (in Hz) of this range is called the "critical bandwidth" and varies dependent on the frequency of the signal being used (fig. 21C). Morgan et al. (1963) state that the threshold of a pure-tone aural alerting signal can be predicted if the spectrum of the noise near the frequency of the tone is known. In making this prediction, it is assumed that the masking is being done by the noise components near the frequency of the signal, those that lie in the critical bandwidth. When used to predict masking, the critical bandwidth is defined so that the sound pressure level of the noise in the critical band is equal to the sound pressure level of the signal at its *masked threshold* (the intensity where 50% of the signals are detected when noise is present). Morgan presented the following procedure for predicting the masked threshold of an aural alert signal at any signal frequency in wide-band ambient noise:

1. Measure the level of the ambient noise at the auditory signal's frequency.

2. Correct this measured level for the wide-band effect by adding the 10-log value of the critical bandwidth (read directly from the left ordinate in fig. 21C).

3. This corrected value is the masked threshold of the aural alert.

These methods are directed toward detecting pure-tone signals, which are harder to detect in noise than multifrequency signals. Van Cott and Kincade (1972) presented two well-accepted guidelines for multifrequency auditory signals:

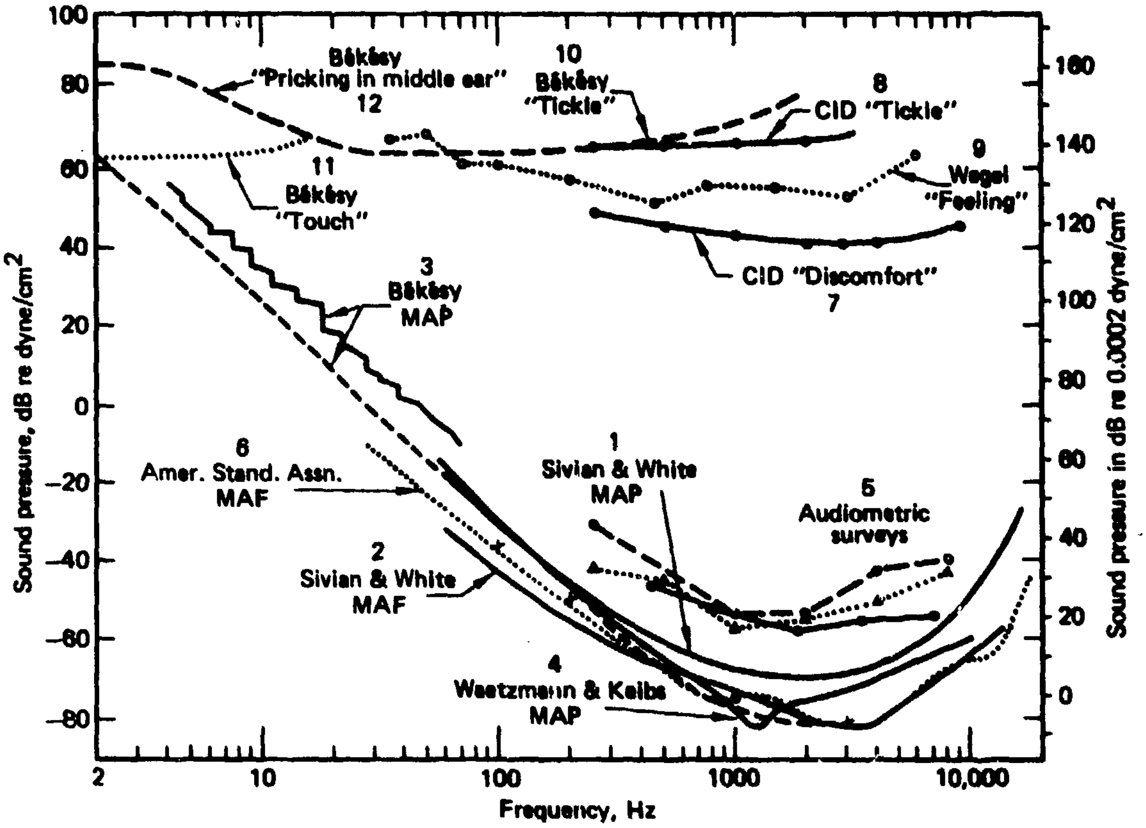
1. A SOUND SIGNAL SHOULD EXCEED ITS MASKED THRESHOLD BY AT LEAST 15 dB FOR GOOD DISCRIMINATION.

2. AN OPTIMUM SIGNAL LEVEL IN NOISE IS HALFWAY BETWEEN THE MASKED THRESHOLD AND 110 dB.

Also to be considered when working with any type of aural alerting signal is MIL-STD-1427B, which requires that auditory signals have a signal-to-noise ratio of at least 20 dB.

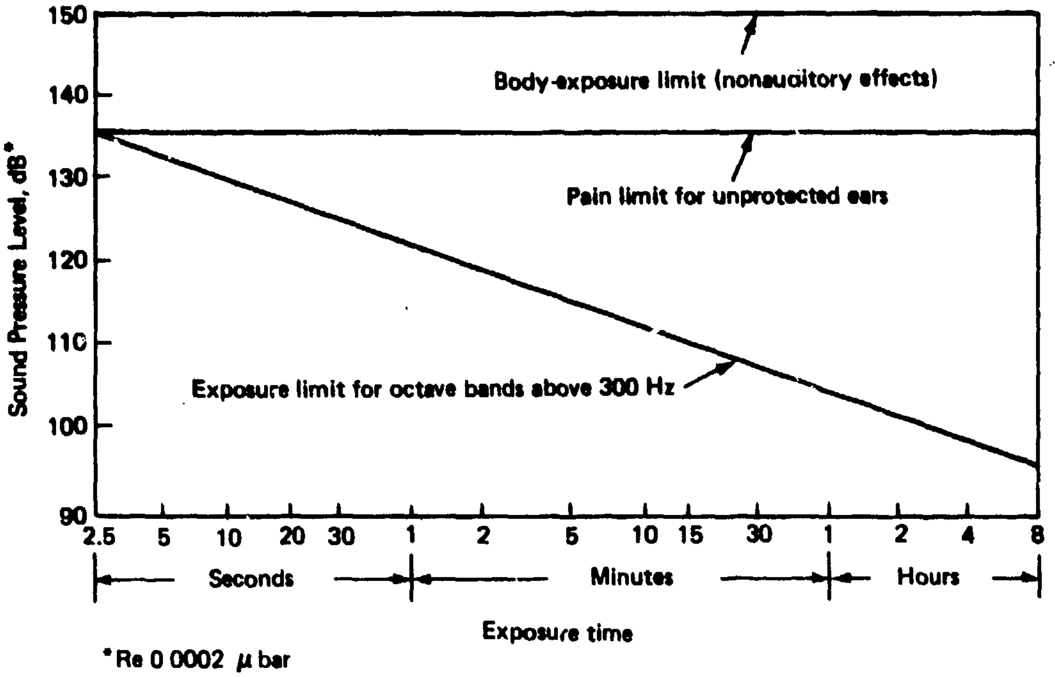
A word of caution should be given about the above methods of determining signal intensity. The signal intensity requirements obtained from the methods directed toward detecting aural alerting signals composed of pure tones should be conservative (high) and may, in fact, be too loud. The guidelines provided by Van Cott and Kincade and by the Military Standard are rules of thumb and may also result in alerting signal intensity requirements that are too loud. Some adjustment may be necessary when installed in the actual cockpit environment. If such adjustments are not made, pilot aggravation and possibly pilot ear damage may result. Stevens (1951) and Eldred (1955) presented guidelines for tailoring these aspects of aural alerting signals.

Stevens presents a composite of the work relating feeling to sound pressure levels (fig. 22). This treatment does not take into consideration the exposure time. Eldred et al. considered this aspect of the auditory environment when he produced the limits set in figure 23. AS CAN BE SEEN, THE UPPER LIMIT FOR SOUND TOLERANCE IS 135 dB. MORE IMPORTANT, HOWEVER, IS THAT THERE IS A TIME/EXPOSURE LIMIT, AFTER WHICH THERE IS A RISK OF DAMAGE FOR UNPROTECTED HEARING.



Curves 1 to 6 represent attempts to determine the absolute threshold of hearing at various frequencies. MAP —minimum audible pressure at the eardrum; MAF—minimum audible pressure in a free sound field, measured at the place where the listener's head had been. Curves 7 to 12 represent attempts to determine the upper boundary of the auditory realm, beyond which sounds are too intense for comfort, and give rise to nonauditory sensations of tickle and pain, etc.

Figure 22 Determinations of the Threshold of Audibility and the Threshold of Feeling (Stevens 1951)



NOTE: PAIN LIMIT FOR UNPROTECTED EARS IS SHOWN AT 135 dB. WHEN EAR PROTECTORS ARE USED, SOUND PRESSURE LEVEL IN SOUND FIELD CAN EXCEED THESE CRITERIA BY AMOUNT OF ATTENUATION PROVIDED BY PROTECTORS. BODY-EXPOSURE LIMIT AT 150 dB IS POINT AT WHICH POTENTIALLY DANGEROUS NON-AUDITORY EFFECTS OCCUR. THIS LEVEL SHOULD NOT BE EXCEEDED IN ANY CASE (ELDRED ET AL' 1955).

Figure 23 Damage Risk Criteria for Various Exposure Times Up to 8 Hr (Eldred, et. al. 1955)

3.1.2.3 Affects of Location on Detection of Sound Signals

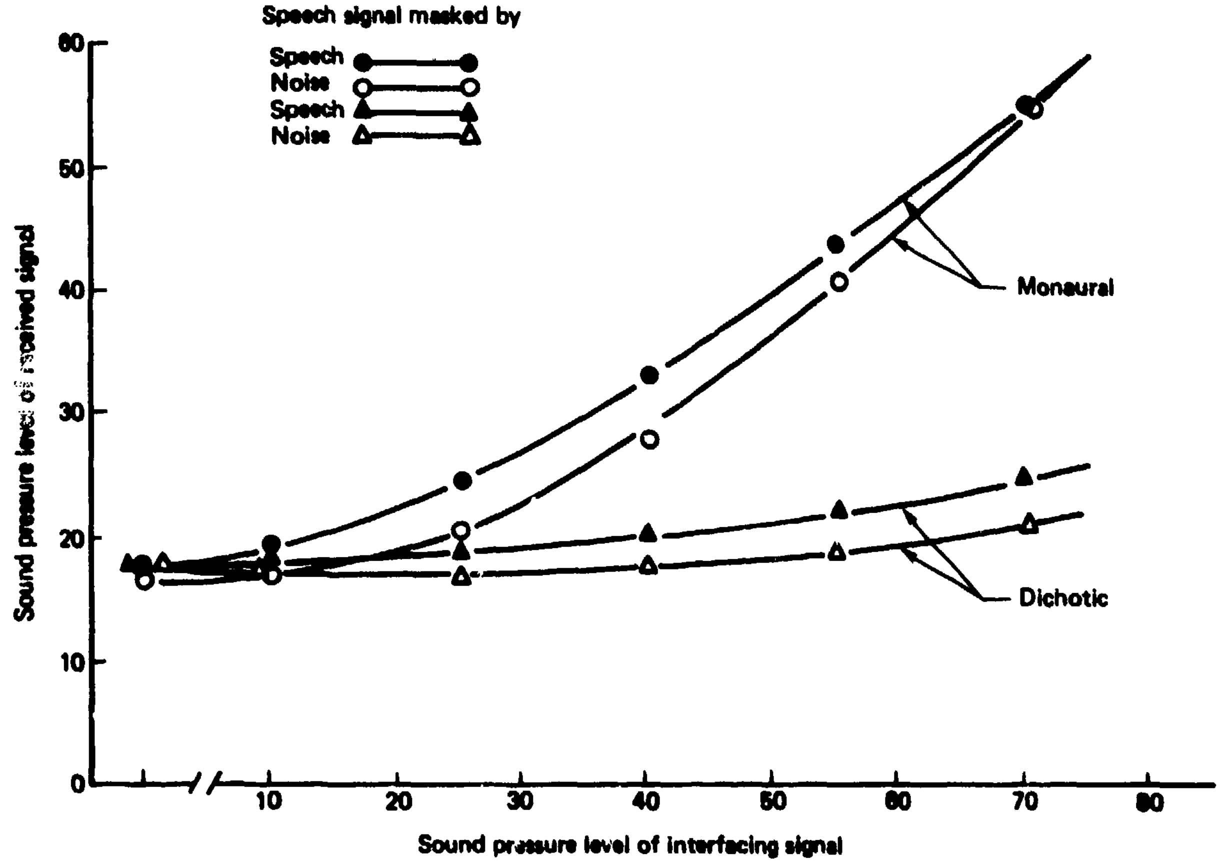
- DICHOTIC METHODS OF PRESENTATIONS SHOULD BE USED FOR AURAL ALERTS.
- IF SINGLE EARPHONE IS USED, IT SHOULD BE WORN ON THE DOMINANT EAR.
- ALERT SHOULD BE SEPARATED FROM DISTRACTING SIGNALS BY 90°.
- USE BROAD-BAND SOUND SIGNALS WHEN LOCALIZATION IS NOT POSSIBLE.

The masking effects of background sounds are affected by the location of the signal sounds relative to the background sounds. Sound signals perceived as coming from a different location than the background sounds are more likely to be detected from signals that cannot be separated in location from background sounds.

Egan, Carterette, and Thwing (1954) had subjects listen to messages under either normal or dichotic conditions. In monaural listening, the message to be received and interfering noise or messages are presented by an earphone to one ear. In dichotic listening, the message to be received is presented by an earphone to one ear, and interfering noise or messages are presented by another earphone to the other ear. Dichotic listening gives location cues that helped discriminate between signals and noise. As can be seen in figure 24, the advantage of dichotic listening is equivalent to an increase of up to 30 dB in the intensity of the signal message. However, this amount of increase should not be expected in a noisy environment where the pilot will not be using full earphones.

If the pilot is going to wear a single earphone and the aural signal is going to be presented over the system, it is important that the pilot's "dominant" ear be determined. (Most people tend to receive messages in noise easier in one ear than in the other ear. The ear that receives messages better is referred to as the dominant ear.) Messages presented to the dominant ear are slightly more likely to intrude upon attention than messages presented to the other ear. Gopher and Kahneman (1971) used earphones to present one series of numbers to the right ear and another series of numbers to the left ear of a group of Israeli Air Force cadets and pilots. The subjects were required to repeat one series numbers and to ignore the other series. An average of 1.1% of the numbers that were to be ignored intruded and were repeated. Most of the intrusions (74%) occurred when the numbers presented to the right ear were to be ignored. The observed higher intrusion rate for messages presented to the right ear is due to the majority of people being right-ear dominant.

THEREFORE, AUDITORY WARNING SIGNALS THAT ARE PRESENTED MONAURALLY SHOULD BE TRANSMITTED TO THE DOMINANT EAR.



Curves show threshold sound pressure level for perception of a received signal masked by an interfering signal

Figure 24 Comparison of Dichotic and Monaural Masking (Egan, et. al. 1954)

To more approximate an open type of situation, Spieth, Curtis, and Webster (1954) asked subjects questions about visual displays. The questions were always presented in simultaneous pairs. Each question in a pair was preceded by a code name. The subjects were to answer the question in each pair that was preceded by their code name and to ignore the other question. Three loudspeakers were used to transmit the messages and could be separated from each other horizontally in either 10° or 90° increments. Both members of a pair of questions could either be transmitted from the same loudspeaker (single-source condition) or from two different loudspeakers. When both members of a pair of questions were transmitted from the same loudspeaker, the subjects answered 66% of the questions correctly. The amount of correct answers increased 86% for 10° to 20° separation of messages and 92% for 90° to 180° separation of messages (fig. 25). Spieth et al. did not determine how much increase in signal message volume would produce the amount of improvement produced by the separation conditions.

The ability to localize a signal is affected by the frequency of the sounds. Mills (1958) found that localization of the pure tones was optimum for tones between 250 and 1000 Hz and four tones between 3000 and 6000 Hz. Localization of sounds was poor for tones of from 1000 to 1500 Hz and for tones around 8000 Hz. Broad-band signals are generally localized much better than pure tones. THUS, WITH BINAURAL LISTENING BROAD-BAND SOUND SIGNALS THAT CAN BE LOCALIZED EASILY ARE MORE LIKELY TO BE DETECTED FROM SOUND SIGNALS THAT CANNOT BE LOCALIZED.

Cherry (1953) also addressed the problem of how a critical verbal message is detected when other messages are occurring at the same time. Of all the factors that may affect the type of detection, the location of the voice seemed the most promising. He presented observers with two speeches,

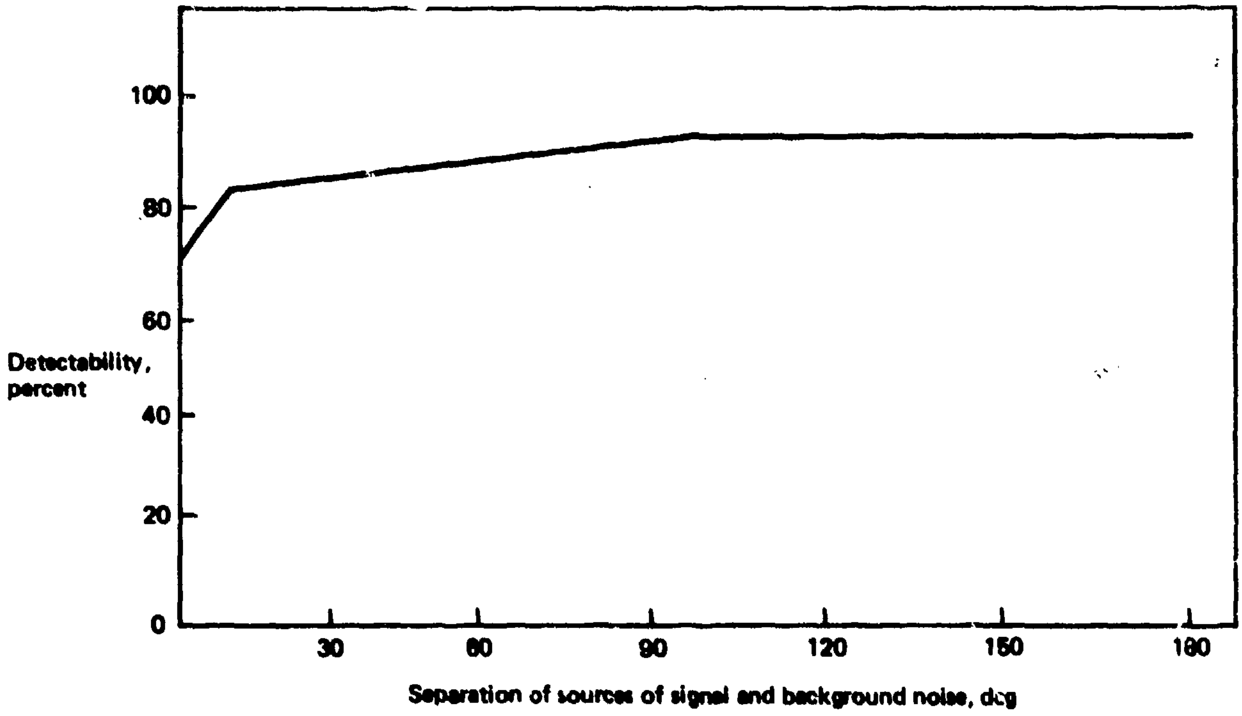


Figure 25 Effect of Aural Alerting Signal Source Location

either mixed to both ears, or one to the left ear and the other to the right ear. The task was to separate and repeat one of the messages. It was found that some messages could be separated if they were presented in the mixed fashion; others could not. The observers had no trouble separating the messages when they were presented to different ears. In fact, after the observer was comfortably repeating the messages in one ear, the messages in the other ear were switched to German. No observer detected the switch.

In summary, IF POSSIBLE, AUDITORY ALERTING SIGNALS SHOULD BE PRESENTED DICHOTICALLY SEPARATED FROM NOISE. IF DICHOTIC SEPARATION IS NOT POSSIBLE, AUDITORY ALERTING SIGNALS SHOULD COME FROM A SOURCE THAT IS SEPARATED BY AT LEAST 90° FROM THE SOURCES OF INTERFERING NOISE OR MESSAGES. IN ADDITION, IF THE LOCATION OF THE SOURCES OF BOTH WARNING SIGNALS AND INTERFERING SOUNDS ARE OPTIONAL, THE ALERTING SIGNAL SHOULD BE PRESENTED TO THE DOMINANT EAR AND THE INTERFERING SOUNDS SHOULD BE PRESENTED TO THE NONDOMINANT EAR. IF LOCALIZATION IS NOT POSSIBLE, BROAD-BAND SIGNALS SHOULD BE USED.

3.1.2.4 Affect of Whether Auditory Signals Are Steady State or Intermittent on Detection

- INTERMITTENT AURAL SIGNALS SHOULD BE USED.
- CYCLE TIME SHOULD BE 0.85 SECOND ON AND 0.15 SECOND OFF.

The auditory sense adapts extremely rapidly to constant stimulation. Steady-state signals tend to become less noticeable after a short period of time. A steady-state sound signal that is not detected at its onset is likely to go unnoticed over an extended period of time. The auditory system does not adapt as rapidly to intermittent or changing signals as it does to steady-state signals. HENCE, INTERMITTENT SOUND SIGNALS ARE MORE LIKELY TO BE DETECTED THAN STEADY-STATE SIGNALS.

MIL-STD-411D requires that an auditory master warning signal have an 0.85-second ON time and an 0.15 OFF time, with the cycle continuing until the system is deenergized.

3.1.2.5 Affect of Message Content on Detection of Auditory Signals

- HIGHER PRIORITY AURAL SIGNALS SHOULD CONSIST OF TWO ELEMENTS–AN ALERTING SIGNAL AND AN ACTION SIGNAL.
- THE USER'S NAME IS A HIGHLY EFFECTIVE ALERTING SIGNAL.

The detection of a sound signal is often affected by the content of the signal. For example, a person's own name is usually more attention attracting than any other auditory message of the same volume. Howarth and Ellis (1961) found that subjects were more likely to detect their own name than other names. Howarth and Ellis recorded the names of 10 subjects. Then they played the recordings back and had each subject write down all of the names that he could recognize. The volume of the recordings was adjusted so that the subject could recognize approximately 50% of the names. The pooled results showed that they could recognize their own names on 77% of the occasions when it was presented, but the other nine names were recognized on only 50% of the presentations.

Moray (1959) had subjects attend to and repeat a continuous message presented to one ear. Other messages were simultaneously presented to the other ear. When the messages presented to the unattended ear were preceded by the subject's name, 51% of the messages were heard. In contrast, only 11% of the messages that were not preceded by the subject's name were heard.

Oswald, Taylor, and Treisman (1960) used an experimental design much the same as Howarth and Ellis (1961), with the exception that the observers were deprived of sleep so that they fell asleep during the experiment. The observers were instructed to move a hand when they heard their name or another specified name. The observers responded 25% of the time to their own name and only 12% of the time to other names. Table 3 summarizes the results of these three experiments. Statistical techniques were used to determine the significance of the difference between responding to one's own name and responding to something else. The probability that the size of the difference observed between the two cases occurred by chance alone is also presented.

The content of nonverbal auditory signals also has an affect on their detectability. Keuss (1972) used two signals in close succession. The first signal (essentially a ready signal) was presented for 25 msec and then the response signal was presented. The intensities of both signals were varied using values of 45-, 68-, 85-, and 110-dB sound pressure levels. The observers were required to push a key when the second signal came on. Figure 26 illustrates the results of this study. Generally, reaction time varied inversely with the intensity of both signals. Probably due to startle, the reaction time tended to lengthen when the second signal was 110 dB. When both signals were 110 dB, the startle effect on reaction time seemed most evident.

Siegel and Crain (1960) ran an experiment under night conditions. Observers were required to perform a tracking task and respond to a warning signal when it appeared. The warning signal was either a light, a single tone, or a double tone. The two-tone auditory signal resulted in significantly shorter (by over a full second) response times than any of the other signals. MIL-STD-1472B states that AURAL WARNING SIGNALS SHOULD NORMALLY CONSIST OF TWO ELEMENTS–AN ALERTING SIGNAL AND AN ACTION SIGNAL. With a two-element signal, the alerting signal should last no more than 0.5 second and all essential information shall be transmitted by the action signal in less than 2 seconds.

In summary, HAVING A PERSON'S NAME OR OTHER PREPROGRAMMED WORD PRECEDE AN AUDITORY MESSAGE APPEARS TO HAVE ABOUT THE SAME EFFECT ON DETECTION AS INCREASING THE LOUDNESS OF THE MESSAGE BY ABOUT 3 dB. WHEN NONVERBAL SIGNALS ARE TO BE USED, A TWO-TONE SIGNAL WILL BE SUPERIOR TO A SINGLE TONE.

Table 3 Data From Three Different Experiments

	HOWARTH, et. al.	MORAY	OSWALD, et. al.
RESPONSE TO OWN NAME	77% (77/100)	51% (20/39)	25% (33/131)
RESPONSE TO OTHER MESSAGE	50.5% (455/900)	11% (4/36)	12% (15/124)
PROBABILITY OF CHANCE DIFFERENCE	0.1%*	1%	1%

* A probability of 0.1% means that if samples of people with the same response variability were tested repeatedly and there was no real difference between responding to one's name and responding to other messages, then a difference as large as observed by Howarth would occur only one time in 1000 tests.

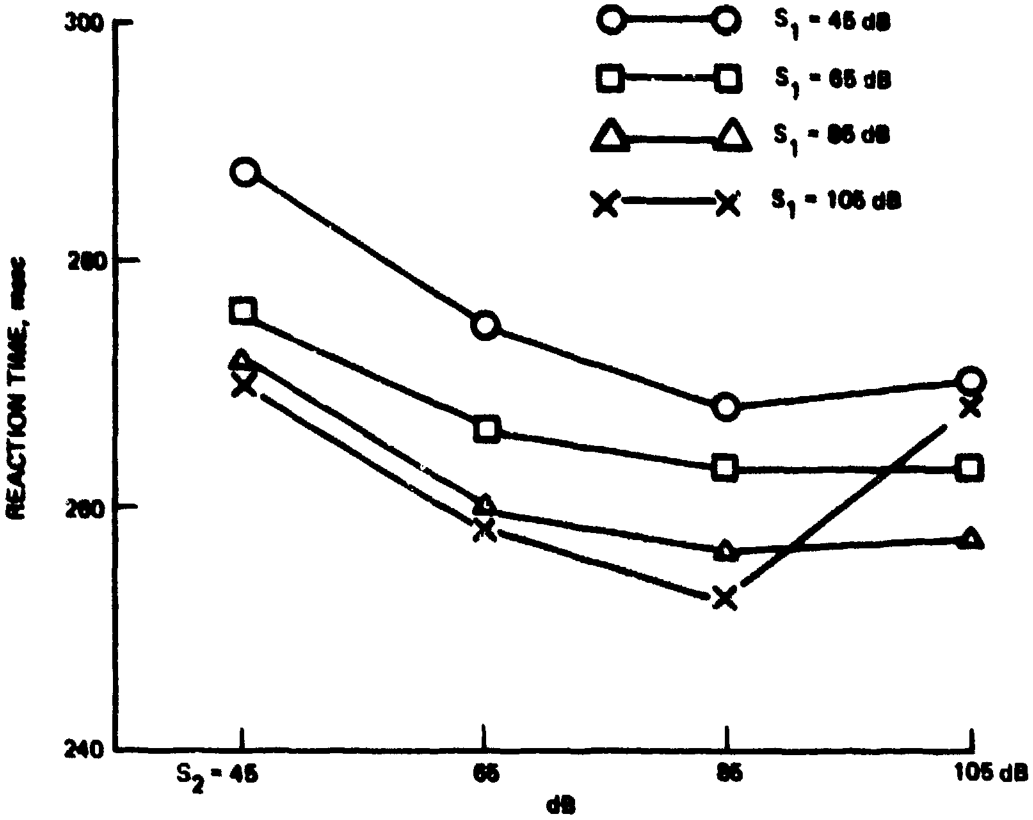


Figure 26 Mean RT to S_2 as a Function of the Intensity of S_1 and S_2 (Keuss 1972)

3.1.3 SIGNAL-RELATED FACTORS THAT AFFECT THE DETECTION OF TACTILE SIGNALS

The detection of tactile signals is affected by:

1. STEADY STATE OR INTERMITTENT NATURE OF SIGNAL
2. PART OF THE BODY SIMULATED
3. INTENSITY OF THE SIGNAL

3.1.3.1 Effect of Whether Tactile Signals Are Steady State or Intermittent on Detection

- TACTILE SIGNALS MUST BE INTERMITTENT FOR DETECTION.
- FREQUENCY OF THE SIGNAL SHOULD BE BETWEEN 200 AND 300 Hz.

The sensation of pressure or touch is due to a continuing deformation of the skin (Nate and Wagoner, 1941). As soon as the shape of the skin reaches a steady state, the sensation of touch stops. Nate and Wagoner placed weights of from 8.75 to 70.0 grams on the subject's skin and took precise measurements of how long the weights continued to sink into the skin. They also asked the subject to give continuous reports of whether he could feel the weight or not. As long as the weight continued to sink into the skin, the subject reported that he could feel the weight. As soon as the movement of the weight stopped, the subject reported that he could no longer feel the weight.

Nate's and Wagoner's findings indicate that for a pressure or touch-type stimulus to produce a continuous sensation, THE STIMULUS MUST PRODUCE CONTINUOUS MOVEMENT OF THE SKIN. CONTINUOUS MOVEMENT CAN BEST BE PRODUCED BY AN INTERMITTENT OR VIBRATING STIMULUS. The rate at which the skin is deformed is important in determining thresholds. For example, the absolute threshold for touch is lower as the stimulator is pressed against the skin more rapidly than if the pressure is applied slowly. In fact, if the stimulator is applied slowly enough, the person will be unaware of the pressure. The skin is maximally sensitive to signals that vibrate at between 200 and 300 Hz (Woodworth and Schlosberg, 1964; Van Cott and Kincade, 1972). THUS, IT IS RECOMMENDED THAT IF A TACTILE SIGNAL IS USED FOR INFORMATION TRANSFER IN THE COCKPIT, IT SHOULD VIBRATE AT 250 Hz.

3.1.3.2 Effect of the Area of the Body That Is Stimulated by Tactile Signals

- AMPLITUDE OF TACTILE SIGNALS SHOULD CORRESPOND TO THE SENSITIVITY OF PLACEMENT AREA.

- SIGNALS SHOULD BE PLACED ON AREAS NOT INVOLVED IN MOTION.

The sensitivity to touch varies widely from one section of the body to another. Wilski (1954) measured the threshold for vibration sensitivity in different regions of the body surface. He reported that the fingers were most sensitive to vibration and the buttocks were least sensitive.

The amplitude of any vibratory stimulus used as an alerting signal must be calibrated to produce a sensation on the part of the body that is stimulated. Hill (1968) states that tactile signals are correctly interpreted more often when placed on body locations not involved with motion.

3.1.3.3 Effect of Signal Intensity on the Detection of Tactile Signals

- PRACTICAL RANGE OF INTENSITIES IS 50 TO 400 MICRONS.

Again, as with the other signaling methods, one would expect the probability and speed of detecting the signal to be related to the signal intensity. Gescheides, Wright, Weber, Kirchner, and Milligan (1969) applied a 60-cps signal to the left index fingertip of their observer. A white light served as a ready signal and was followed 1 to 2 seconds later by the tactile action signal. The observer's task was to judge the presence of the action signal as quickly as possible. Not only was the signal intensity varied, but the probability of occurrence was also varied. The results from this study can be seen in figure 27, where the signal intensities are given in decibels with a reference level of 1.75 microns. A DECIBEL IS DEFINED AS 10 TIMES THE LOG TO THE BASE 10 OF A SPECIFIED INTENSITY (P_1) DIVIDED BY THE REFERENCE INTENSITY (P_0), I.E.,

$$\text{DECIBEL} = 10\,\text{LOG}_{10}\frac{P_1}{P_0}$$

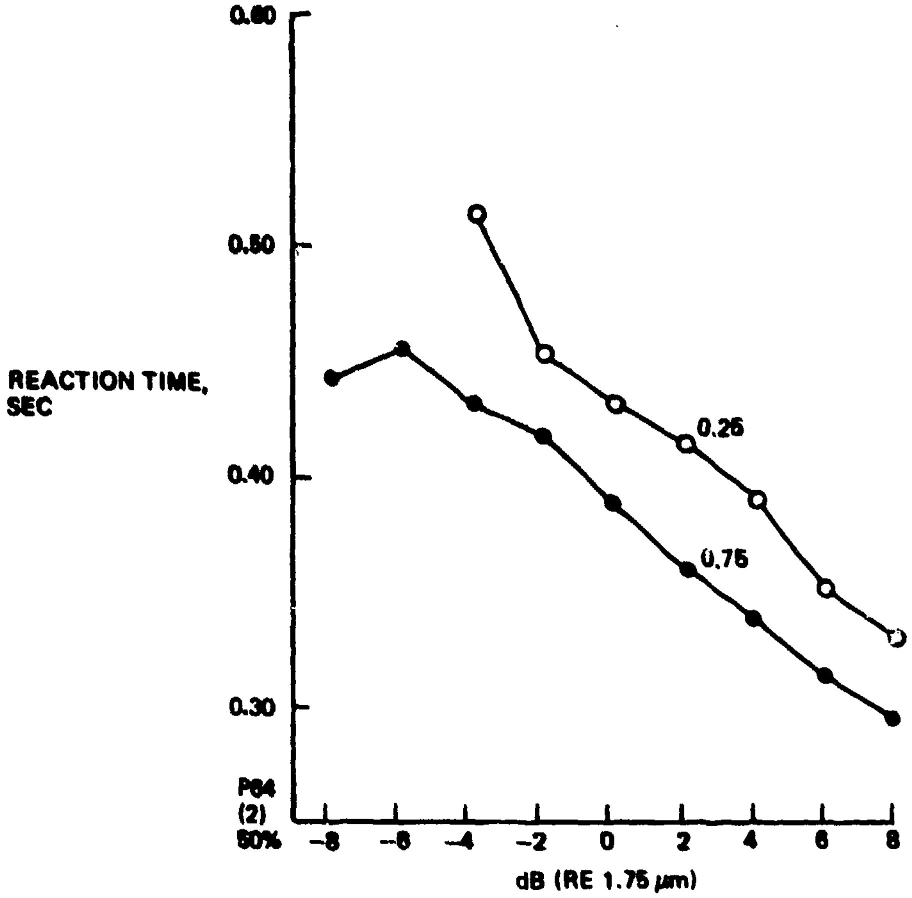


Figure 27 Mean Reaction Time (In Seconds) Obtained Under Signal Probability Values of 0.25 and 0.75 Plotted as a Function of Signal Intensity (Weber, et. al. 1969)

The two lines in the figure represent the two probabilities of signal occurrence. As can be seen at 8 dB (11 microns), the decrease in reaction time has not leveled out. This is reasonable, since Geldard (1957) reports that the lowest useful intensity of vibration that can be detected 100% of the time is about 50 microns.

THE PRACTICAL RANGE OF SIGNALING INTENSITIES IS FROM 50 MICRONS AS A MINIMUM TO 400 MICRONS.

3.1.4 EFFECT OF PRESENTING BOTH VISUAL AND AUDITORY SIGNALS ON DETECTION PERFORMANCE

- PRECEDING VISUAL SIGNALS WITH AUDITORY SIGNALS PRODUCES FASTER RESPONSE.
- INTERVALS BETWEEN SIGNALS SHOULD BE BETWEEN 0.1 and 0.3 SECOND.
- BOTH SIGNALS SHOULD COME FROM THE SAME SIDE OF THE OBSERVER.

All the signaling systems covered so far have used a single signaling device. One major drawback to this type of system is the dependence on the single human sensor having sufficient channel capacity to handle the signal when it occurs. Also, it is not surprising that auditory signals are generally superior to visual signals for those situations in which attention is not constantly focused on the visual signals (Siegel, 1960). The question arises as to whether there would be any further gain from combining auditory and visual signaling devices to produce a bimodal signal. The first impulse would be to say that detection probability and sensitivity would increase, but the reaction time would remain the same as that of the auditory signal.

Klemmer (1958) used red, green, and orange lights and 100-, 700-, and 5000-cps tones as the action signals. The observer's task was to press one of three buttons, depending on which light or tone came on. For the bimodal test, a tone and light combination (i.e., 100-cps tone and red light) indicated which button to push. The signal-button combinations were the same as in the single-channel case. Klemmer found that he could improve performance from an 84% correct detection and response in the single-channel case to 95% correct in the bimodal presentation. Fidell (1969) used an auditory signal and the same signal on an oscilloscope as the visual signal. There was an improvement in detection sensitivity as a function of bimodal signal presentation. This improvement was as great as 3 dB. Klingberg (1962) required each of his observers to respond to a 1.5° visual angle signal (corresponds to 0.75 inch times 0.75 inch aircraft warning light) combined with an 800-cps auditory signal. The auditory and visual signal strength were equated in a preliminary bimodal matching study. The primary response measure was the number of signals missed during each half hour. The probability of signal detection for the bimodal signals was significantly higher than for the same signals presented individually.

The same parameters that affect reaction time to a single-channel signal also affect bimodal presentations. Another factor, the time separation between the two signals, also has a real effect on the detection time. Studies (Carroll, 1973; Bate, 1969; Bertelson, 1968) have shown that a simultaneous presentation of auditory and visual signals produces a faster reaction time than either of the signals individually. Bertelson (1968) goes further and demonstrates that by preceding the visual signal with the auditory signal an increase in reaction time can be obtained. He postulates that the warning signal is used by the observer to start preparatory adjustments required to respond to the action signal. He presented his observers a clock that served as the warning signal and a light that appeared at specified intervals after the click. The results from this study are presented in figure 28.

These data show a decrease in reaction time, with an increase in the time between the presentation of the two stimuli. Minimum reaction time seems to be reached at an interval between 100 and 300 msec long. Geblewiczowa (1963) used larger intervals (0.5, 1.5, and 2.5 seconds) and found that an 0.5-second interval produced the shortest reaction time. The study demonstrates that the interval length, if it gets too large, loses its effectiveness. IF THE AUDITORY AND VISUAL SIGNALS ARE TO BE SEPARATED TO INCREASE THE SPEED OF RESPONDING, THE INTERVAL BETWEEN THE TWO SIGNALS SHOULD BE BETWEEN 100 AND 300 MSEC LONG. The same time interval was found by Keuss (1972) when using two auditory stimuli. He recorded the observers' reaction times to a tone (S_2), which was preceded by another alerting tone (S_1). The intensities of the two tones and the interstimulus intervals (ISI) were varied during the testing. The results are presented in figure 29. As can be seen, the reaction time is inversely related to the interstimulus interval until the interval reaches 200-250 msec.

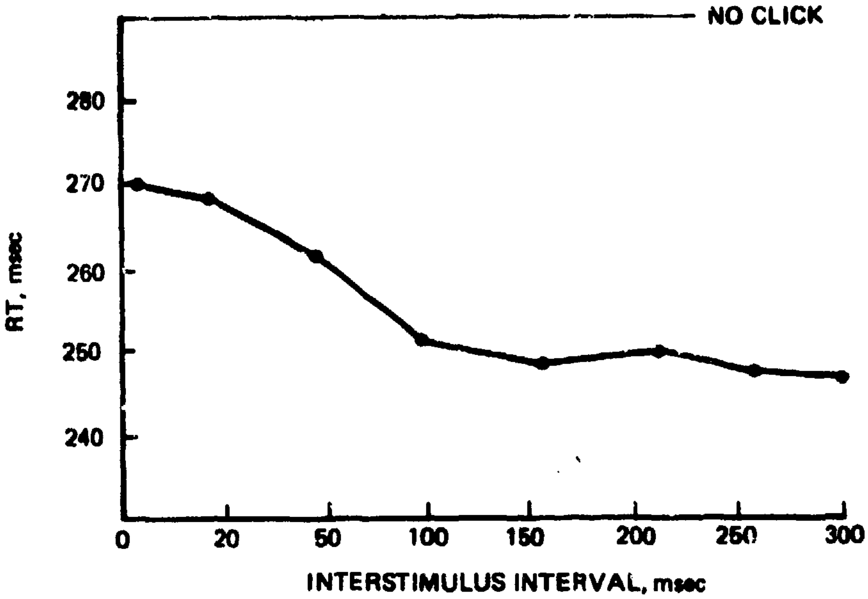
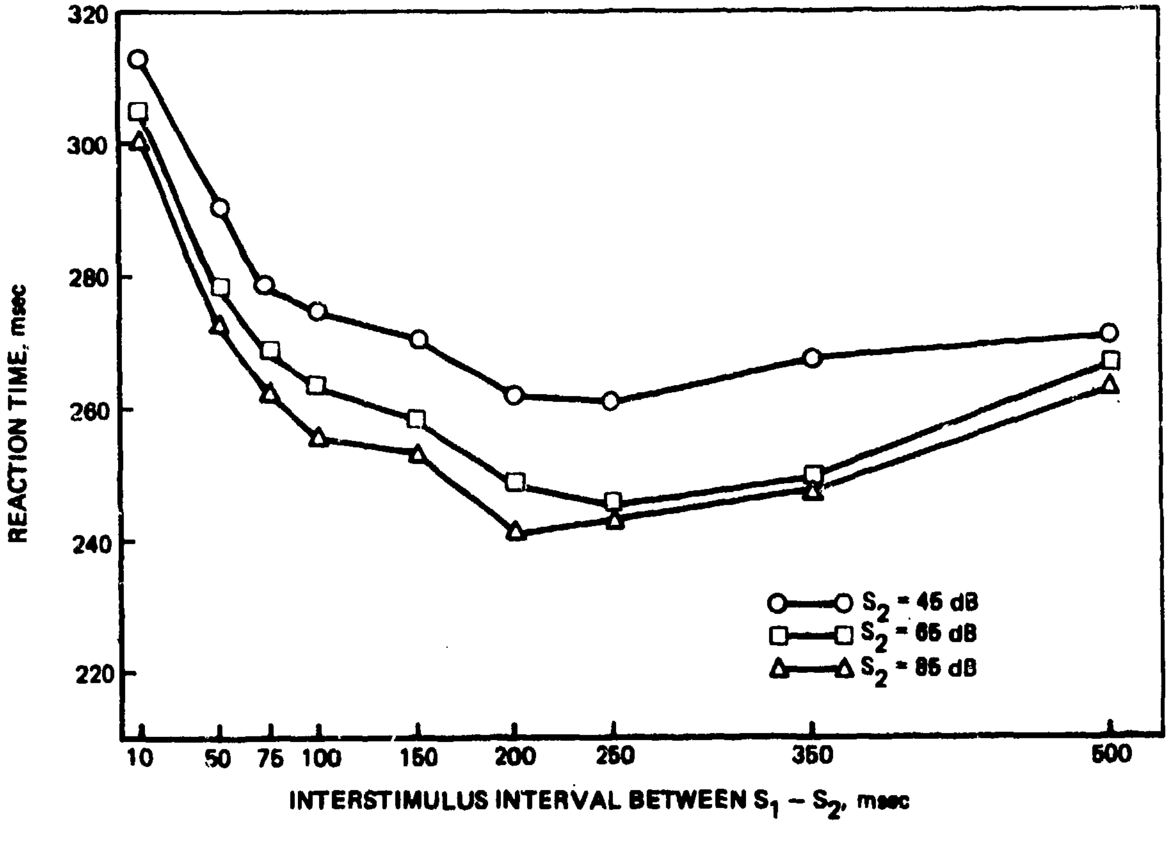


Figure 28 Mean RT as a Function of the Interstimulus Interval



NOTE: RT IS AVERAGED OVER ALL INTENSITY LEVELS OF S$_1$.

Figure 29 Mean RT to the Action Signal (S_2) as a Function of Interstimulus Interval and the Intensity Level of S_2 (Perriment 1969)

Finally, the location of the signals with respect to each other is also a factor affecting the time to react to the signal. Perriment (1969) required his observers to respond to a light and sound signal by depressing two of the four buttons located on a response panel to identify the direction (left or right) of each signal. The two signals could be presented either both on the same side or on opposite sides. It was found that the reaction times were relatively the same for the conditions where both the signals came from the same side, whether it was from the right or left. The same was true for the two conditions where the signals were on opposite sides. Therefore, the data were pooled in two sets called unilateral presentation (same side) and bilateral presentation (opposite side). The separation of the buttons was also varied, being either 6, 12, or 24 inches apart. The results of the experiment may be seen in figure 29. Not only does the unilateral condition produce lower reaction time, but it is also more stable over the control separations.

In summary, FOR HIGHER PROBABILITY OF DETECTION AND FASTER REACTION TIMES, A BIMODAL PRESENTATION SHOULD BE MADE. THE AUDITORY SIGNAL SHOULD BE THE ALERT AND THE VISUAL THE ACTION SIGNAL. THE TIME BETWEEN THE TWO SIGNALS SHOULD BE BETWEEN 0.1 AND 0.3 SECOND AND BOTH SIGNALS SHOULD APPEAR TO COME FROM THE SAME SIDE OF THE OBSERVER.

3.2 EFFECT OF ENVIRONMENTAL FACTORS ON DETECTION OF SIGNALS

The previous discussion has considered mainly the effects of different stimulus variables on the detection of signal stimuli, with only minimum regard to conditions present when the stimuli were presented. There is a vast amount of evidence that an individual's ability to detect a particular stimulus is strongly affected by:

1. Other stimuli or distractors that are presented at or about the same time
2. Cognitive workload imposed on the individual
3. Vigilant state of the individual

A short discussion of the information-processing characteristics of human beings will help clarify the role of distractors, workload, and vigilance on the detectability of signal stimuli. There apparently is a limited range of rate at which human beings process information most effectively (Poulton, 1960). When information is presented at rates slower than the optimum rate, an individual will tend to not monitor the information sources and misses a substantial proportion of the information that is presented. Information rates above the optimum range produce cognitive overload. Individuals under cognitive overload will miss part of the information that is presented and process some of the information incorrectly. At extremely high rates of information presentation, an individual's performance will deteriorate and the total amount of information that he processes will be less than when information is presented at an optimum rate.

The difficulty of any cognitive tasks affects the amount of externally presented information that an individual can process. An increase in the cognitive workload will result in a decrease in the amount of signal stimuli that an individual can process effectively. Usually, the signal stimuli that a person must process are presented along with numerous other irrelevant or distracting stimuli. The person must discriminate between signal and distracting stimuli before he can fully process the signal stimuli. The separation of the relevant from the irrelevant stimuli takes up part of the person's information-processing ability and reduces the amount of signal stimuli that he can process. Thus, both distracting stimuli and cognitive workload reduce the amount of signal stimuli that a person can effectively process.

3.2.1 EFFECT OF DISTRACTOR SIGNALS ON DETECTION OF SIGNALS

- THE CLOSER THE TARGET IS TO DISTRACTORS IN TIME AND SPACE, THE SLOWER THE RESPONSE.
- TACTILE DISTRACTORS ARE MOST DISRUPTIVE TO VISUAL SIGNALS.
- BIMODAL PRESENTATION OF SIGNALS IS SUPERIOR WHEN DISTRACTION IS PRESENT.
- SIGNALS MUST BE PRIORITIZED SO THAT LOWER PRIORITY SIGNALS MAY BE ATTENUATED.

Distracting visual, auditory, and tactile stimuli may all have an adverse effect on the detection of visual, auditory, and tactile signal stimuli. Table 4 is a 3 by 3 matrix of the nine possible combina-

Table 4 Combinations of Distractor and Signal Modalities that Could be Investigated

		DISTRACTOR MODALITY		
		VISUAL	AUDITORY	TACTILE
SIGNAL MODALITY	VISUAL	CRAWFORD 1962, 1963 ERIKSEN et. al. 1972 DOLEGATE et. al. 1973 SCHORI 1973 SHIFFRIN et. al. 1974	ADAMS et. al. 2962 SCHORI 1973 SHIFFRIN et. al. 1974	SCHORI 1973
	AUDITORY	ADAMS et. al. 1962 SHIFFRIN et. al. 1974	CHERRY 1953 EGAN 1954 POULTON 1953 SHIFFRIN et. al. 1974	
	TACTILE	SHIFFRIN et. al. 1974	SHIFFRIN et. al. 1974	

tions of distractor and signal stimuli that could be investigated and the studies relating to each combination. The literature search conducted for this paper did not reveal any single study covering all nine cells of the matrix. Therefore, a number of experiments, each of which covered only part of the cells, will be discussed. General conclusions based on these experiments will then be presented.

As stated earlier, the presence of either flashing or steady distractor lights adversely affects the detection of signal lights (Crawford, 1962 and 1963). These results were based on stimuli that were separated by more than 1° of visual angle. More recently, Eriksen and Hoffman (1972) investigated the effects of visual distractors that were placed as close as 0.5° of visual angle from letters used as visual signals. Either other letters or block discs were used as distractors. The distracting signal always occurred either simultaneously with or following the target signal. The time between the target and distractor varied between 0 and 300 msec. Figure 30 shows the results of the study.

As can be seen, THE MORE SIMILAR THE DISTRACTOR (LETTERS) TO THE TARGET, THE LONGER IT TAKES TO REACT. ALSO, THE CLOSER THE DISTRACTOR IS TO THE TARGET IN BOTH TIME AND SPACE, THE HARDER IT IS TO SEE THE TARGET. The longer the interval between the onset of the target and the onset of the distractor, the less effect any of the qualities of the distractor have on reaction time. At approximately 150-msec separation all the curves merge. Colegate, Hoffman, and Eriksen (1973) found a similar increase in reaction time to visual signals when more distracting letters were added to the display.

Adams and Chambers (1962) had subjects perform visual or auditory tracking tasks. The addition of irrelevant auditory distractors produced a detriment in performance on the visual tracking task. Likewise, irrelevant visual distractors degraded the performance on the auditory tracking task.

Schori (1973) compared the performance of visual, auditory, and tactile tracking tasks on a simultaneous secondary warning light monitoring task. The tracking tasks required the subjects to use a steering wheel in an automobile cockpit mockup to compensate for changes in a track produced by an irregularly shaped cam. The subject received a signal from the left side when he was too far left and a signal from the right side when he was too far right. The signals were either lights, white noise, or painless shock. The visual task–monitoring a warning light–employed small red lights on either side of the cockpit. The subject had to press a button each time a light on either side came on. Performance on the tracking task was equally good with all three types of displays. However, performance on the warning light monitoring task was poorer for the tactile tracking condition than for either the visual or auditory tracking conditions. There was no statistically significant difference between the visual and auditory tracking conditions on the warning light task. It was concluded that the detection of visual signal stimuli was more adversely affected by tactile distracting stimuli than either visual or auditory distracting stimuli.

One recurring finding in research on the detectability of signal stimuli in the presence of distracting stimuli is that BIMODAL PRESENTATION OF SIGNALS IS EQUAL TO OR BETTER THAN SINGLE-MODAL PRESENTATION OF SIGNALS (Adams and Chambers, 1962; Klemmer, 1958).

Buckner and McGrath (1961) had subjects perform a vigilance task in which each subject was presented 24 signals during a 60-minute session. For any one session, all of the signals were either (1) visual, (2) auditory, or (3) combined visual and auditory. The detection rate for all three types of signals was close to 100% at the beginning of the sessions and decreased over time. However, the minimum detection rate was higher for the bimodal signals (89%) than either type of unimodal signals (visual 72%, auditory 84%).

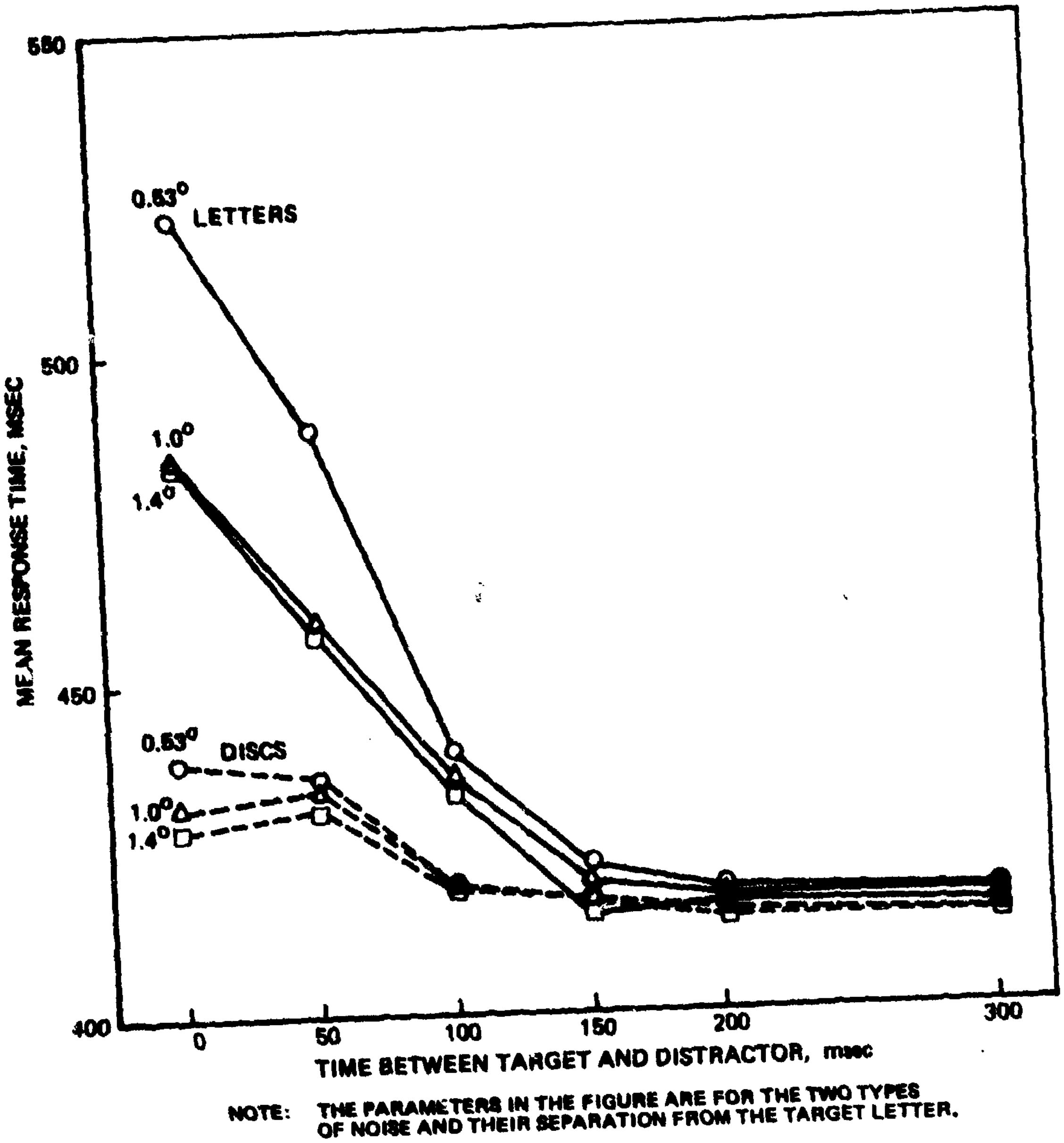


Figure 30 Mean Time to Vocalize the Target Letter as a Function of the Time Between the Onset of the Target and the Onset of the Noise Elements (Eriksen and Hoffman 1972)

A series of experiments was conducted by Siegel and Crain (1960) on the detection times of different cautionary signals in a flight task simulator. Under conditions where the visual and auditory inputs and tasks were comparable to flight conditions, the mean reaction times to auditory signals were faster than to visual signals (2.2 versus 2.70 seconds).

In summary, any kind of distracting signal will have a detrimental effect on the detection of any kind of warning signal. In the presence of visual and/or auditory distractors, the rank order of EFFECTIVENESS OF TYPES OF WARNING SIGNALS FROM BEST TO POOREST ARE: (1) TACTILE, (2) AUDITORY, AND (3) VISUAL. HOWEVER, TACTILE SIGNALS MAY HAVE A

MORE DISRUPTIVE EFFECT THAN VISUAL OR AUDITORY SIGNALS ON OTHER ACTIVITIES. Thus, it is quite likely that a signal's ability to penetrate distracting stimuli is directly related to its disruptive effect on other activities. Signals must be prioritized so that important signals temporarily attenuate other signals that could serve as distractors.

3.2.2 EFFECT OF WORKLOAD ON DETECTION OF SIGNALS

- OCCURRENCE OF A WARNING SIGNAL SHOULD SUFFICIENTLY CHANGE THE SENSORY ENVIRONMENT TO OVERCOME EXISTING WORKLOAD LEVEL.

Workload refers to tasks a person is performing when a signal is presented. The workload on an individual is dependent on the number of tasks that he has to perform in a given time period and the difficulty of these tasks. However, the most difficult aspect of this area is the measurement of workload. Rolfe and Lindsay (1973) wrote a paper to examine some of the techniques being used to study the demands of the work situation on the individual. Their emphasis was on aircrew workload. They felt that the measurement of workload was necessary because, to a large extent, the reliability of the man is a function of the load that is placed upon him. Inherent in this statement is the important point that the operator can be underloaded as well as overloaded. Workload is difficult to measure because of the wide range of physical and psychological factors, which imparts the loading of an operator. Conclusions that were made include: (1) performance measures should be supplemented by the addition of measures that can give an indication of the nature of the demands that the task imposes and the effort expended to meet the demand; (2) research indicates that no single supplementary measure can adequately provide information that satisfies both above requirements, and therefore a combination should be used; and (3) of the measures assessed, observation, subjective assessment, and physiological response are the most suitable techniques for use in the flight environment.

An example of workload measurement is presented by Rolfe and Chappelow (1973) where they had a four-man crew (pilot, copilot, navigator, and engineer) use a questionnaire to assess the workload incurred on a flight from Gander to Lyneham. The results of the assessment may be seen in figure 31.

Conrad (1951 and 1954) performed a series of experiments in which subjects had to detect and respond to visual signals on four clocks. The rate of signal presentation could vary from 40 to 160 signals per minute. The responses consisted of turning a knob under the clock where the signal occurred. As the number of signals and clocks to be monitored increased, the percentage of signals that were not detected increased (fig. 32).

The probability that a subject would miss a signal was increased more than twofold while subjects were responding to another signal. Under conditions of high task loads, some subjects attended to only part of the clocks and missed all the signals on the other clocks for up to 30 seconds. Also, some subjects would block and miss all signals under high task loads for up to 3 seconds.

In a later experiment, Conrad (1955) varied the number of clocks that had to be monitored from 4 to 16. Regardless of the number of clocks to be monitored, 25 signals were presented per minute. In this experiment, the amount of time between stimulus onset and response was recorded. Increasing the number of clocks to be monitored from 4 to 12 produced a twofold increase from 0.6 to 1.2

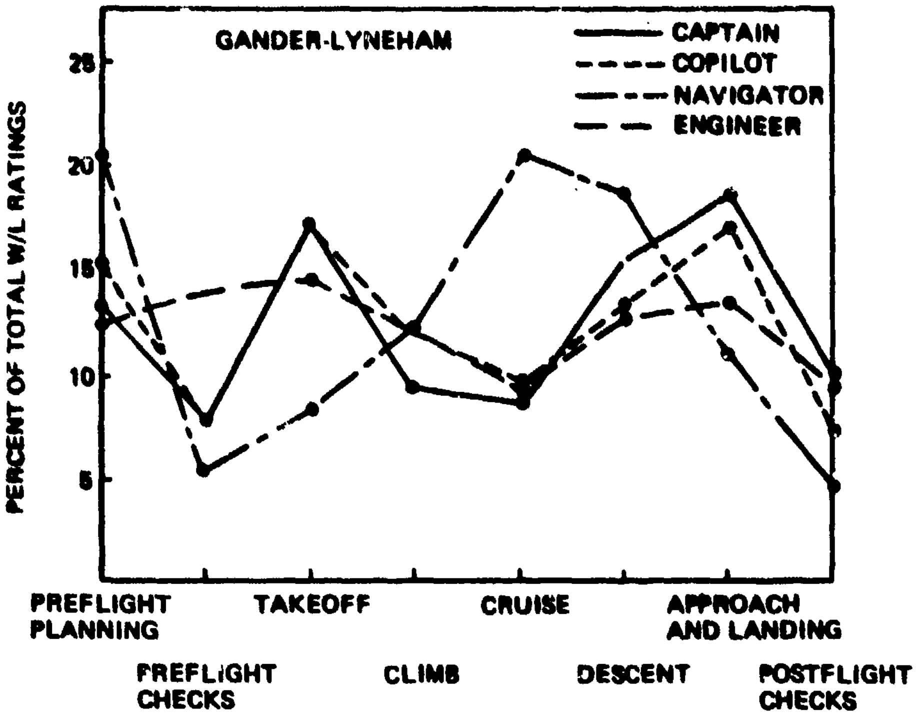


Figure 31 Patterns of Aircrew Workload (Rolfe and Chappelow 1973)

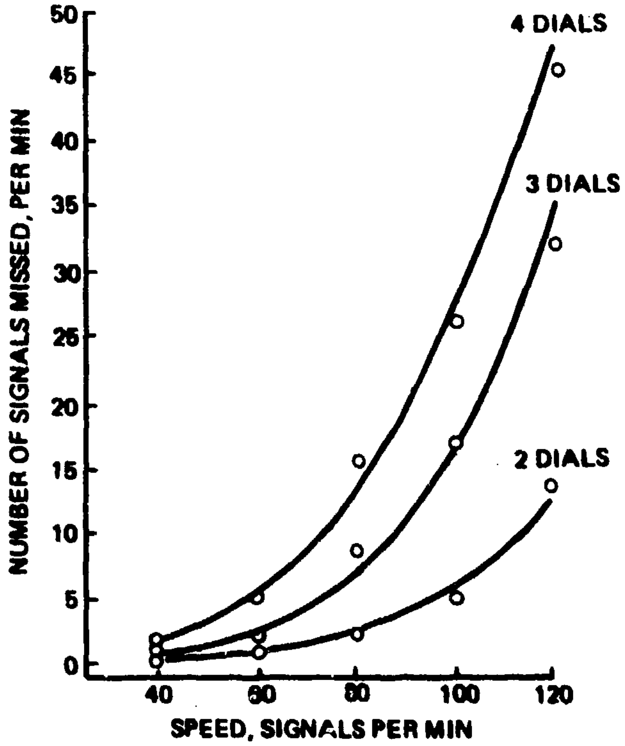


Figure 32 Effects of Speed Stress and Load Stress on Errors of Omission

seconds in the mean time from stimulus onset to response, even though the signal rate was held constant at 25 signals per minute.

Senders (1952) reported that an effective method to reduce the workload and, hence, the detection time for dial signal stimuli, was to have all pointers in the same orientation for no signal (or normal situations). Senders had subjects search for a dial pointer indicating a signal in arrays of dials. When the pointers that indicated no signal were aligned, each additional dial added approximately 0.01 second to the detection time. When the pointers indicating no signal were not aligned, there was an average increase of 0.18 second for each additional dial. The mean detection time for a pointer indicating a signal was 0.25 second for aligned no-signal pointers and 2.88 seconds for unaligned no-signal pointers.

In summary, THE HIGHER THE WORKLOAD IMPOSED ON A PILOT, THE MORE LIKELY THAT A SIGNAL (ESPECIALLY VISUAL) WILL GO UNNOTICED. WHEN POSSIBLE, THE OCCURRENCE OF A WARNING SIGNAL SHOULD SUFFICIENTLY CHANGE THE SENSORY ENVIRONMENT TO OVERCOME THE AMOUNT OF WORKLOAD IMPOSED AT THE TIME OF THE SIGNAL. Measurements of workload should be made and the effect of additional tasks and information should be determined.

3.3 EFFECT OF VIGILANT STATE OF OBSERVER ON DETECTION OF SIGNALS

- IF SIGNALS ARE WELL ABOVE THRESHOLD IN ALL PARAMETERS, THE VIGILANT STATE OF THE USER HAS LITTLE EFFECT ON SIGNAL DETECTION.

The probability that an observer will detect a particular signal will fluctuate considerably over time, even when signal and environmental conditions are constant. Changes in an observer's efficiency in detecting signals are usually ascribed to changes in the observer's state of vigilance. Vigilance tasks usually require subjects to detect brief, near-threshold signals. There are copious quantities of data indicating that low signal presentation rates have a detrimental effect on the detection of signal stimuli (Adams, Humes, and Stenson, 1962; and Adams, Humes and Sieveking, 1963).

Adams had subjects monitor a 22-inch screen on which either 6 (Adams et al., 1962) or 36 (Adams et al., 1963) aircraft symbols moved at constant speeds. Each aircraft symbol was identified by a letter and three numbers. The signal stimulus to be detected was a change in the identifying letter of one of the aircraft symbols from a G to an F. There were a total of 135 such signals presented during each 3-hour session. Each critical signal (the F) remained on for 20 seconds. The subjects indicated detection of a signal by moving their right hand (from a rest button) and pressing a button on a panel. The time from onset of the stimulus until the subject removed his hand from the rest button was called the detection time. The percentage of signal stimuli detected was high. The lowest percentage detection was for the condition with 36 aircraft symbols. Even in this condition the mean detection rate was 98.2% and the lowest rate for any one session was 97%. The mean detection time was dependent upon the number of signal sources (aircraft symbols) that had to be monitored.

When only six signal sources were monitored, the mean detection times were in the range of 1 to 2 seconds. The mean detection times for the 36-signal-source condition were in the range of 3 to 6 seconds.

Bowen (1964) used a simulated "noisy" radar scope on which a target signal, slightly brighter and larger than the noise spots, would appear. Each observer was to maintain a watch for the target signal and depress a button when he detected it. The observers experienced three different signal frequencies: 1, 10, and 20 per hour. The signals varied by having two different flash rates—a difficult signal with a duty cycle of 0.5 second on and 1.5 seconds off, and an easier signal with a duty cycle of 0.5 second on and 0.75 second off. The results of the study can be seen in figure 33. The only real drop in detection performance occurs with the most impoverished condition—a slow flash rate signal, which is difficult to detect, occurring after a considerable blank period. As the situation becomes richer in information, the detection performance is level over time and may possibly improve. Davenport (1968) showed the same effect by increasing the duration and intensity of auditory signals. It shall be noted that in these experiments the subject's sole duty was to detect the target stimuli that were all presented within a restricted area or time. In addition, visual and auditory distracting stimuli were kept to a minimum. Any additional tasks or the presence of distracting stimuli would be expected to produce a detriment in performance on the signal monitoring task. However, AS LONG AS A SIGNAL IS WELL ABOVE THRESHOLD IN ITS PHYSICAL PROPERTIES, THE DATA SEEM TO INDICATE THAT THE LENGTH OF THE TIME PERIOD IN WHICH THE SIGNAL MAY OCCUR (WITHIN NORMAL BOUNDS) WILL HAVE RELATIVELY LITTLE EFFECT ON ITS DETECTION.

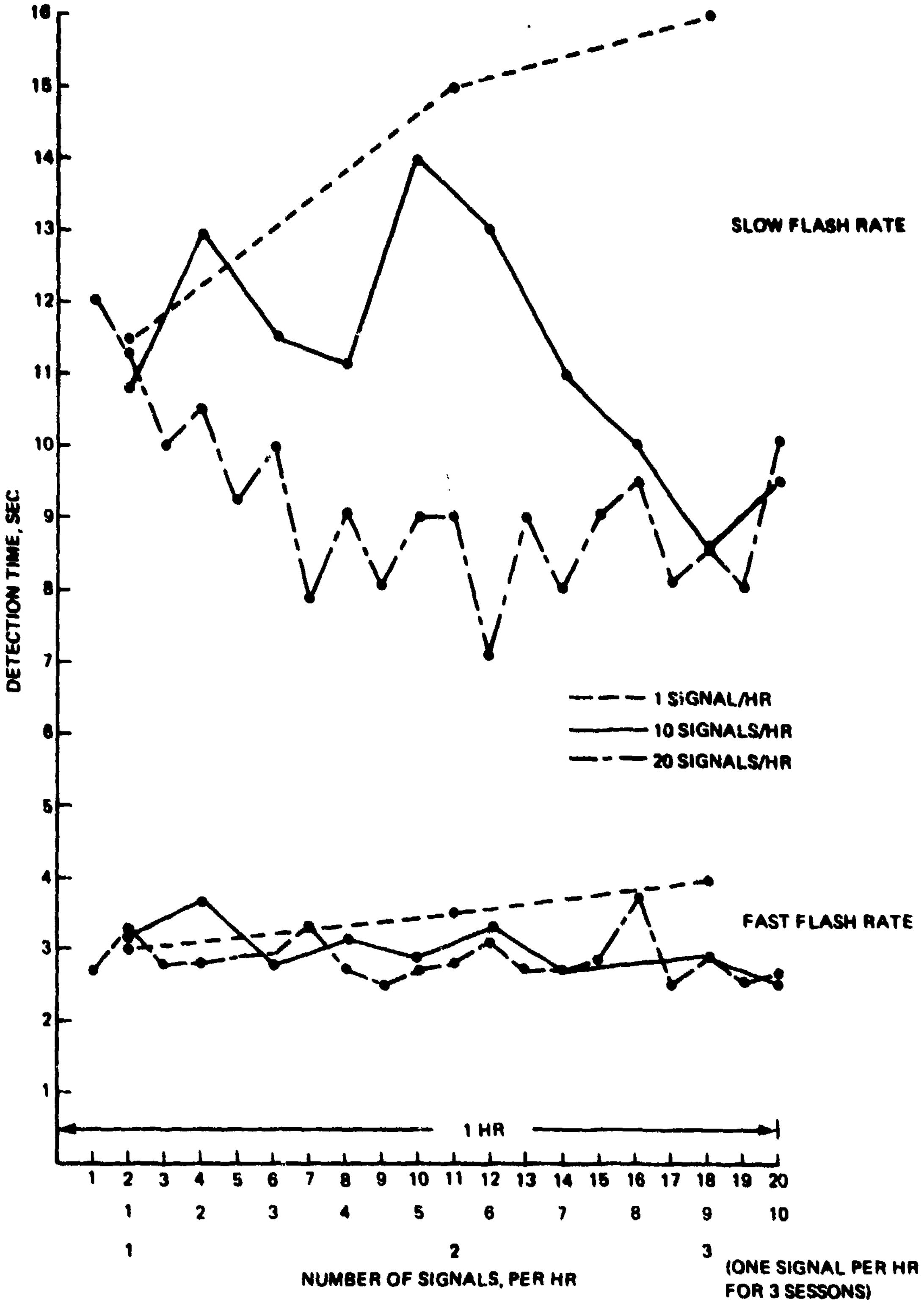


Figure 33 Signal Detection as a Function of Signal Frequency

4.0 FACTORS THAT AFFECT TIME FROM DETECTION TO RESPONSE

The above discussion has dealt mainly with the detection of signals. However, if a signal is to be effective, the person needing the information must both detect the signal and make the appropriate response. Therefore, the signal must convey information about the nature of the problem and/or tell the operator how to respond. There will always be a finite interval of time between the detection of the signal and the completion of the response. The length of this interval is dependent upon:

1. Signal-dependent factors
2. Environmental factors
3. Previous experience

4.1 SIGNAL-DEPENDENT FACTORS THAT AFFECT THE TIME FROM DETECTION TO RESPONSE

The major factors that affect the time from detection to response are:

1. Number of steps in the data collection
2. Length of the signal

A tabulation of response times obtained in the literature reviewed and the conditions under which those times were obtained was made for the purpose of detecting trends and unique characteristics of combinations of stimuli. These data are presented in table 5. From an overview of these data, it is obvious that tactile stimuli and a combination of visual/auditory stimuli produce the fastest response. However, the tactile stimuli are not recommended for alerting stimuli because of their possible disruptive effects (sec. 3.2.1). Of the combination visual/auditory stimuli, the visual/voice combination appears to be more effective than the visual /tone combination for complex information transfer. The data also indicate that voice stimuli consistently produce a faster response than visual stimuli.

4.1.1 EFFECT OF NUMBER OF STEPS IN DATA COLLECTION ON TIME FROM DETECTION TO RESPONSE

An operator cannot make a correct response to a signal until he knows what the proper response should be. If the initial signal contains adequate information, the operator may initiate action at once. However, if the initial warning does not give adequate information of the nature of the problem, then the operator must obtain more information before he can take correct action. Thus, the extra steps in the data acquisition will increase the time to the correct response. It should be noted that any time saved in gathering information about a problem and responding to it reduces the effective workload on the pilot, and increases the amount of time that can be allocated to other tasks.

4.1.1.1 Examples of How the Number of Steps in Data Collection Affects Identification Time

- VOICE MESSAGES MOST EFFICIENTLY TRANSFER HIGH-PRIORITY INFORMATION.

TABLE 5 TYPICAL STIMULI RESPONSE TIMES

NATURE OF STIMULI	RESPONSE TIME, SEC	TEST CONDITIONS
VISUAL VISUAL AND BUZZER VISUAL AND VOICE	12.12 4.02 2.40	TRACKING TASK; NO IMPACT ON CONCURRENT TRACKING TASK PERFORMANCE
VISUAL AND BUZZER VISUAL AND VOICE	4.57 1.94	TRACKING TASK; BETTER TRACKING WITH VOICE WARNING
VISUAL AND TONE VISUAL AND VOICE	9.35 7.89	
VISUAL AND BUZZER VISUAL AND VOICE	2.63 1.62	
VISUAL VOICE	128.27 3.03	HIGH-SPEED LOW-LEVEL MILITARY FLIGHT TESTS
VISUAL VOICE	44.05 2.93	VISUAL CONSISTED OF ANALOG INSTRUMENTS AND LIGHTS IN AN F-100 AIRCRAFT
VISUAL (STEADY) VISUAL (FLASHING)	2.0 1.3	HUMAN FACTORS TEST IN A STERILE LABORATORY ENVIRONMENT
AUDITORY VISUAL VOICE BUZZER	2.2 2.7 1.94 2.57	SIMULATION OF A TYPICAL COCKPIT ENVIRONMENT
TONE VOICE	9.35 7.89	F-111 SIMULATOR; EACH ALERT CONSISTED OF A MASTER CAUTION LIGHT, AN ALERT IDENTIFICATION LIGHT, AND AN AURAL ANNUNCIATION OF THE TYPE DESCRIBED TO THE LEFT
VISUAL AUDITORY TACTILE	0.494 0.453 0.381	NO LOADING
VISUAL AUDITORY TACTILE	SLOWEST FASTEST	NO LOADING EXCEPT VISUAL AND AUDITORY DISTRACTORS

The effect of the number of steps in the data collection was shown in a series of experiments by Pollack and Tecce (1958). The subjects in these tasks were required to detect and identify warning signals while performing a complex tracking task that involved watching a changing pattern of lights and making discrete changes in a joystick and rudder controls. The warning signals were presented on 24 visual displays (RCSGES "Magic Eye" tubes) that were arranged in 2 banks, 12 on each side of the tracking display. The signals for the monitoring task were enlargements in the opening of any one of the magic eye tubes.

When a warning signal was activated, the subjects had to first push a master button on the joystick and then press a button under the activated warning signal. The scores for the tracking task were the number of correct movements per minute (tracking score). The warning signal task was scored for time to press the button under the correct warning signal (identification time).

There were three different warning conditions:

1. Visual-only display

2. Buzzer and visual display

3. Voice and visual display

In the buzzer condition, a buzzer coincided with the onset of any visual warning signal. In the voice condition, the onset of a visual signal was accompanied with a specific vocal message telling which visual warning signal was on. The results of this experiment are presented in table 6. The differences between the mean response times for the visual-only condition and for the other two conditions were statistically significant. The difference between the response times for the buzzer and the voice conditions and the differences between the tracking scores for the three conditions were not statistically significant.

In a second experiment, the subjects were required to reproduce spoken messages as well as perform the tracking and warning signal monitoring tasks. In this experiment, the voice condition was superior to the buzzer condition on both detection and identification time (1.94 and 4.57 seconds, respectively). Pollack and Tecce ascribed the faster mean identification times in the voice conditions to the subjects getting enough information from the voice warning so that they did not have to scan the visual display before identifying the source of the warning.

Table 6 Mean Performance Scores for the Three Signaling Systems

WARNING SYSTEM	TRACKING MATCHES/MIN	DETECTION TIME/SEC	IDENTIFICATION TIME/SEC	TOTAL RESPONSE TIME
VOICE + VISUAL	8.44	1.44	2.40	3.84
BUZZER + VISUAL	7.87	1.26	4.02	5.28
VISUAL ONLY	7.30	11.16	12.12	23.28

Bate (1969) and Bate and Bates (1968) also researched the same signaling systems. Their findings differed somewhat in that the visual/tone system was more effective than either the visual or the voice/visual system. The possible reason for this finding was that the response task required the observer to look at a single annunciator panel to locate the signal. Therefore, the extra length of the voice signal did not give the observer any additional information over the tone. This finding supports the contention that voice systems should be used only when a complex response situation exists, and then only when speed and accuracy are essential.

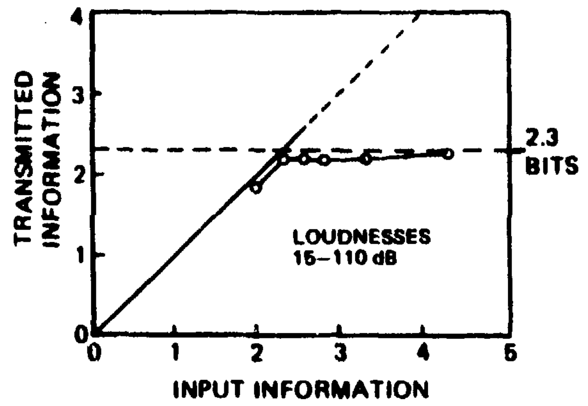
Kemmerling, Geiselhart, Thorburn, and Cronberg (1969) had 12 Air Force pilots fly a 100-nautical-mile simulated flight in an F-111 simulator. Equipment failure warnings were given the pilots at three points in the mission. Each failure was signaled to the pilots by a master caution light, a light on the annunciator panel, and an auditory signal. For one group of pilots, the auditory signal was a tone. For the second group of pilots, the auditory signals were voice recordings of the nature of the failure (voice annunciator). The mean response time to the three failures were 9.35 seconds for the tone warning group and 7.89 seconds for the voice annunciator group. The faster mean response times for the voice group were attributed to the pilots being able to respond immediately to the warning without scanning the annunciator panel for more information.

4.1.1.2 How Number of Variable Dimensions of Signal Stimuli Affects Number of Steps in Data Collection

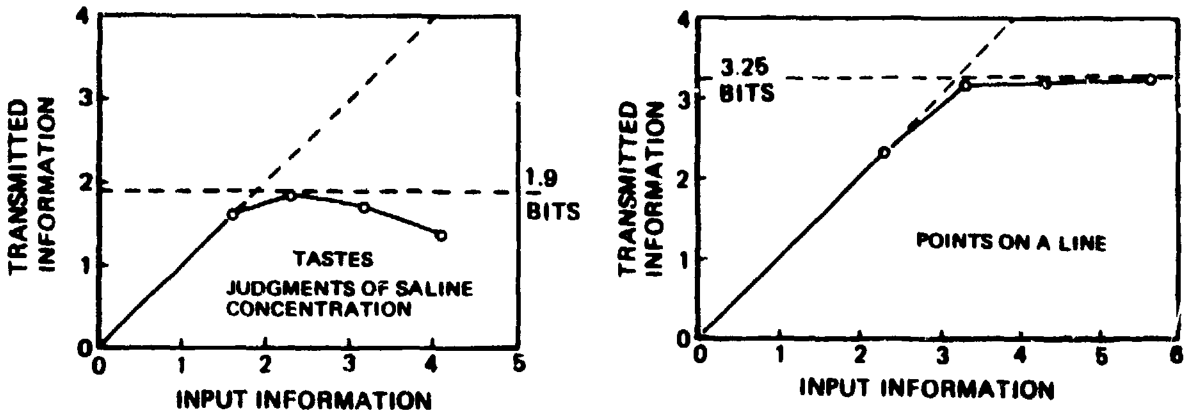
- FOR A SIGNAL THAT VARIES ON ONLY ONE DIMENSION, DO NOT EXCEED NINE DIFFERENT SIGNALS.
- VERBAL LABELS INCREASE THE NUMBER OF DIFFERENT SIGNALS THAT CAN BE IDENTIFIED.
- TACTILE SIGNALS ARE POOR FOR CONVEYING LARGE QUANTITIES OF INFORMATION.

The major factor in the number of steps in the information-gathering process is the amount of information in any one step. The major limitations on information transmission by signal stimuli are due to properties of human observers. Even though humans can make precise judgments about minute differences *between* stimuli, they are extremely limited in their ability to make absolute judgments *about* stimuli (Miller, 1956). In other words, when presented with two signals, a person can tell quite accurately whether they are different. For example, Shower and Biddulph (1931) reported that under ideal conditions listeners could detect frequency differences between tones as small as 2 or 3 Hz. However, when presented with single auditory signals that varied in only one dimension, he could identify the signals (by name or response) only as long as the number did not exceed 7 ±2 signals.

Miller (1956) supports this position by citing a number of experimental results (fig. 34). The data on information transfer in these experiments are given in "bits" of information. THE GENERAL RULE FOR THE DEFINITION OF A BIT IS THAT EVERY TIME THE NUMBER OF ALTERNATIVES INCREASES BY A FACTOR OF TWO, ONE BIT OF INFORMATION IS ADDED (e.g., two signals are one bit, four signals are two bits, eight signals are three bits, etc.).



NOTE: CHANNEL CAPACITY FOR ABSOLUTE JUDGMENTS OF AUDITORY LOUDNESS. (GARNER, 1953.)



NOTE:

CHANNEL CAPACITY FOR ABSOLUTE JUDGMENTS OF SALTINESS. (BEEBE-CENTER, ROGERS, AND O'CONNEL, 1955)

NOTE:

CHANNEL CAPACITY FOR ABSOLUTE JUDGMENTS OF THE POSITION OF A POINTER IN A LINEAR INTERVAL. (HAKE AND GARNER, 1951.)

Figure 34 Three Experiments on the Identification of Unidimensional Signals

Pollack (1952) found that listeners were much poorer at correctly identifying which one of a series of frequencies had been presented. Pollack also analyzed his data in terms of the number of bits of information conveyed by a particular set of tones. As the amount of information is increased by going from 2 to 14 different pitches to be judged, the amount of transmitted information approaches as its upper limit a channel capacity of about 2.5 bits per judgment, or 6 different pitches (fig. 35).

Fortunately, as Miller reports, there are some data on what happens when we attempt to identify signals that differ from one another in several dimensions. (A dimension is defined as any systematic difference between signal parameters, e.g., frequency, brightness, intensity, location, etc.) Klemmer and Frick (1953) tested the capability of humans to identify the location of a dot in a square. Their results are presented in figure 36. The 4.6 bits of information are 24 different positions that can be identified by name. Although this is an increase over a unidimensionally changing

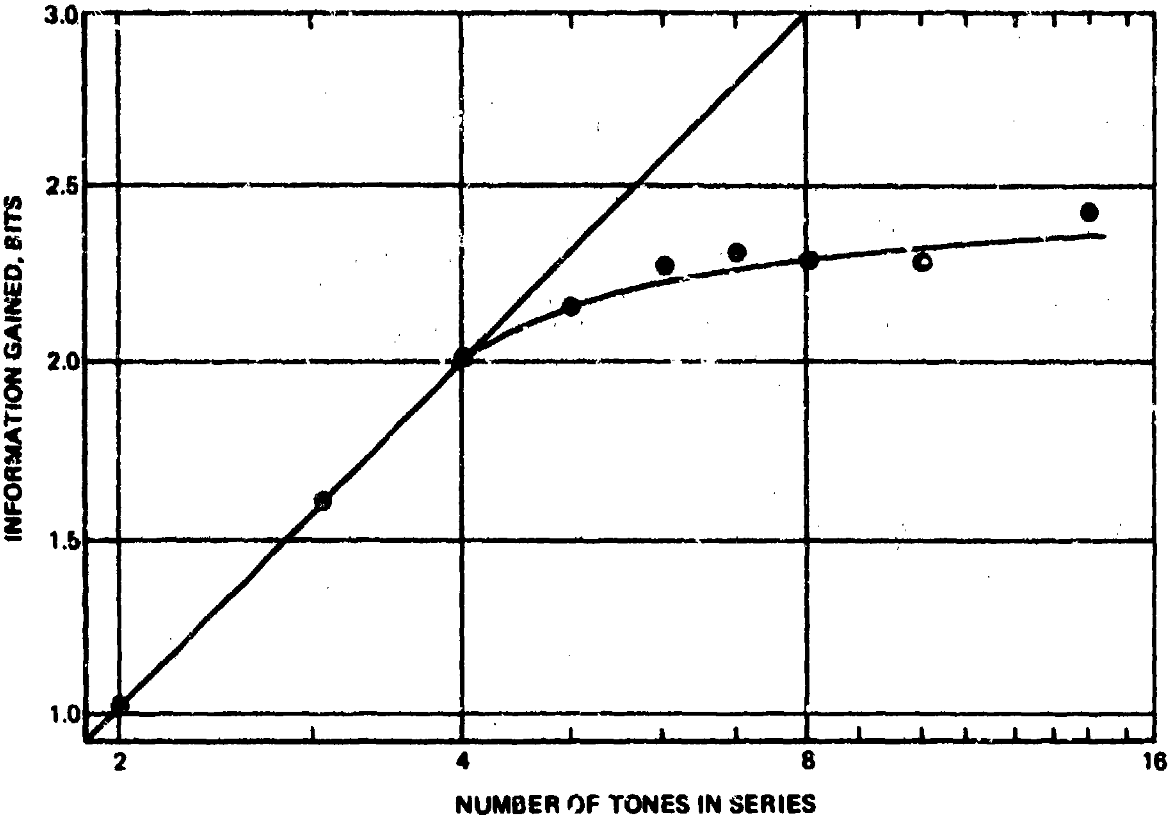


Figure 35 Information Transferred With a Series of Tones (Pollack 1952)

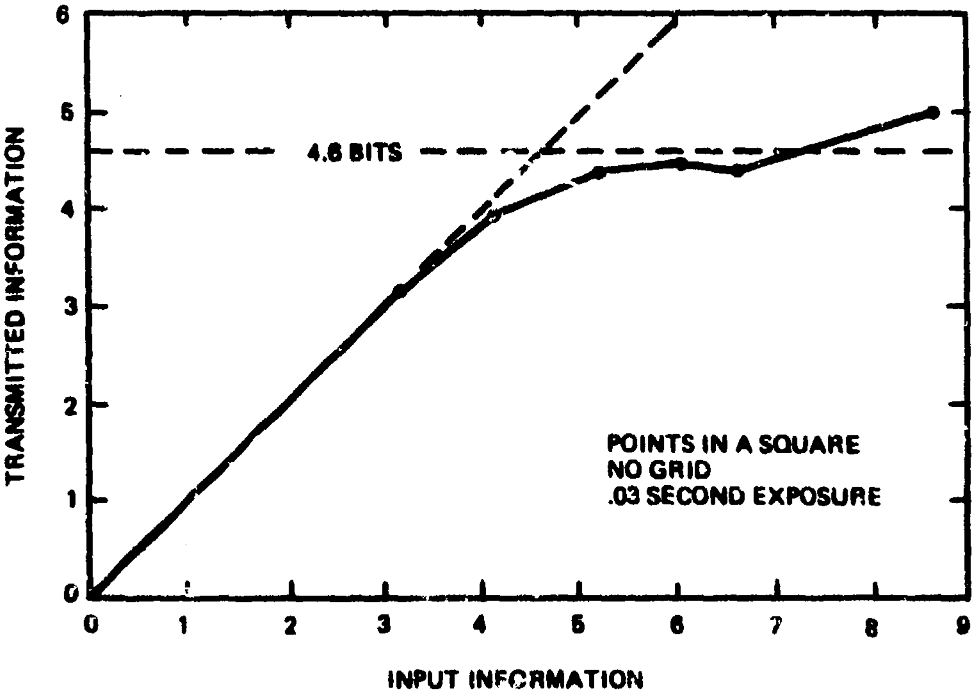


Figure 36 Channel Capacity for Absolute Judgments of the Position of a Dot in a Square (Klemmer and Frick, 1953)

signal, it is not as large as the expected 5.6 bits (2.8 bits or 7 locations from each dimension) or 49 different signal locations from a two-dimensional signal. It is, however, almost within the lower bounds of the range of 4.64 bits or 25 locations. The more dimensions the signal processes, the less efficient (relative to a perfect system) the identification process becomes.

Pollack and Ficks (1954) also found that increasing the number of dimensions on which sounds varied increased the total amount of information transmitted. However, THE AMOUNT OF INFORMATION CONVEYED BY ANY ONE DIMENSION DECREASED AS MORE DIMENSIONS WERE USED. With a six-dimensional auditory display, two-thirds of the listeners could receive 5.3 bits of information when each dimension was divided into two (binary) levels. The information conveyed was increased to 7.2 bits when five levels of each dimension were used. However, the error rate increased from an average of 2.9% per dimension for the binary display to 35.6% for the quinary display.

The disparity between the accuracy of making discriminations and making absolute judgments with auditory signals has also been found to hold for all other sensory changes (vision, touch, etc.) as well. However, the number of levels of signals that can be absolutely identified depends upon the channel and dimension tested. The highest information-carrying dimensions are the visual dimensions of linear position (3.2 bits; Hake and Garner, 1951) and hue (3.1 bits; Eriksen, 1952). One of the poorer dimensions is the tactile dimension of pressure (1.7 bits; Hawkes, 1961).

The tactile sense, because of its lack of dimensions that can carry information and the small number of absolutely identifiable levels of each dimension, is a poor channel for conveying large quantities of information. Vision and audition both have a number of dimensions that can convey information and therefore are often used to convey large amounts of information. Numerous visual and auditory coding systems have been devised and tested. Some coding systems involve unidimensional signals such as the sets of colors developed by Conover and Kraft (1958). Other coding systems have used combinations of dimensions. One of the most elaborate, and probably one of the most efficient, coding systems is the language used in daily communication.

In summary, the amount of information conveyed by any one stimulus dimension is extremely small. AS THE NUMBER OF VARIABLE STIMULUS DIMENSIONS INCREASED, THE AMOUNT OF INFORMATION THAT COULD BE CARRIED BY A SIGNAL WAS ALSO INCREASED. It was noticed by Pollack and Ficks that the high level of performance on the binary display was accomplished by the attachment of verbal labels to different signals. THE LISTENER'S PERFORMANCE SEEMED TO IMPROVE WHEN HE COULD IDENTIFY EACH SIGNAL IN TERMS OF A VERBAL LABEL. Visual and auditory channels can both accept a number of signal dimensions, permitting them to convey large quantities of information. The touch channel, on the other hand, does not possess this characteristic.

4.1.1.3 Voice Warning Systems

- VERBAL SIGNALS PRODUCE SIGNIFICANT IMPROVEMENT IN RESPONSE TIME, ESPECIALLY DURING PERIODS OF STRESS OR HEAVY WORKLOAD.
- WORDS IN SENTENCES ARE SUPERIOR TO THE SAME WORDS ALONE.
- USER MUST BE FAMILIAR WITH THE MESSAGES.

Under high-stress conditions, the audio-visual load on the pilot may reach saturation levels, causing a potential decline in efficiency and performance. Therefore, a system that can transmit warning information under these loads without degrading performance is essential. One way to accomplish this type of warning is to provide more information per message and allow the transmission of only absolutely essential messages. A warning system using voice messages to inform the pilot of aircraft status and incorporating a priority attenuation system meets these criteria. As it has been shown previously (Pollack et al., 1958; and Kemmerling et al., 1969), VERBAL WARNINGS PRODUCE SIGNIFICANT IMPROVEMENT IN RESPONSE TIME, ESPECIALLY DURING PERIODS OF HEAVY WORKLOADS OR STRESS. Even though this is an important aspect of a warning system, another one of the more important advantages is often overlooked. THE VOICE WARNING SYSTEM ALLOWS THE PILOT TO EVALUATE THE CRITICALITY OF THE SITUATION WITHOUT BRINGING HIS EYE SCAN BACK INTO THE COCKPIT. As in other real-time environments, the verbal warning should only be used in the highest priority situations, since overuse could detract from this impact.

There are two basic types of voice systems. The first uses prerecorded presentations of actual speech and requires a recorded message for each warning it is to present. It has the advantage that messages are close to everyday speech, and thus relatively easy to understand. On the other hand, it is difficult to centralize these voice recordings, and a technique for reliably and rapidly accessing a central unit has not, to the author's knowledge, been developed in a size that can be adapted to an aircraft cockpit.

Another system would use the onboard computer to control a voice synthesizer or digitizer to generate prestored warnings and recovery procedures. Since the computer is used, rapid access and a wider range of messages is possible. The major drawback with this system is that synthesized voice does not sound the same as "real world" speech. Much of the intonation is missing and some of the sounds are difficult for a computer to reproduce.

Simpson (1975) hypothesized that pilot experience with aircraft terminology and events that are likely to occur would tend to overcome this drawback. To test this hypothesis, she presented pilots and nonpilots (policemen familiar with radio communications) with 16-sentence-length messages, either synthesized or human speech. The messages were either in common or aircraft terminology and were matched for similar meaning. The observers were to repeat the messages after they were presented. (The correctness of their repetition was their articulation score.) Figure 37 shows results of the first presentation of the messages in this study. Although both groups of observers did less well on the synthesized speech with the common phraseology, they had equal articulation scores between them on each of the voice tapes (synthesized and human). This was not the case when aircraft phraseology was used. The pilots did better under this condition. In fact, the articulation score for the pilots using the synthesized voice system was equivalent to that of the nonpilot using the human voice system.

Another parameter of voice systems that must be considered when assessing and developing system effectiveness is the context of the messages. Simpson (1976) points out that WORDS IN SENTENCES ARE MORE INTELLIGIBLE THAN THE SAME WORDS PRESENTED ALONE. The reason is that real world context provides redundancy, which permits a person to miss a word and still make a relatively good guess as to what it was. This phenomenon can be seen in the previous study where pilots were able to perform better on a degraded system because they were familiar with the types of phraseology and context being used. Simpson poses the question: If familiarity

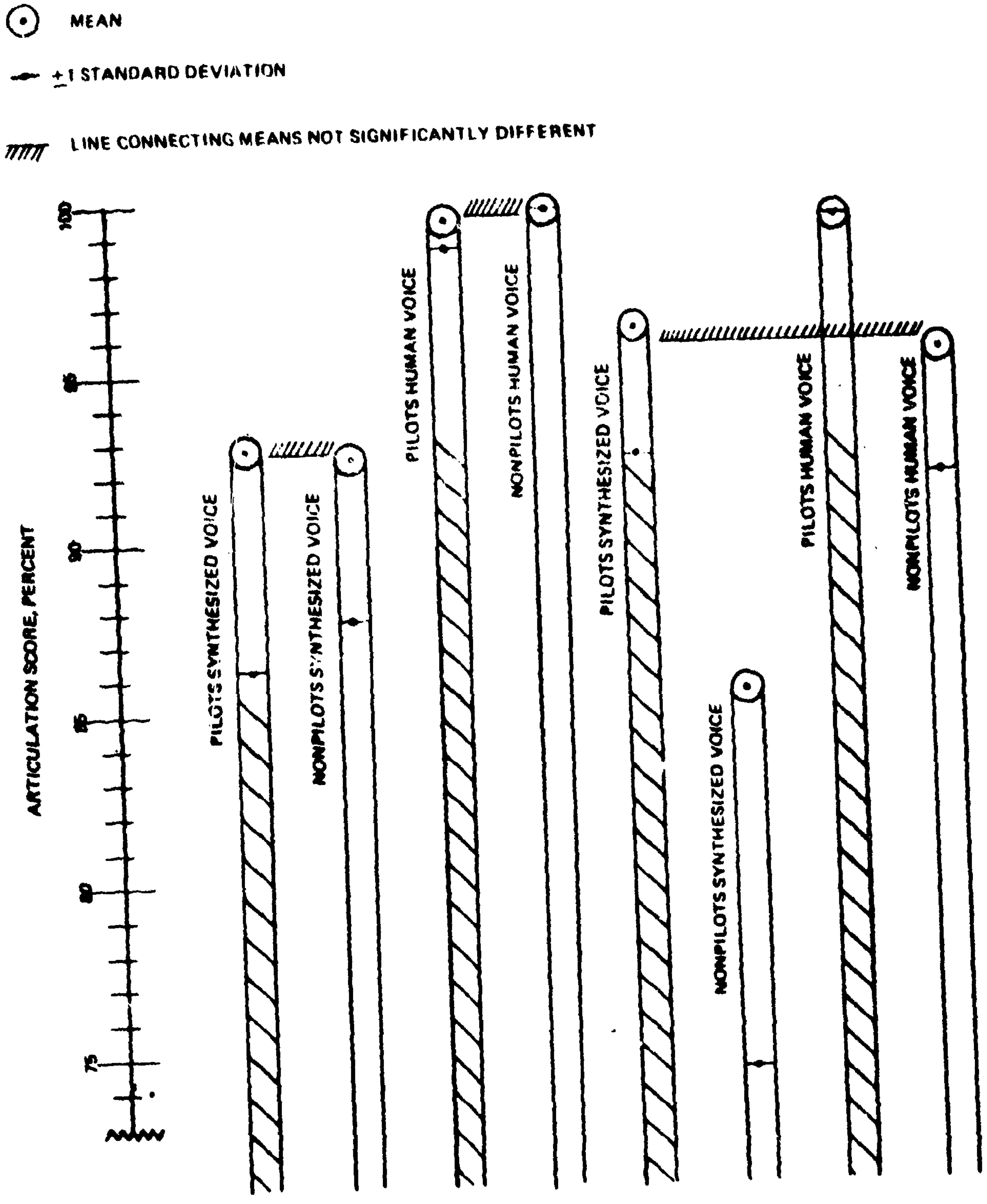


Figure 37 Articulation Performance on Two Types of Voice Warning Systems (Simpson 1975)

with the context of messages allows the operator to use a degraded system, can the messages be shortened to decrease response time and preserve adequate recognition performance? To answer this question, she presented voice-synthesized keyword and sentence-length messages to airline pilots in several signal-to-noise ratios under two conditions:

1. No familiarization with the actual message set before testing
2. Prior familiarization with all messages

For testing, the pilots were divided into two groups so that each pilot would receive each keyword message only once. One group would receive the words alone and the other would receive them in sentences. Each message was presented twice in succession. The pilots' task again was to key a microphone (the "understand" response used for response times) and repeat the message (articulation score). Simpson found that warning messages consisting of monosyllabic keywords were repeated more accurately over a wider range of signal-to-noise ratios when the words were in sentences than when they were presented alone (fig. 38). Polysyllabic words, on the other hand, did not show this tendency; the articulation scores for both sentences and isolated words were relatively the same (fig. 39). This seems to indicate the THE OPERATORS NEEDS SOME "WARMUP" OR ALERT TO THE VERBAL MESSAGE. The short, monosyllabic keywords did not give him enough time to prepare himself to receive the message. The response time results are presented by group in figure 40. As can be seen, these data closely follow the articulation scores.

In summary, VOICE WARNING SYSTEMS SHOULD BE USED TO REDUCE WORKLOAD UNDER HIGH-STRESS SITUATIONS. THEY SHOULD CONVEY HIGH-PRIORITY MESSAGES AND HAVE THE ABILITY TO ATTENUATE MESSAGES OF LOWER PRIORITY. THEY SHOULD CONTINUE UNTIL THE SITUATION INITIATING THEM IS CORRECTED OR SOME MULTISTEP PROCESS HAS BEEN USED TO CANCEL THEM. SINCE THEY DO INDICATE THE HIGHEST PRIORITY WARNINGS, FALSE SIGNALS ARE EXTREMELY UNDESIRABLE.

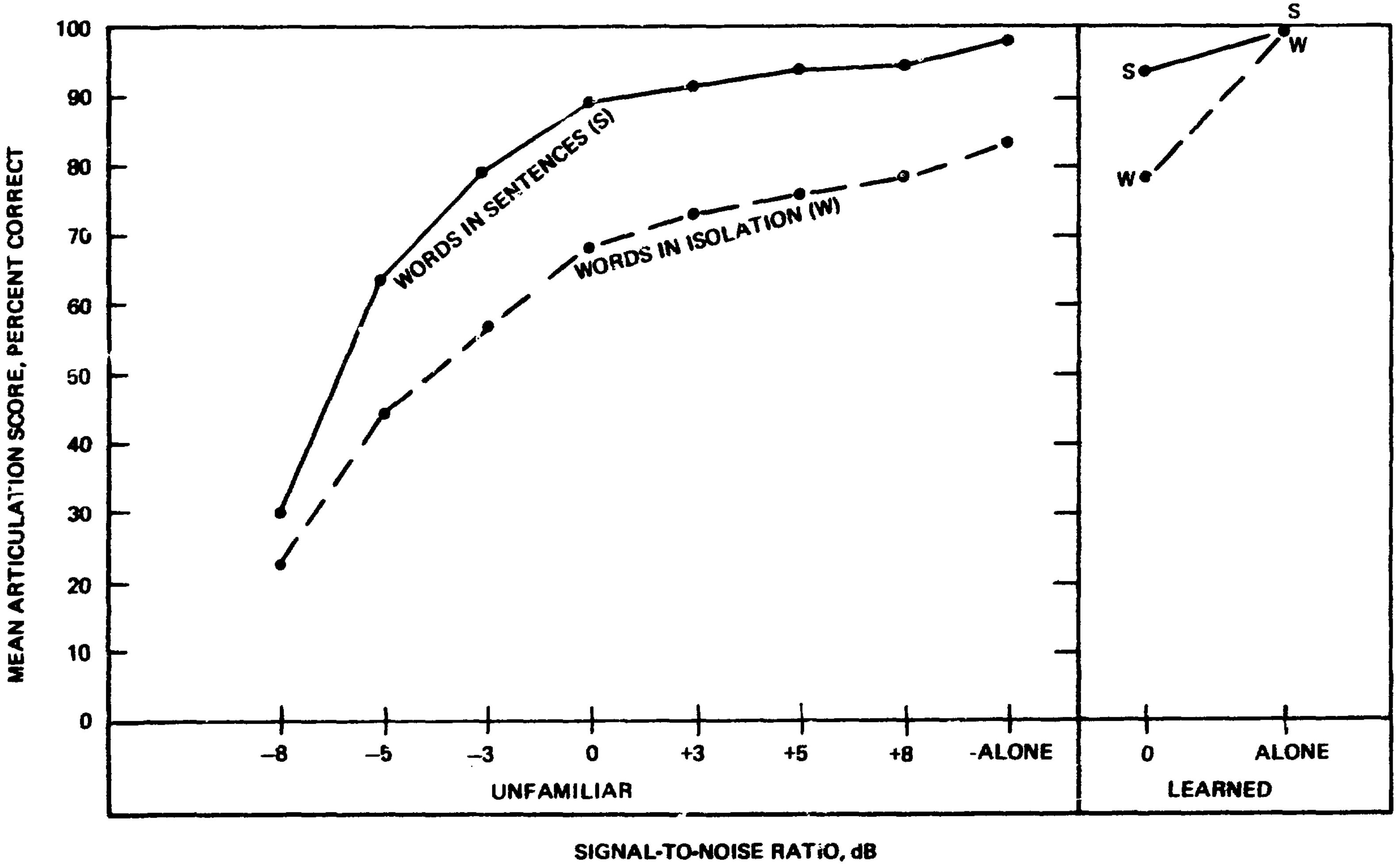
MESSAGES SHOULD BE CONSTRUCTED OF SHORT SENTENCES OF POLYSYLLABIC WORDS TO ALLOW THE PILOT TO MAKE USE OF THE CONTEXTUAL REDUNDANCY AND ALERTING NATURE OF THE LONGER MESSAGE. THE CONTENT AND TERMINOLOGY SHOULD BE FAMILIAR TO THE PILOT.

4.1.2 HOW LENGTH OF SIGNAL AFFECTS TIME FROM DETECTION TO RESPONSE

The time from detection to response is also affected by the time required for each step in the data collection. At each step in the data collection the observer must detect and locate a signal and then process the information in that signal. The time for each step is dependent upon (1) the time to process the information in the present step, and (2) the time to change from one signal source to the next one.

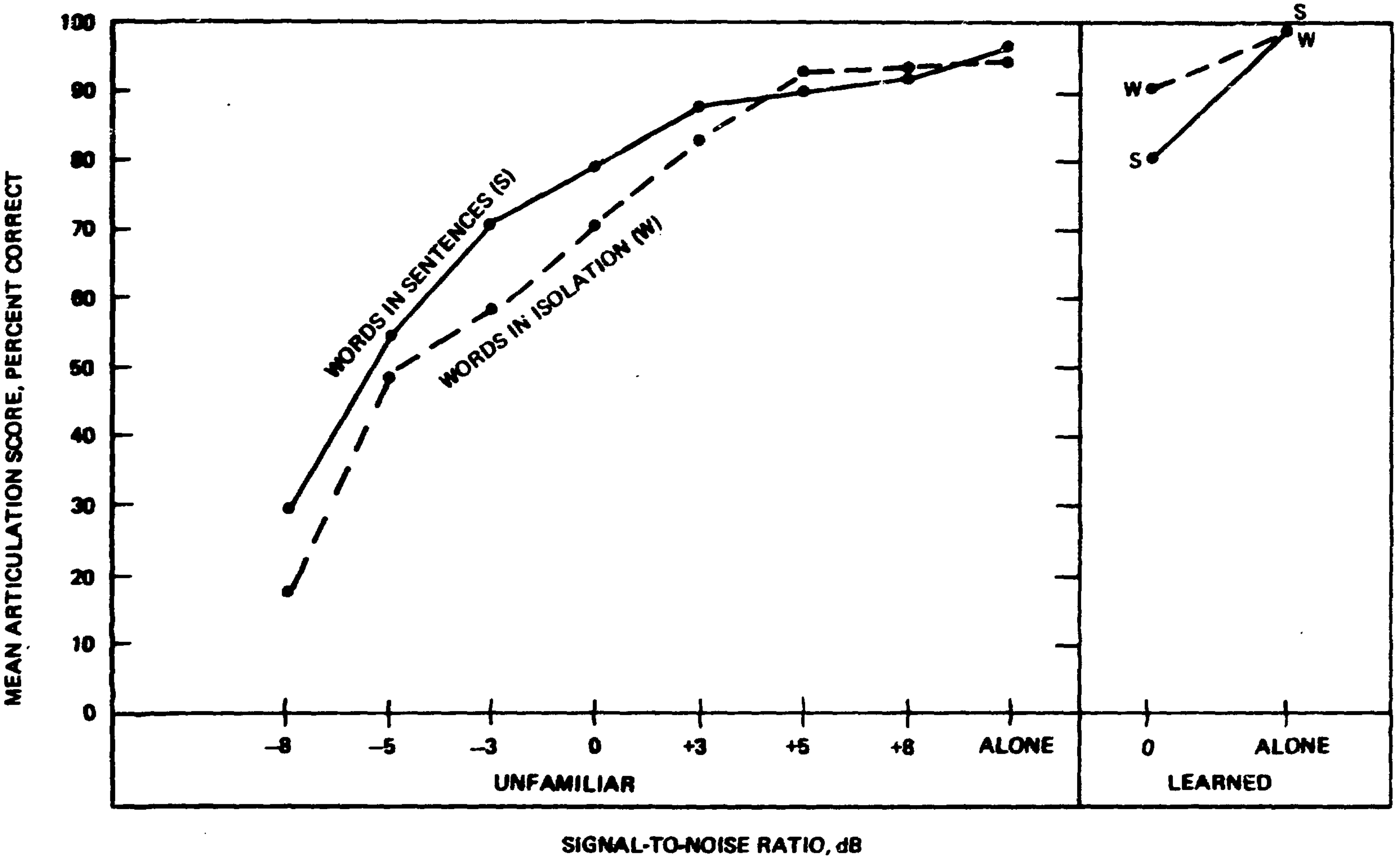
4.1.2.1 Factors That Affect Time To Process Information in a Step

- THE PRESENCE OF A MASTER WARNING DECREASES RESPONSE TIME.
- DARK LETTERING ON A LIGHTED BACKGROUND PRODUCES FASTEST RESPONSE TIME.



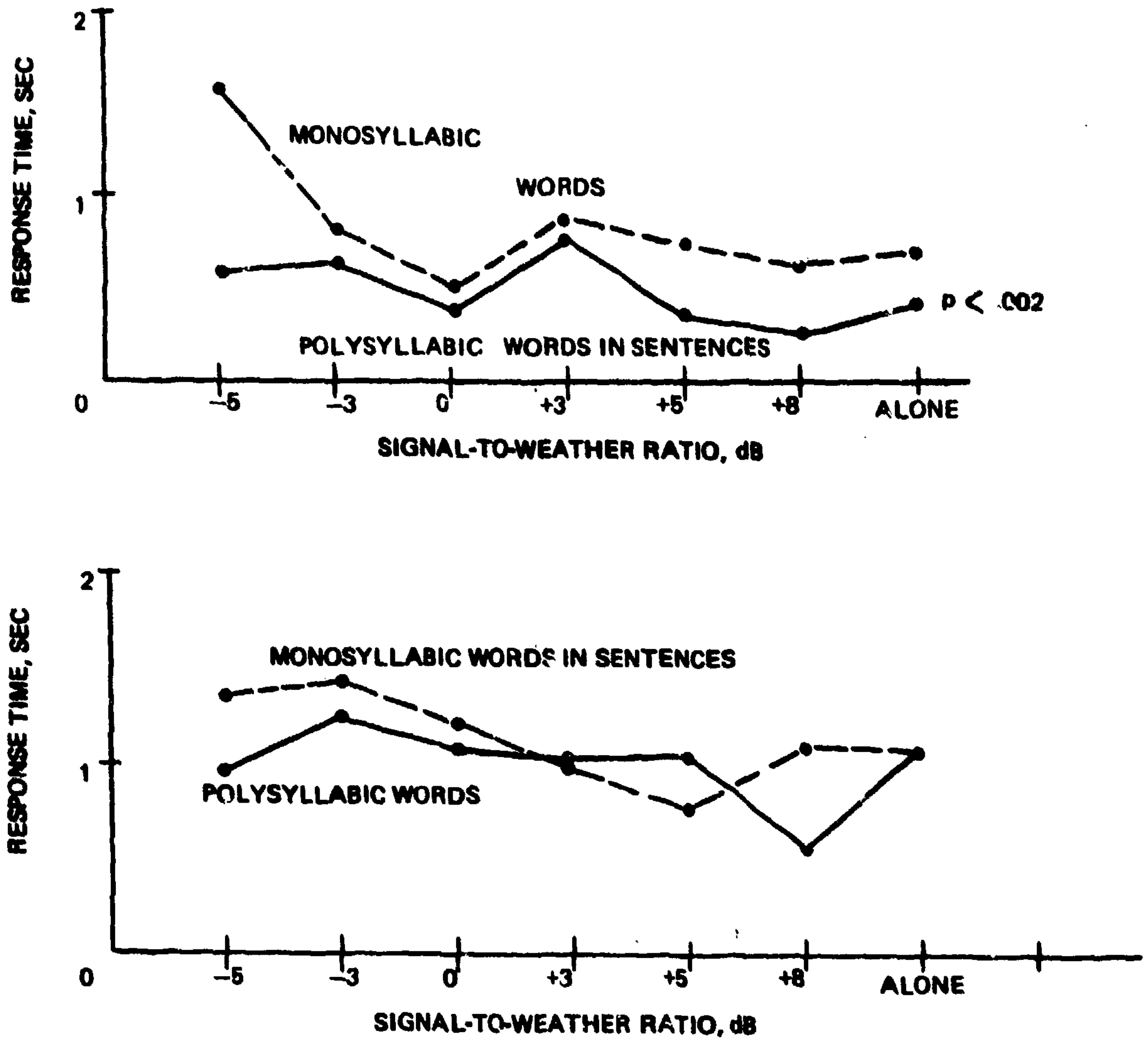
NOTE: MEAN ARTICULATION SCORES FOR KEY WORDS IN SYNTHESIZED SPEECH COCKPIT WARNINGS HEARD IN BACKGROUND OF CONTINUOUS WEATHER BROADCAST AT 7 SIGNAL-TO-NOISE RATIOS AND IN SILENCE. 8 AIRLINE PILOTS PER GROUP FOR UNFAMILIAR MESSAGES. 4 AIRLINE PILOTS PER GROUP FOR THE SAME MESSAGES LEARNED BEFORE TESTING. (SIMPSON, 1976.)

Figure 38 Monosyllabic Words: In Isolation and in Sentence Context



NOTE: MEAN ARTICULATION SCORES FOR KEY WORDS IN SYNTHESIZED SPEECH COCKPIT WARNINGS HEARD IN BACKGROUND OF CONTINUOUS WEATHER BROADCAST AT 7 SIGNAL-TO-NOISE RATIOS AND IN SILENCE. 8 AIRLINE PILOTS PER GROUP FOR UNFAMILIAR MESSAGES. 4 AIRLINE PILOTS PER GROUP FOR THE SAME MESSAGES LEARNED BEFORE TESTING. (SIMPSON, 1976.)

Figure 39 Polysyllabic Words: In Isolation and in Sentence Context



NOTE: RESPONSE TIMES FOR PILOT GROUP 1 (TOP) AND GROUP 2 (BOTTOM) CORRECTLY RECOGNIZED AND PREVIOUSLY LEARNED.

Figure 40 Response Times for Two Groups of Pilots and Messages of Different Contextual Makeup (Simpson 1976)

- HIGH PRIORITY LEGENDS SHOULD BE 0.125 TO 0.25 INCH HIGH WITH A HEIGHT-TO-WIDTH RATIO OF 5:3 AND A STROKE WIDTH 0.125 TO 0.166 OF THE HEIGHT.

THE HEIGHT OF A MASTER WARNING DECREASED THE RESPONSE TIME AS DOES A POSITIVE LEGEND DISPLAY. The 0.25-inch legend height appears satisfactory for displays consisting of black letters on an illuminated background (fig. 41). If time is not limited (i.e., advisory signals) 0.375-inch illuminated legends on a dark background may be used. The data for missed signals also follow this pattern (fig. 42). The percentages of misses for the negative display times master on-off were not included in this figure. For negative displays, 5.8% of the signals were missed with the master on as compared to 56.3% misses with it off. Positive displays incurred 3.3% misses with the master on and 20.4% with it off. What is interesting here is that WITH A MASTER SIGNAL, THERE IS VERY LITTLE DIFFERENCE IN THE RESPONSE ACCURACY BETWEEN POSITIVE AND NEGATIVE DISPLAYS.

MIL-STD-411D requires that warning legends be opaque with a translucent background. The legends will be from 0.125- to 0 25-inch high. Caution and advisory legends will be translucent on an opaque background and the same height. MIL-SPEC-18012B delineates the height-to-width ratio as 5:3 and the stroke width as 0.125 to 0.166 of the height.

4.1.2.2 Factors That Affect Time to Change From One Signal to the Next One

- FOR HIGHEST PRIORITY SIGNALS. THE PRELIMINARY SIGNAL (ALERT) SHOULD GIVE SOME INDICATION WHERE TO LOOK FOR THE ACTION SIGNAL.

- RAPID ALTERNATION BETWEEN SENSORY CHANNELS SHOULD NOT OCCUR, ESPECIALLY IN HIGH-STRESS SITUATIONS.

THE LONGEST TIME FOR SHIFTING FROM ONE SIGNAL TO ANOTHER OCCURS WHEN THE SECOND SIGNAL IS A VISUAL SIGNAL AND THE FIRST SIGNAL DOES NOT GIVE THE PRECISE LOCATION OF THE SECOND SIGNAL. For example, in the experiments by Pollack and Tecce (1958) discussed previously, subjects would receive either a buzzer warning or a voice warning of the existence of a warning light. In the buzzer warning condition, the subjects had to scan two visual displays for the warning light. The voice warning condition eliminated the need for the visual scan. The total mean reaction time was faster for the voice than for the buzzer condition by 1.62 seconds in one experiment and 2.63 seconds in a second experiment. The 1.62- to 2.63-second longer reaction times for the buzzer condition were a measure of the search time, or the time to shift from one signal to the next.

Klemmer (1956) gave observers tests in which they attempted to follow flashing lights and brief tones by pressing appropriate buttons. Only one channel was activated at a time and the rate of alternation between channels was varied systematically between tests. The rate of stimulus presentation in the active channel was either two or three per second in separate tests. Results indicate that forcing the observer to alternate regularly between visual and auditory tests more rapidly than once every 2 seconds lowers his overall performance on both tasks sharply (fig. 43). Therefore, GREAT CARE SHOULD BE TAKEN IN SELECTING SIGNALING SYSTEMS SO THAT A CONTINUOUS AND RAPID ALTERNATION BETWEEN SENSES IS NOT LIKELY TO OCCUR IN HIGH-STRESS SITUATIONS.

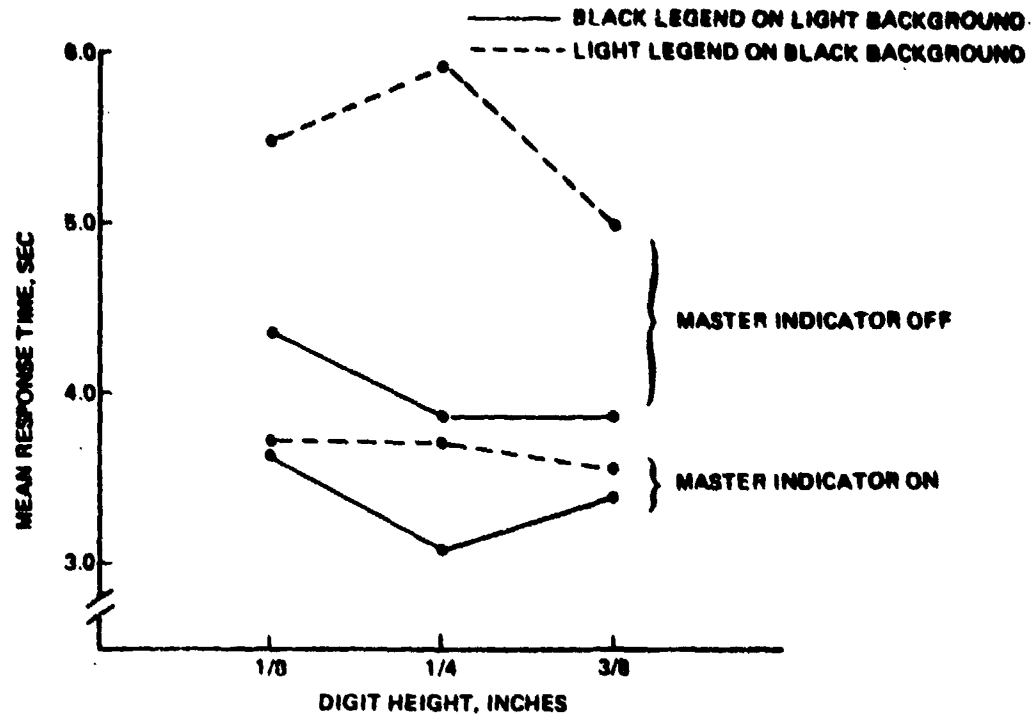


Figure 41 Mean Response Times as a Function of Legend Height and Polarity

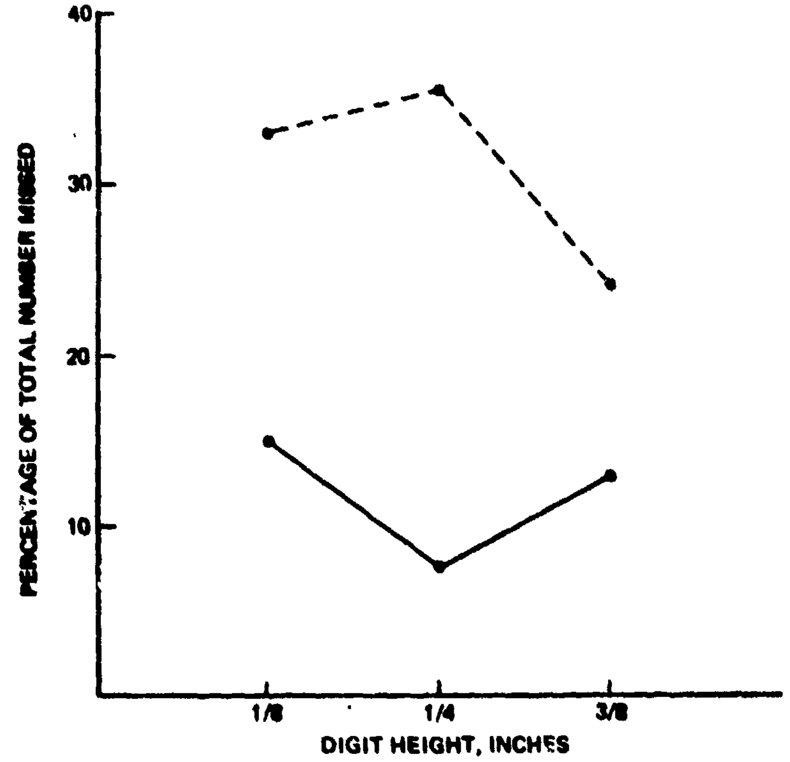
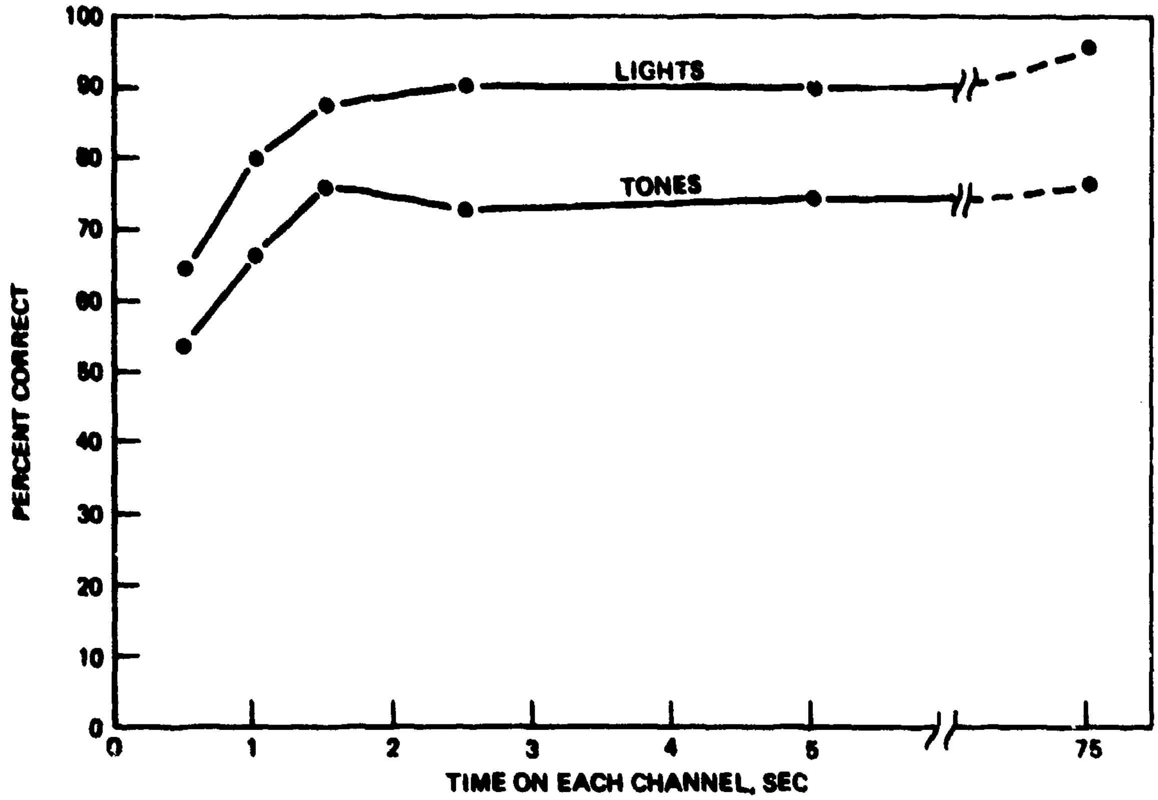


Figure 42 Accuracy of Definition as a Function of Legend Height and Polarity



NOTE: TWO-PER-SEC STIMULUS RATE.

Figure 43 Percentage Correct (Average for Three Subjects) During Alternation Between Auditory and Visual Channels as a Function of Time Between Alternations (Klemmer 1956)

4.2 EFFECT OF ENVIRONMENTAL FACTORS ON TIME FROM SIGNAL DETECTION TO RESPONSE

IN GENERAL, ANY ENVIRONMENTAL FACTOR THAT INCREASES THE DEMANDS ON THE OBSERVER WILL INCREASE THE TIME FROM SIGNAL DETECTION TO RESPONSE. An example of how the response to one signal can affect the reaction time to a second stimuli was demonstrated by Smith (1969). Smith presented two stimuli (S_1 and S_2) as numbers that subtended 9.5° of visual angle in adjacent windows directly in front of the subjects. The subjects had to push one of eight buttons in response to one stimulus and verbalize a name in response to the other stimulus. The response to either stimulus was dependent upon the number of possible responses to that stimulus as well as the number of possible responses to the other stimulus. As is shown in table 7, increasing the number of possible responses to S_1 increased the reaction time to both S_1 and S_2.

Table 7 Time for Responses to Two Stimuli

S1 ALWAYS PRECEDED S2 BY 60 msec

NUMBER POSSIBLE RESPONSES TO S1	TIME TO RESPOND, SEC RESPONSE TO S1	TIME TO RESPOND, SEC RESPONSE TO S2
2	0.48	0.62
4	0.59	0.72
8	0.67	0.78

4.3 EFFECT OF PREVIOUS EXPERIENCE ON RESPONSE TO SIGNALS

- ALL SIGNALS SHOULD BE STANDARD BETWEEN AIRCRAFT.
- CONFUSING SIGNALS SHOULD BE CHANGED.

Airplane pilot performance is strongly affected by skills learned previously in other situations. The effect of a previously learned skill on performance in a new situation is called transfer of training. There are two types of transfer of training—positive transfer and negative transfer. Positive transfer is any improvement in performance due to previous experience and usually occurs when the responses to be made in a new situation are similar to the responses made in a previous situation. Negative transfer is any detriment in performance due to previous experience and often occurs when the responses to be made in a new situation are different than the responses made in a previous situation.

Fitts and Jones (1961) made a classic study of the often disastrous effects of negative transfer on aircraft crew performance and found that the stimulus-response relationships were often not the same in different aircraft. For example, three types of aircraft (B-25, C-47, and C-82) each had the three controls of the throttle quadrant (throttle, fuel mixture, and propeller pitch) arranged differently. Pilots who usually flew one of these three types of aircraft would occasionally fly one of the other types. The pilot would sometimes make an incorrect response in the unfamiliar aircraft. Occasionally the pilot would operate the propeller pitch control when he wanted to increase the throttle. The resultant loss of airspeed was often fatal.

At present there are several different types of signals for a variety of conditions in aircraft. The use of signals is not rigidly standardized between aircraft. Thus, the steward's call in one type of commercial jet might be similar to the altitude warning in another type of commercial jet. A failure to respond to an altitude warning because it was identified as a steward's call could be disastrous.

To prevent misidentification of warning signals:

1. THE ALERTING SIGNALS IN ALL AIRCRAFT SHOULD BE STANDARDIZED.
2. OTHER SIGNALS THAT MAY BE CONFUSED WITH WARNING SIGNALS SHOULD BE PROHIBITED.

5.0 GUIDELINES FOR SELECTING ALERTING SIGNALS

The experimental results reviewed in this paper were used as guidelines on using time to detection and time for detection to an effective response as criteria for signal selection. As pointed out previously, the priority of a signal is based solely on the time a pilot has to respond before the point where his response will not change the outcome of the situation. Therefore, in the following guidelines the methods for minimizing detection and response times will be presented. These methods will pertain to high-priority signals, and for lower priority signals a less rigid criteria can be used.

5.1 GUIDELINES FOR MINIMIZING TIME FOR DETECTION OF ALERTS

- Present high priority alerting signals both visually and aurally (secs. 3.2.1 and 4.1.1).
    1. Maximize the probability of detection of each mode of the warning signal.
- The detectability of high-priority visual alerting signals should be maximized as follows:
    1. Present visual alerting signals as close to the operator's line of sight as possible. Maximum deviation of 15° for high priority alerts and 30° for lower priority (sec. 3.1.1.1).
    2. Visual alerting signals should subtend at least 1° of visual angle (sec. 3.1.1.2).
    3. Visual alerting signals should be twice as bright as other visual displays on the instrument panel (sec. 3.1.1.3).
    4. A visual alerting signal should be flashing against a steady-state background (sec. 3.1.1.4).
    5. High-priority visual alerting signals should be colored red, cautionary signals, amber, and advisory signals green or blue (sec. 3.1.1.5).
    6. Legends on high-priority signals should be opaque with an illuminated background. On lower priority signals the legend should be illuminated with an opaque background (sec. 4.1.2.1).
    7. Legend height should be at least 0.25 inch with a height-to-width ratio of 3:5 and a stroke width of at least 0.125 of the height (sec. 4.1.2.1).
    8. If visual signals are to be located in the peripheral visual field, a master signal should be used (secs. 3.1.1.2 and 4.1.2.1).
    9. False signals should be minimized and a method of canceling the signal should exist (sec. 3 [illegible]).
- The detectability of auditory alerting signals should be maximized as follows:
    1. Auditory alerts should be multiple frequency with more than one frequency in the range of 250 to 4000 Hz (sec. 3.1.2.1).
    2. The amplitude of an auditory alerting signal should be at least 15 dB above the amplitude of the masked threshold (sec. 3.1.2.2).

3. An auditory alerting signal should be intermittent or changing over time (sec. 3.1.2.4).
4. Auditory alerting signals should be dichotically separated from auditory distractors and noise. If dichotic separation is not possible, warning signals should come from a location that is separated by at least 90° from the sources of interfering noise or signals. In addition, if the location of both the source of the warning signal and the source of the interfering sounds are optional, the warning signal should be presented to the dominant ear and other sounds should be presented to the nondominant ear (sec. 3.1.2.3).
5. An attention-intruding signal (e.g., the person's name) should be given at the beginning of an alerting signal (sec. 3.1.2.5).
6. Exposure/time constraint must be followed on all levels of signal priority (sec. 3.1.2.2).

- The use of tactile alerts is not recommended due to the possible disruptive effects of tactile stimuli (sec. 3.2.1). However, if tactile alerting signals are used, then detectability may be maximized as follows:
    1. Tactile warning signals should be delivered by a vibratory apparatus that will always be in contact with the body (sec. 3.1.3.1).
    2. The amplitude of the vibration should be detectable by the region of the body that is stimulated (sec. 3.1.3.2).
- Other general guidelines are:
    1. A warning signal should be presented until the crew responds (sec. 3.3).
    2. Distracting stimuli and the workload should be minimized while warning signals are being presented (sec. 3.2.1).

5.2 GUIDELINES FOR MINIMIZING TIME FROM DETECTION TO EFFECTIVE RESPONSE

- The number of steps in the data collection should be minimized (sec. 4.1.1).
- Voice signals should be used along with visual signals (sec. 4.1.1.3).
- The effectiveness of voice signals may be maximized as follows:
    1. The language and phraseology should be familiar to the pilot (sec. 4.1.1.3).
    2. The message should be preceded by an alerting tone, word, or phrase (sec. 4.1.1.3).
    3. Synthesized voice systems may be used if every effort is made to simplify the communication task (sec. 4.1.1.3).
    4. The warning system should have capability of attenuating other voice systems while the warning is activated (sec. 3.1.2.3).
- A warning signal should not be confusable with any other signal (sec. 4.1.1.2).

APPENDIX A

This appendix contains a categorization of abstracted works pertaining to caution and warning systems. It also contains related military standards.

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Visual signals - size	Elliott 1968	For a simple reaction time* (RT) task, the RT for a 1^0 visual angle light was no different than for a 3^0 light *Simple reaction time is the time to react to a stimulus when that is the only task to be accomplished	Merriman 1969	Reaction time to Grimes warning lights (1/8" x 7/10" legend with border illumination, decreased as the width of the border increased leveling off at .75 sec for a width of 1/4"	MIL STD 411D	● A 3/16 inch border shall surround legends
	Freoberg 1907	Simple RT decreased as the size increased leveling off at 2^0 visual angle	Sheehan 1972	Response times to alphanumeric legends decreased as size increased leveling off at 1 sec for 1^0 visual angle		
Visual signals - brightness and contrast	Pabb 1962	Simple RT decreased as brightness increased leveling off at 180 msec for 30-ft-L. Signal size was 1^0 10 min of visual angle. Lighted signal was presented in a dark room.			MIL-STD 411D	● The legend on a signal when energized shall be readable under direct sunlight (10,000 ft-L) When not energized the legend should not be readable and shall not appear energized in direct sunlight.
	Rains 1962	Found that a 1.59 mL signal with a 4 minute visual angle and a .023 sec flash was the detection threshold for a white signal in a simple RT task. Lighted signal was presented in a dark room.				● Brightness shall be no less than 150 ft-L. Warning lights should be dimmed to 15+3 ft-L when the pilots primary instrument light control is "on". Advisory lights should be dimmed to 3+5 ft-L, when the primary light control is at max. intensity.
	Kohfeld 1971	Simple RT decreased as intensity increased leveling off at 220 msec between 1 and 100 mL for white light. Signal was presented in a dark room.			MIL-STD 1472B	● Brightness of rear lighted displays shall be at least 10^0 greater than the brightness of the area around the display. A dimming control should be provided.
	Hoyland 1936	Found that for moderate brightness levels there was no relationship between brightness and RT except for completely dark adapted subject who reacted to a 250 ft-C signal faster.			MIL-C 81774A	● Contrast between lighted and unlighted portions of a display, under high ambient illumination (10,000 ft C) shall be a minimum of 3 when calculated as: $C = \frac{E_1 - B_2}{B_2}$ B_1 = Brightness of illuminated portion B_2 = Brightness of unlighted portion
	Matteson 1971	A low level of brightness of the area surrounding the signal caused a small decrease in RT (25 msec) over no surrounding light. There was no further effect of surround on RT until the surround became brighter than the signal.				
	Teichner 1954	Simple RT decreased as intensity increased leveling off at 25 ft-C for larger objects (3-5.2 minutes visual angle) and 45 ft-C for smaller objects (1-2 minutes)				
	Gerathewohl 1953	Flashing signals produced faster RT (2 sec) than steady signals when contrast levels were less than one. For levels greater than one there was no significant difference between the signals for the lowest contrast $\frac{\text{(Signal Luminance − Background Luminance)}}{\text{Background Luminance}}$ Level (.15) the average number of misses for the steady signal was 50% and for the flashing signal was 5%.				
Visual signals - location	Coates 1972	For monocular viewing simple RT was fastest at the middle position +4° for the gazing scan pattern and at +24° for the scanning pattern	Rich 1971	Using very small (4 minutes visual angle) stationary targets 83% were detected when the target was on the line of sight and 35% when it was 30° to 40° left or right.	MIL STD 411D	● Normal envelope of vision for both pilot and copilot is a 30^0 cone symmetrical about a line from eye position to the top of the instrument panel

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Visual signals – location (cont)	Rains 1962	Simple RT for the right eye was fastest at 0° and increased as the horizontal angle increased. It had not leveled out at 30°. Signals to the left produced faster RT's than to the right and signals above horizontal produced faster RT's than those below.	Siegel 1960	Found that response to signals located at 0° horizontal displacement from pilot's centerline of vision was faster than to signals located at either 33° or 95°. Mean response time for signals at 95° was 1.2 seconds slower than for signals at 0°.		● Light signals shall not be located within the pilots or copilots basic flight instrument group when warning lights have to be located outside the 30° cone of vision a master signal must be provided within the cone.
	Sharp 1967	Using a sound as a cue for a visual signal found no difference in visual RT as the horizontal displacement of the signal increased from 0° to 75°.				● Except where specifically authorized advisory lights shall not be located on the main instrument panel.
	Sharp 1968	For visual RT with no auditory cue there was an increase in the RT variability as the horizontal displacement of the signal increased from 57° to 83°. However, the mean RT did not change over this range. The RT increased sharply at displacements greater than 83° and, 96°, 25 percent of the signals were missed entirely.			MIL-STD 1472B	● Viewing distance from eye reference to display shall not be less than 13 inches preferrably not less than 20 inches or greater than 2C inches.
	Haines 1975	Described zones of equal RT for different colored signals. The lowest RT zone (330 msec) for red lights covered a signal displacement of 30° left, 35° right, 20° up and 25° down. The lowest RT zone (270 msec) for white lights was from 45° left to 50° right and 20° up to 25° down.				
	Teichner 1954	Simple RT to a white light increased from .004 sec at 3° horizontal displacement from the centerline of vision to .024 sec at 45°.				
Visual signals – format	Crawford 1962	Used white signals with red and green distractors. Found no difference in a simple RT task between steady and flashing signals with no distractors. Flashing signals with steady distractor produced fastest RT.	Noble 1958	Alternating and flashing lights produced superior detection (not qualitified) in both day and night conditions. If a steady light was missed it was more likely to remain missed.	MIL-STD 411D	● Flashing light presentation shall have flash rates of 3 to 5 per second. The "on" time shall be approximately equal to the "off" time.
	Gerathewohl 1953	Flashing signals produced a faster response time (by 2 sec) when contrast levels were less than one. For levels greater than one, there was not a significant difference in response time to flashing and steady signals.				
	Edwards 1971	Built a reliable statistical model (utilizing paired comparison techniques) to classify flashing lights of various characteristics in order of their attention-attracting value.				
Visual signals – color	Coates 1972	Red lights were detected significantly faster than green in a vigilance task. However, the difference was only 17 msec.			MIL STD 411D	● Warning signals will have red background with opaque letters. Caution signals will have yellow letters with opaque background. Advisory signals will have green, blue or white letters on an opaque background.
	Jones 1960	Color coding is not suited for situations that demand rapid and precise identification but it is valuable in tasks that require a "locate" process.			MIL C 25050A	● Red lights shall not be yellower nor less saturated than the light transmitted by an NBS 3215 filter from a 2854°K source. Other colors are given as coordinates of the C I E chromaticity diagram.
	Weingarten 1972	Simple RT to a red light was significantly faster than to a green one. However, the difference was only 25 msec.				
	Haines 1974 1975	In a simple RT task, the RT to a red light was 16° slower than to green or yellow lights. RT was significantly slower (up to 28°) in the peripheral field. Red signals were affected more by displacement than the others in both RT and misses. The fastest RT (288 msec) was for yellow signals. 150 RT maps are provided for each color for the full visual field.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Visual signals – color (cont)	Pollack 1968	The effect of color on RT decreased as brightness increased and there is relatively little effect due to color above .0023 ft-L. For brightnesses where there was an RT difference due to color RT's increased as the spectrum went from blue to red.				
	Bartlett 1968	Simple RT to red signals was significantly faster at the line of sight than at a displacement of 12° horizontally.				
	Warm 1967	In a simple RT task during vigilance the RT to signal offset was faster than to onset. There was no difference in RT between red and green signals.				
	Reynolds 1972	Performed simple response time task varying signal color, background color, and ambient light level. A red signal on blue background with dim ambient resulted in the fastest response time (1 sec). Response time for red was the fastest (2.019 sec). The other colors were as follows: green 2.341 sec , yellow 2.992 sec and white 3.93 sec. Results indicate that red signals attract the greatest amount of attention.				
	Hill 1947	Detection thresholds for red, white, yellow and green lights were nearly equal over a range of background luminance from 10^{-6} to 10^{4} ft-C.				
Visual signals – workload, fatigue, and vigilance	Singleton 1953	Response time in a 4 choice task increased significantly from the first to the second half of the trails during a 1 hour test period.	Adams 1961	Contrary to experiments with only a single stimulus source there was no decrement in percent correct over a 3 hr period for more complex tasks (6 or 36 stimuli) Response latency declined significantly for the single stimulus task and not at all for the complex tasks.		
	McCormack 1960	Simple RT increased significantly throughout a 30 minute task.				
	Malomsoki 1970	Simple RT showed an immediate increase with physical exercise.				
	Crawford 1962	Found that simple RT doubles when going from 0 to 10 distractors (.8 to 1.5 sec) and trebles when going to 21.				
	Teichner 1974	Loss of detection performance on displays requiring no eye movement was relatively small over the 3 hour vigilance period.				
	Poulton 1966	Detection performance during vigilance will be better if the pilot s senses are kept active or if he is a member of a team.				
	Hyman 1952	Simple RT to a given signal increased as the information in the signal increased. A linear function was described for the relationship between RT and signal information (0 to 3 bits).				
	Bowen 1964	For a high probability event (20/hr) the RT (7 sec) was less affected by the time on the task than the RT (14 sec) for low probability events (1/hr).				
	Ware 1964	Detection decreased from 85 to 65 percent when going from 1 to 4 signal sources and a 5-10 percent decrease was observed over a 3 hr period for all conditions.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Visual signals - pilot age	Tolin 1968	Older subjects (66-87 years) exhibited a 30% slower RT and a 76% slower movement time. Increasing the task complexity did not have a differential effect for RT but the older subjects did show increasingly slower movement times.				
	Szafran 1969	Visual accommodation drops from 6 diopters in younger pilots (30) to 4 diopters in older pilots (45). Flash rate fusion frequency reaches a minimum at age 35 and increases with age. There is no evidence of change in dark adaptation. Information processing, effective auditory threshold or auditory detection.				
	Tallend 1966	Percent correct detections decreased significantly (10 to 15%) with age for a range of signal durations from .5 to 3 seconds.				
	Teichner 1954	Simple RT decreases to age 30 then increases. However, at age 60 it was still faster than at age 10.				
	Rabbit 1967	Subjects over the age of 60 do not get as much advantage out of redundant information as the 17-28 year olds.				
Visual signals - legend characteristics	Van Laer 1961	Visual acuity is satisfactory at brightness levels of .1 to .01 mL in a dark room.	Siegel 1960	Dark legend on luminated background was superior in both RT and accuracy to luminated legend on dark background. For dark legends with a height-width ratio of 5:3 1/4 in. height was superior to 1/8 in. but the same as 3/8 in. for a 28 in. viewing distance.	MIL-STD 411D	● For warning signals use a red background with opaque letters, for caution signals use yellow letters on an opaque background and for advisory signals use green, blue or white letters on an opaque background.
	Taylor 1961	Near threshold legends must be within 1° of direct line-of-sight. Legends must be twice threshold size when the displacement angle gets to 4°.	Bendix 1959	For dark legend on luminated background a bold character with a stroke width of 1/5 of the height should be used. For lighted legends a medium to light character style with stroke widths of 1/8 - 1/10 of the height should be used.		● Legends shall be 1/8 to 1/4 inch high. A 3/16 border should surround the legend.
	Peters 1959	Developed a height formula for legends where $H = .0022D + K_1 + K_2$. H = Height in inches D = Viewing distance K_1 = Correction factor for illumination & viewing conditions K_2 = Correction for importance	Brown 1953	The optimum height-width ratio for transluminated legends is 1:1 for uniform stroke black letters. The width should be no less than 2/3 the height use 9/64 in. height for the bulk of legends and 11/64 for emphasis for 28 in. viewing distance.	MIL-C 81774A	● Width of letters shall be 3/5 of the height except for "I" which shall be one stroke in width and the "M" and "W" which shall be 4/5 the height. Stroke width of the characters shall be 1/7 of the height.
			White 1960	At 28 in. viewing distance for critical markings legends height should be from .15 to .3 in. in low brightness (down to .03 ft-L) 4.1 in. to 2 in. in high brightness (down to 1.0 ft-L) and for non-critical markings it should be from .05 in. to .2 in. in any brightness.	MIL-M 18012B	● With a 28 inch viewing distance legend height shall be between .15 and .30 inches except critical markings which shall be no less than .2 inches. Width shall be 3/5 the height except "4" which shall be one stroke wider and "1" and "I" which shall be one stroke wide.
			Atkinson 1952	NAMEL style of legend produced fewer reading errors than either the Berger or the AND styles.	MIL-M 18012B	● Stroke width shall be from 1/8 to 1/6 of the height and shall be uniform. There shall be one stroke width between letters in a word and one letter width between words.
			Van Cott 1972	When legend is used to report status the legend should be lighted and the background dark.		
Memory for signals	King 1963	Found in 3 experiments that subjects could reproduce brightness, flash rate and duration up to 28 days after seeing the standard with little difference from a reproduction made 2 min. after seeing the standard signal. However, only brightness was not significantly different from the standard.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Auditory signals - format	Howarth 1961	A person has a lower recognition threshold to his own name than to other names.	Pollack 1958	Voice warning was superior to a buzzer in time to identify a malfunction. Voice warning was superior even when extraneous messages were presented	MIL STD 411D	● A non verbal audio master warning signal should (1) sweep from 700 cps to 1700 cps in .85 sec. (2) have interruption interval of .12 sec. (3) repeat until unit is de-energized. Actual signal specs are given in the standard for specific events.
	Moray 1959	When attending to one ear, a person can pick up messages in the other ear if the message is preceeded by his name.	Siegel 1960	A two tone master signal was superior to a single tone.		● Voice messages shall be used only for "hazardous or imminent catastrophic conditions requiring immediate action." They shall only be used in conjunction with red warning signals. They shall always start at the beginning of the message.
	Keuss 1972	By varying the intensity and interstimulus intervals of two auditory signals, found that simple RT to the second signal decreased leveling off at an 85 dB intensity and a 200 msec interval.	Simpson 1975	Familiarity with phraseology contributes to intelligibility. Pilots scored 96.4% correct on a synthesized speech system.	MIL-STD 1472B	● Audio warning signals should normally consist of 2 elements, an alerting signal and an action signal. With a two element signal a .5 sec alerting tone shall be provided. If speed is essential all information should be transmitted in the first 2 seconds, for a single element this time should be .5 sec.
	Geblewiczowa 1963	Auditory signals that are judged pleasant always give a slower RT than those judged unpleasant. There is an inverse relationship between RT and the number of ready signals (prealert signals).	Thorburn 1971	Experienced 358 pilots felt that a voice warning system contributes to flight safety, it reduces pilot workload.		● Tone frequency shall be between 200 and 5000 cps and shall be different from electrical power sounds in the system.
			Kemmerling 1969	Voice warning system allowed the pilot to analyze the situation without bringing his visual attention into the cockpit.		● Verbal signals shall consist of an initial alerting signal and a brief standardized speech message.
Auditory signals - workload, fatigue, and vigilance	Hohmuth 1970	When an auditory and visual vigilance task are performed simultaneously the performance on the primary visual task is not affected by the secondary auditory task. However, performance on a primary auditory task is affected by a secondary visual task.			MIL-STD 1472B	● For verbal systems a message priority system shall be established and more critical messages shall override less critical ones.
	Zwislocki 1956	Deterioration of the auditory threshold is linear with regard to the square of the time on the task.				
	McGrath 1965	Signal detections (recognition of change in signal state) decreased over a 90 min. period for both easy and hard auditory signals.				
	Davenport 1968	By increasing either signal duration or intensity the detection performance could be improved over an 80 min. test. General detection performance degraded with time.				
	Alluisi 1963	Even with high multiple (5) task activity auditory vigilance performance declined (number of missed signals increased) over a 4 hour period.				
	Pope 1962	Found no correlation between subjects visual and auditory vigilance performance.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Auditory signals – loudness and ambient noise	Egan 1950	Gives curves that show the masking effect of a 400 cps tone and a 90 cps band of noise at different levels of intensity.	Webster 1964	When either the speaker (microphone) or the listener (earphones) are in quiet, satisfactory intelligibility has been obtained to 125 dB jet noise. Good intelligibility has been obtained in noise by using a wide speech band-width (3 octaves) centered between 1000 cps and 1800 cps, using minimum or no sidetones, conforming AVC circuit to preferred listening levels, peak clipping of 12 dB at maximum power, having a flat response and minimum distortion in audio circuitry.	MIL-STD 1472B	• A signal to noise ratio of at least 20 dB shall be provided
	Fletcher 1933	Presents a definition of loudness and techniques for measuring it. Gives equal loudness contours for different frequencies. Demonstrates how to calculate the loudness of a complex tone.				• Verbal alarms for critical functions shall be at least 20 dB above the speech interference level.
	Hirsh 1950	When speech and noise are presented simultaneously, the lowest threshold to the speech occurs when the speech is presented directly to an ear and the noise is separated by at least 90°.	Van Cott 1972	A sound signal should exceed its masked detection threshold by at least 15 dB and the optimum sound level in noise is halfway between the masked threshold and 110 dB.		• Volume shall be designed to be controlled by the operator.
	Kohfeld 1969	Simple RT is inversely related to the intensity of a ready signal.				
Auditory signals – disruptive effects	Harcum 1973	Target detection deteriorated significantly in a 60-85 dB noise. A sorting task was not affected. When difficulty was rated both tasks were rated more difficult with noise.	Kemmerling 1969	Pilots presented a tone warning scanned the annunciator panel to determine the severity of the problem where those with a voice system did not have to.	MIL-STD 1472B	• Audio signals should not be of such intensity as to cause discomfort or "ringing" in the ears as an after effect.
	Glass 1972	Performance is less disrupted when the noise is seen as necessary.				• When audio signals delivered to a headset might mask other essential audio information separate channels may be provided.
Auditory signals – one vs two ears	Cherry 1953	Selective attention can be exhibited with very high accuracy when different information is presented to each ear. Subjects did not detect a language change in the rejected ear but they did detect a change from male to female and from speech to a tone. They had no trouble switching attention from ear to ear.			MIL-STD 1472B	• When earphones are worn a dichotic presentation should be used when feasible, alternating the signal from ear to ear.
	Egan 1954	When presenting a message and a distractor the message can be 30 dB less intense when each is presented to a different ear than when they are both presented to the same ear.				
	Gopher 1971	During selective attention there are significantly more intrusions from the interfering ear when it is the right ear than when it is the left. There is no difference in omissions.				
	Poulton 1953	When a message and distractor are presented simultaneous the predominant mistake is mis hearing.				
Auditory signals – signal number and memory effects	Miller 1956	For a signal that varied only in one dimension (frequency, intensity, duration, etc.) only 7 ± 2 signals could be identified accurately.				• When several different audio signals are to be used discriminal differences in intensity, pitch, etc. shall be provided. If absolute discrimination is required the number of signals shall not exceed 4.
	Pollack 1952	A trained listener can identify 40-60 sounds presented individually. However, subjects could only identify 5 tones which differed only in frequency.				
	Schulman 1970	When looking at the slope (m) of the line formed by relating the probability of false alarms to the probability of signal detection it was found that m increases with the increase in the probability of signal occurrence.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Auditory signals – signal number and memory effects (cont)	King 1963	Found in 3 experiments that subjects could reproduce loudness, frequency and duration up to 28 days after hearing the standard sound with little difference from a reproduction produced 2 min. after hearing the standard sound. However, all reproductions were significantly different from the standard.				
Auditory signals – effects of pilot age	ASA 1954	One of the more reliable signs of aging in males is a progressive loss of hearing in higher frequencies.				
Bimodal presentation visual and auditory	Klemmer 1958	Found no difference in the accuracy of response to three tones or 3 colored lights. When tone and light were presented simultaneously accuracy increased from 84% to 95%. Performance declined if senses were alternated faster than once every 2 seconds.	Bate 1969	Median response time was fastest to a tone-visual warning signal (1.7 sec) and slowest to a visual signal (4.5 sec).		• When used with a visual display audio signals shall be supplementary or supportive in nature.
	Morrell 1967	Simple RT to a visual signal decreased when the time between the visual signal and a following auditory signal decreased from 120-20 msec.	Siegel 1960	The fewest number of warning signals were missed when visual and auditory signals were presented together. For the individual signals auditory was superior to visual.		
	Morrell 1968	Simple RT was faster over a wider range of interstimulus intervals when the sequence was visual-auditory than when it was the reverse.	Bate 1967	Response time to a tone-visual warning signal was faster (6.7 sec) than to a visual signal (7.8 sec). However, missed targets in the primary task were much less for the voice (74) or tone visual (83) systems than for the straight visual (111).		
	Perriment 1969	In Bimodal presentations simple RT was faster when the two signals came from the same side.				
	Doumas 1969	Simple RT to a visual signal was fastest with a preceding tone of 400 msec length. RT was also inversely related to the intensity of the auditory signal.				
	Fidell 1969	Simultaneous presentation of visual and auditory signals improved detection sensitivity as much as 3 dB.				
	Gablewiczowa 1963	Simple RT is directly related to the interval between visual and auditory signals. A .5 sec interval produced the fastest RT when the auditory signal preceeds the visual.				
	Klingberg 1962	The probability of signal detection was significantly higher with a bimodal presentation. Detection was superior for auditory signals. Bimodal detection was the only task that did not deteriorate over the 1 hour test period.				
	Buckner 1963	Simultaneous presentation of visual and auditory signals improved detection probability during prolonged vigilance				
	Carroll 1973	Simple visual RT decreased from .49 sec to .27 sec with the introduction of a 60 dB tone.				
	Bertelson 1968	Simple RT to a visual signal decreased when preceded by a click (RT = 270 msec with a 20 msec interval and RT = 240 msec with a 150 msec interval). Simultaneous presentation produced a faster (20 msec) RT than no click.				
Tactile signals – detectability	Geldard 1957	The lowest vibration detected 100% of the time was 50 micrometers. In a range from 50 - 400 micrometers 3 levels can be identified.				

Area of concern	Author	Nonaircraft related test data findings	Author	Aircraft related test data findings	Mil std/ guide no.	Military standard/design guideline
Tactile signals – detectability (cont)	Geschneider	The intensity of vibrotactile signal is directly related to probability of detection and inversely related to RT.				
	Hill 1968	Tactile displays were correctly interpreted more often when their location was on a body part not involved in motion.				
	Shiffirn 1974	Performance was not reduced when 3 senses are used simultaneously for signals as compared to using senses individually.				
	Swets 1969	d' for a vibrotactile signal is linearly related to signal intensity.				
Tactile signals – effectiveness	Johnston 1972	Simple RT was fastest to tactile signal under all work-load conditions.				
	Davenport 1969	Bimodal presentation of auditory and tactile signals was superior to either individually. Auditory was superior to tactile.				
	Loeb 1962	Auditory signals were superior to tactile in both number of misses and RT. Tactile signals were more affected by vigilance.				
Tactile signals – signal number	Diespecker 1969	Subjects were able to learn a 9 element (3 intensities and 3 durations) code and perform over a range of durations.				

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APPENDIX B

This appendix contains a literature search bibliography of journal articles, reports, and warnings relating to aircraft alerting systems.

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