METHODS OF AUDITORY DISPLAY
FOR AIRCRAFT COLLISION AVOIDANCE SYSTEMS

by

Richard Glenn Hector

A Thesis Submitted to the Faculty of the

DEPARTMENT OF SYSTEMS ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 7 1

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED:

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

William R. Ferrell
W. R. FERRELL
Professor of Systems Engineering

July 15, 1971
Date

ACKNOWLEDGEMENT

The author wishes to acknowledge the following individuals for their assistance in carrying out the study:

Dr. William R. Ferrell, his thesis advisor, for his guidance.

Dr. Roger Weldon, Dr. Paul Skinner, and Dr. D. McClelland for their interest.

Miss Marilyn LeMoine and Mr. Richard English for their assistance as subjects in the experiments.

TABLE OF CONTENTS

TABLE OF CONTENTS--*Continued*

LIST OF TABLES

LIST OF TABLES--Continued

LIST OF ILLUSTRATIONS

ABSTRACT

When two aircraft are physically oriented so that continuation on their individual flight paths will result in collision, the final decision of the pilot to take avoiding action is most often based on visual detection of the other aircraft. Considerable laboratory experimentation has been conducted and reported on various aspects of visual detection, although little has been reported on methods to aid the pilot in visual searching. A head-up aid is desirable, rather than an in-the-cockpit display. For this reason, an auditory display was investigated. The display requires auditory localization in both the horizontal and vertical dimensions. Experimentation was conducted to determine physical factors of localization in the vertical plane. The results of the research and experimentation indicated that the external portion of the ear, the pinna, imposes a pattern of organization on the high frequencies of the sound whose source is located vertically. Specifically, this pattern is a shift in the dominant frequencies and attenuated frequencies with change in elevation. This knowledge allowed the proposal of a full two-dimension stereophonic auditory display for the pilot to localize the intruding aircraft.

CHAPTER I

INTRODUCTION

The purpose of this thesis was the conceptual development of a pilot warning display for reducing the incidence of midair collisions of aircraft. An auxiliary purpose in this research was to determine the physical factors of vertical sound localization.

The pilot warning display was conceptually developed as a component of the general class of systems known as Aircraft Collision Avoidance Systems. Categories within this class are: Pilot Warning Indicator (PWI), Collision Avoidance Systems (CAS), and Traffic Monitoring Systems (TMS). PWI generally refers to devices which aid visual detection of an intruder aircraft. Such instruments merely warn the pilot of the presence of other aircraft; though they may provide information on the intruder's location. The next higher category CAS, is intended to carry out more complex functions, such as discrimination between real intruders and ones which do not present any hazard. The highest category includes the concept of "preventive flying." Obviously, the more complex function the system has, the more it costs. Although there is much overlap in these categories, the pilot warning display proposed was directed mainly towards PWI.

In developing the pilot warning display, the decision was made to develop an "auditory" display. Other methods have been proposed, such as cockpit instruments which give azimuth and elevation of the intruder, or head-up displays such as the Matrix or Hedge display (Vallerie 1968). A relatively simple auditory display, called the Dunlap Auditory Display, has also been proposed. However, the auditory display proposed in this report is based on the natural localization ability of man. Such a system greatly increases the accuracy of location indices over the Dunlap Auditory Display. In addition, this allows the pilot to have a response to the auditory signal compatible with his habitual behavior rather than one learned for the specific purpose of localization. This should result in more reliable performance, especially in the stressful situations of potential collisions.

CHAPTER II

AIRCRAFT COLLISION AVOIDANCE SYSTEMS

The increase in air traffic and the concomitant increase of midair collisions have created a serious safety problem which demands an immediate solution. Aircraft accident reports indicate that the highest percentage of midair collisions occur in the vicinity of airports under good visibility and involve private light aircraft. In 1969, Aviation Week (1969) said "Typical midair collision in 1968 involved two general aviation aircraft, one with an instructor and student aboard, making visual flight rules approach to an uncontrolled airport in good weather on a Sunday afternoon in August." Many of these accidents could have been prevented if the pilots had been able to maintain adequate visual surveillance outside their aircraft, especially in terminal areas around airports. Adequate visual surveillance, however, is extremely difficult if not impossible since pilots must simultaneously attend to other tasks involving the primary control of their aircraft. Military operations, in particular, make surveillance of the outside airspace even more difficult since they usually require pilots to give the most attention to their cockpit instruments and little to the outside airspace. Many of the near misses reported in recent years involved military fighter aircraft at high speeds. Although less frequent, airline collisions are more disastrous, as was the 1960 Staten Island crash of a Constellation and a DC-8 which took 134 lives and the 1967 North Carolina crash which took 79 lives in a Boeing 727 and 3 lives in a Cessna 310 (FAA 1967). Collision avoidance appears to be beyond the natural ability of pilots, especially in view of their visual limitations and high workload requirements.

Pilot Warning Indicator

As mentioned in the introduction, Aircraft Collision Avoidance Systems can be divided in the order of ascending sophistication. The simplest system, PWI or the Pilot Warning Indicator (also called Proximity Warning Indicator) is intended for small general aviation aircraft and light military aircraft. The PWI equipped aircraft electronically "see" other PWI equipped aircraft. Generally, it is upward compatible so that it also sees CAS or TMS equipped planes. The PWI system gives the pilot an indication of the presence of an intruder within a predetermined range of his aircraft. National Business Aircraft Association's analysis (FAA 1967) indicates that information priorities for PWI are: (1) knowledge of presence of another aircraft, (2) relative elevation of the intruder, and (3), and perhaps equal, relative bearing of the intruder. Cost requirements of PWI must be in the $500 to $1000 range to be accepted and used by general aviation. NASA is convinced that there is no reasonable possibility at present of developing a successful passive or non-cooperative system (Brown 1967). At present, most work is directed towards developing a cooperative system in which all aircraft would have to carry a minimum amount of equipment. Some of the passive PWI work is being done on infrared detection which shows promise of being able to detect other aircraft under conditions of visibility less than required for visual flight. Most of the cooperative systems work on the concept of transponders and direction detectors. NASA's Langley Research Center has worked on a continuous-wave Doppler radar/transponder concept (Brown 1967). Another concept being evaluated is high-intensity xenon lights as a source of an active infrared system.

Collision Avoidance System

The next higher system in the order of sophistication is CAS, or the Collision Avoidance System. This system is intended for some military aircraft, executive-jet aviation, air taxis, and smaller air carriers. It includes a "threat evaluator" computer, which provides a defensive-flying capability by informing the pilot that he is in a threatening situation. This system is both upward and downward compatible. The system displays the optimum avoidance route, giving the pilot time to check the validity of the indicated evasive action. Cost of such a system is in the order of $30,000 to $100,000.

Traffic Monitoring System

The final order of sophistication is TMS, or Traffic Monitoring System. Although it is intended for larger air carriers and military aircraft, it will probably be introduced long after CAS is put into use. Hence, CAS would be utilized until TMS is fully developed. This system provides the feature of "preventive flying." The system allows the pilot to keep out of trouble of his own making by showing him where potentially dangerous traffic is located and how it is moving from moment to moment. The cost of such a system would be well over $100,000.

In both CAS and TMS, the pilot depends on the computer for the command to avoid the intruder. In either system, the computer may actually perform the maneuver, however, the pilot will generally want to validate the evasive action by his observation of the intruder. So even here, there exists the same demand for visual detection of the intruding aircraft. And although the auditory display system is proposed for PWI, it may have application in the more sophisticated systems.

CHAPTER III

PWI DISPLAY SYSTEMS

The sensors of the PWI system are expected to pick up an intruder aircraft before the pilot would normally see it visually. And when the aircraft becomes an intruder, the system must demand the pilot's immediate attention and aid him in the visual search. The display must minimize the time for the pilot to switch between the display and the visual search of the intruder. Hence a head-up display is most desirable, as it has been shown that the time required to shift fixation from the environment outside a cockpit to an inside instrument and then back again is in excess of two seconds (Wulfeck, Weiz, and Raben, 1958, p. 215).

Cockpit Instrument Display

Approaches to the design of PWI displays have generally been a combination of a simple auditory alarm for alerting the pilot and an instrument display giving azimuth and elevation of the intruder. Such displays may require several shifts of vision from the cockpit instrument to visual search. The accuracy of transferring instrument azimuth and elevation into visual position is unreliable. Saltzman and Garner (1950, p. 458) report that the accuracy of visual estimation of azimuth position has a standard deviation between 4° and 8° for azimuth angles between 15° and 100°. Thus this display is time-consuming and may be an inaccurate process. Furthermore, it increases the workload of the pilot since all intruders are not hazardous. Moreover, it would increase the workload in the vicinity of the airports where the workload is at its highest and where the potential of collision is at its greatest. Therefore, a display system which requires visual switching would waste time, interfere with the pilot's normal functions, and place the task of transferring the displayed position information to the outside environment on the pilot.

Head-Up Displays

An alternate approach might be to install a head-up projection display to reduce or eliminate the amount of visual switching involved in the detection of the intruder. However, the cost of such a system cannot be justified except in the commercial jet aircraft where CAS or TMS would be employed. In addition to cost, other factors must be taken into consideration. For example, the display should be capable of being retrofitted to all kinds of aircraft. Also, it must not interfere with existing cockpit instrument configurations.

Visual Head-Up Displays

Several methods which conform to these requirements were mentioned in the introduction (Vallerie 1968). The Matrix Display consisted of a matrix of "grain of wheat lamps" installed in the windshield of the aircraft. The pilot received an initial auditory warning and then located the intruder by searching the area about the flashing lamp in the windshield. Conceivable, range information could be encoded by varying the flash rate of the lamp. The second display mentioned, the Hedge Display (Heads-up, Edge Lighted) consisted of two strings of lights: one along the bottom of the windshield and another along the vertical frame. Again, initial warning was given with an auditory signal and the intruder was located by the intersection of perpendicular lines from synchronized flashing lights from the edge of the windshield. Multiple intruders would be kept separate by synchronizing the pair of lamp flashes for each intruder. The great limitation in both the Matrix and Hedge Displays is not obvious, although very critical. The display does not work unless the intruder is within the field of vision of the windshield. Both displays, however, are excellent in locating the intruder if he is within the field of vision.

Auditory Head-Up Display

The third display mentioned, the Dunlap Auditory Display, has similar pitfalls, although it had the potential to be omnidirectional. This display consists of three speakers mounted in the cockpit around the pilot: one on his left, one in front, and one on his right. Each speaker corresponded to a sector of airspace surrounding his aircraft, thus giving azimuth. Relative elevation was given by varying the pitch of the signal. If the intruder was at the same altitude, the signal remained at 2500 Hz. If the intruder was higher or lower, the pitch was swept either 500 Hz above or below the 2500 Hz signal. The Dunlap Auditory Display took twice as long to locate an intruder than did either of the spatial displays (Matrix or Hedge).

CHAPTER IV

AUDITORY DISPLAY SYSTEMS

Several a priori considerations suggest advantages of acoustic displays over visual displays. With lights near or on the windshield, the display requires reaccommodation of the eyes. The fact that the auditory display could be omnidirectional is very important. In addition, the ease of retrofitting aircraft with speakers makes it exceedingly attractive. And, for those pilots with earphones, additional gear for the "display" beyond that necessary to generate the auditory signal might not be necessary at all.

To improve over the basic Dunlap Auditory Display would be an easy task. Add more speakers and azimuth could be more accurately located. Sweep the base tone in proportion to relative elevation, and elevation could be more accurately located. However, azimuth could be located accurately by using the "stereophonic effect" known to hi-fi enthusiasts for years. This could be accomplished with earphones as well as speakers. It also seems that elevation information could be presented more naturally than by sweeping pitch up or down. If the apparent position of a signal could be made to vary up or down, then both azimuth and elevation of the intruder could be determined by locating the phantom sound source. Such a display would require no training, and no time would be lost in decoding the display information into location. Hence, the acoustic display may aid the visual search to a point where looking in the correct direction for detection of the intruder would be automatic.

CHAPTER V

EXPERIMENTAL PROGRAM

The experimental program was conducted for the purpose of understanding vertical localization and to attempt to create a phantom vertical sound from a stationary sound source. Since much recent work has been performed on sound localization in the equatorial plane and on the creation of phantom sound in this plane, no other experimentation was necessary.

The experiments on vertical localization are grouped into two basic types: (1) localization of an actual sound source, and (2) localization of a phantom sound. Experiments on localization of an actual sound source (Chapter VI) were conducted to determine how well sound can be located in the vertical plane. Experiments on localization of a phantom sound source (Chapter VII) were attempts to cause a stationary sound source to be "located" at phantom positions. Not all experiments were original, but some were conducted to establish standards on the abilities of the listeners. These standards were then used to compare the results of different experiments. This procedure was adopted because time was limited and also because both experiments and literature searches were being conducted at the same time. Hence, Chapters VI and VII are interwoven with both the experiments and reports found in the literature search. This is both logical and necessary to show the reasons and background for each experiment and to show the development of the experimental program.

Method Of Analysis

All experiments had a basic input-output relationship; that is, a sound presentation was made (input) and the subject attempted to locate the sound source (output). The results were then evaluated by forming a contingency table, whereby responses were matched with presentations (Appendix A). Average values and standard deviations of the responses for each different presentation are then made, e.g., Table I.

Table I

Sample Listing of Contingency Table

	Input								
Output	1	2	3	4	5	6	7	8	Total
1	0	1	0	0	0	0	0	0	1
2	1	1	0	0	0	0	0	0	2
3	4	1	2	0	0	0	0	0	7
4	2	0	4	2	1	0	0	0	9
5	1	4	3	2	3	1	1	1	16
6	2	0	1	4	6	1	2	1	17
7	0	2	0	1	0	5	4	2	14
8	0	1	0	1	0	3	3	6	14
Total	10	10	10	10	10	10	10	10	
Avg	3.9	4.8	4.3	5.7	5.5	7.0	6.9	7.3	
Std Dev	1.3	2.1	.9	1.2	.7	.9	.9	1.0	3.4

Input number refers to actual position level or to stimulus I. D. number. Output number refers to listener's response to the apparent position.

The square root to the total sum of the squares of standard deviations, $\sqrt{\Sigma\sigma_i^2}$, is printed at the end of the row of "STD DEV". Following this table, average input value and its standard deviation, and average output value and its standard deviation are optionally printed; e.g., Table II.

Table II

Sample Listing of Average Input/Output

```
AVG. INPUT VALUE =  4.500    STD DEV = 2.291
AVG. OUTPUT VALUE = 5.675    STD DEV = 1.709
```

Spearman's coefficient of correlation of input to output is then calculated. Basically, this is a rank order statistic whereby increasing input values should have increasing output values, as can be seen in the average output values in Table I. Along with the correlation coefficient, R, is the probability of significance. A t-statistic is applied to determine if R shows an actual correlation. A rejection of correlation was made at the 0.95 probability level. Table III shows a sample listing of the two values.

Table III

Sample Listing of Correlation Values

```
SPEARMAN'S COEFFICIENT OF RANK CORRELATION = .68
     PROBABILITY OF SIGNIFICANCE = 1.0000
```

Finally, the input-output relation is evaluated as a channel or information system. A basic schematic for an informational channel is shown in Figure 1. The source is made up of a defined class or set of possible inputs and the rules for selecting inputs from the set. The selected input is transmitted over a channel to a receiver and then to a destination. In terms of the experiment, the input set is the location or phantom location of the sound source. Selection is from a list of random numbers. The sound is transmitted by a loudspeaker through the air and received by the listener who attempts to locate the source, and enters it on his answer sheet.

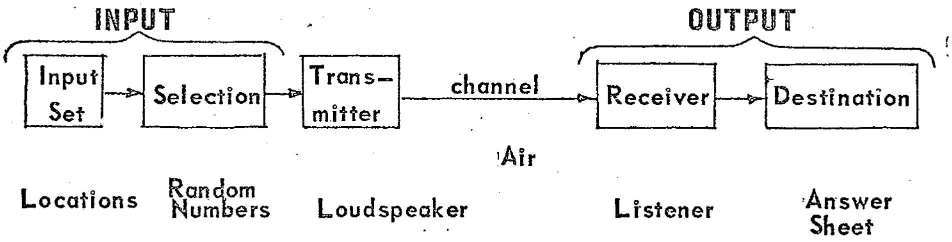


Figure 1. Schematic of Information Channel

The method for computing the information transmitted, information lost, and noise introduced in the channel is straightforward. The basis for the method is explained in detail in Appendix A. Table IV shows a sample of the evaluation of the channel. Information transmitted gives approximately the log base 2 of the number of locations which can be accurately found. Equivocation would show a lack of distinction between inputs, while noise shows a lack of distinction between outputs.

Table IV

Sample Listing of Information Values

INFORMATION TRANSMITTED = .842 BITS
EQUIVOCATION = 2.158 BITS
NOISE = 1.851 BITS

For an experiment to be successful in terms of good localization ability, both the correlation coefficient and the number of bits of information transmitted must be high. The best correlation coefficient possible, of course, is unity, while the subject is not expected to transmit more than about 3 bits per stimulus in most one-dimension absolute judgement experiments.

Experimental Environment

The sound generating and related equipment along with their configuration for each experiment is described in Appendix B. Also listed in Appendix B is other information pertaining to each test.

The first nine tests were conducted in a hard wall room and are considered to be just preliminary tests since echo, external sounds, etc. were uncontrolled. All the other tests were conducted in an anechoic room. This room was approximately 9 feet 2 inches from floor cones to ceiling cones, 8 feet 8 inches wide, and 9 feet 2 inches deep. Located 1 foot 7 inches from the back of the room was a 92 by 60 inch white cloth panel, which concealed a speaker mounted by a system of pulleys. The opaque panel, illuminated from the front, was divided horizontally into 23 numbered sections, each 4 inches high. The section nearest the ceiling was numbered 1 and the section nearest the floor was 23. The speaker, a Jenson Tweeter, was mounted in a cabinet 4 inches behind the panel. The cabinet measured 6 by 8 by 9 1/2 inches, with a 2 by 6 inch rectangular hole in the front. Due to the physical limits on the pulley system holding the speaker cabinet, the speaker could not be positioned any higher than 3 nor any lower than 22. Midpoint between these numbers, 12.5, corresponded approximately to the subject's eye level.

Experimental Procedure

During the test, the listener was seated facing the panel at a distance of approximately 7 feet from ear to speaker. No chin or headrests were provided, although the listeners were asked to minimize head movement by placing their head in the same position with respect to a center marking on the panel at the 12.5 level, 0° azimuth. The experimenter was in an adjacent room and communicated with the listener by means of an intercom. In the experiments of locating an actual sound source, an experimenter aide was behind the screen to move the speaker.

In all experiments, except where specifically mentioned, the listeners were asked to give the apparent location of the sound source. They were, of course, unaware of the actual location of the speaker except in the phantom sound experiments when the speaker was always placed at the 12.5 level or when an earplug-phone was used. The listener was allowed as much time as desired to make his judgement on the apparent location. Generally this was about 5-10 seconds. The level was reported and the sound source was turned off. The listener then recorded his response on mimeographed data sheets and then stated the next presentation number to insure correct sequencing. If speaker position movement was required, the aide would indicate that the speaker had been relocated by an "OK". Speaker position or desired phantom position was varied according to quasirandom sequences which were generated by the computer. The sequences were controlled so that each stimulus appeared an equal number of times. However, the listeners were unaware of this fact. The length of the sequences was generally around 80. In case of duplicated positions in a sequence, the speaker would be moved and then put back in its original position. This insured that the lack of noise from the pulley system would not reveal duplicated positions.

The following chapters present eleven different experiments made up of thirty-four individual tests. Eleven preliminary tests were conducted, but these were discarded.

CHAPTER VI

EXPERIMENTS ON LOCALIZATION OF AN ACTUAL SOUND SOURCE

Localization of a sound source in the equatorial plane is generally explained by physical cues which consist of differences in intensity and phase (or time of arrival) of a sound at the two ears. However, Jongkees and Groden (1946) and Nordlund (1962) report that these cues do not completely account for the accuracy nor sensation in equatorial localization. Locating a sound source in the vertical plane has long been known to be less accurate, but just why vertical localization is possible at all has not been well understood. Early experiments by Angell and Fite (1901a, 1901b) showed that for complex sounds, the accuracy of localization in both the horizontal and vertical planes does not differ greatly when the localization is monaural instead of binaural (Appendix C). This remarkable result gave rise to the concept that changes in the quality of complex sounds are used for localization. But the question remained how the quality of complex sound was changed, and in what fashion it was changed. More recent experiments by Roffler and Butler (1968a) showed that a listener's ability to locate a sound source in the vertical plane was greatly impaired when the pinna was eliminated. Other results of their experiments showed that in order to locate a sound in the vertical plane (1) the sound must be complex, (2) the complex sound must include frequencies above 7K Hz, and (3) the lower frequencies neither hinder nor assist in the accuracy.

Taken together, these results suggest that vertical localization accuracy is not based on binaural differences, but on the "quality of the high frequencies" of the sound after having been gathered by the pinna. This led us to believe that the pinna shaped the higher frequency portion of the sound spectrum which was then correlated to height position. In order to validate this proposition, a number of experiments were conducted on localization of an actual sound source. The first experiments were conducted to verify the principal findings cited above and to set standards on the abilities of the listeners. In brief (see Table V), we performed experiments to test how accurately noise could be located (Experiment A) and if the cue from change in loudness with height of sound source added to the ability to locate the source (Experiment B). Although localization was good, inter-subject differences forced us to use the same subjects. No degradation was found in localization ability when tests were performed at constant loudness. Following these tests, experiment C was conducted to determine if the low frequencies contributed to the "quality of sound." It was found that high-pass noise was located with equally as good accuracy as with broad-band noise. The final experiment, test 28, was the only original experiment in this chapter. Here, the complexity of the located sound was investigated. Three high frequency mixed tones were located with only slightly degraded accuracy. The results of these experiments led us to further investigation of the pinna and the high frequencies, as reported in Chapter VII.

Table V

Summary of Experiments on Localization of Actual Sound Source

Experiment	Test No.	Stimulus	Objective	Result
A	12–17	broad–band noise	test S's locating ability	inter–S difference, good locating ability
B	20–21	broad–band noise	check if loudness changes used as locating cue	no loss in performance w/o loudness change
C	22–23	high–pass noise, >6.3K Hz	check if low freq. part of spectrum contributes to locating ability	loss of low freq. has no effect
D	28	3 mixed tone noise	check if 3 tone noise is adequately complex	slight accuracy loss over test No. 12–17

Experiment A

During our initial experiments, it was learned that variation between individuals was too great to permit one to make reliable comparisons between the effects of different stimuli when different subjects were used for each stimulus. For instance, in the experiment of locating broad-band noise above 2K Hz, 6 tests were made on 4 different individuals. The results shown in Table VI show that although subjects M and R were consistent and have nearly the same results, they are quite different from those individuals in tests 12 and 13. From test 14 on, the same two subjects were used to provide consistency.

Table VI

Results of Experiment A - Broad-band Noise Greater Than 2K Hz

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmitted	Equivocation	Noise
12	D	5.8	.93	2.22	2.10	1.30
13	J	6.2	.97	2.69	1.64	1.29
14	M	7.5	.96	2.82	1.50	1.46
15	R	6.1	.96	2.90	1.42	1.32
16	M	7.3	.96	2.77	1.55	1.59
17	R	4.6	.97	2.83	1.49	1.31

Experiment B

During these initial experiments, there was the possibility of an added cue of change in loudness due to the speaker not remaining a constant distance from the ear with change in vertical position. An experiment was devised to measure the amount of information added by this cue. By using the Loudness Analyzer and directing the microphone at the sound source from a point where the listener's ears would be, a calibration was made to keep the sound source at the constant 10 sones$_G$.[1] The same stimulus as in the previous experiment was used. The result of the experiment, in Table VII shows no advantage was lost by eliminating the loudness changes. Hence, in subsequent experiments, the small change in loudness due to correlation between height and distance from the ear was not considered to be a significant factor in our localization tests.

---

1. Sones$_G$ is an inferred measure of the loudness in sones. It is automatically computed by the Loudness Analyzer. For details of the computation and theory see Hewlett-Packard (1968).

Table VII

Results of Experiment B - Broad-band Noise Greater Than 2K Hz, Calibrated at 10 Sones$_G$

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmitted	Equivocation	Noise
20	M	4.4	.98	2.81	1.51	1.33
21	R	5.1	.97	2.73	1.59	1.45

These two experiments also confirmed that broad-band noise is located quite reliably. If vertical position is considered as a single dimension, absolute judgement of it results in transmission of between 2 and 3 bits per stimulus which compares favorably with absolute judgement of other unidimensional auditory stimuli.

Experiment C

The next experiment was performed to confirm one of the Roffler and Butler (1968a) results. They reported that good vertical localization of broad-band noise was not impaired even when the noise was high-pass filtered with a 7K Hz lower cutoff. In our tests, broad-band noise was filtered by a 24 db/octave filter, with a lower cutoff at 6.3K Hz and an upper cutoff at 10K Hz. The results in Table VIII show that localization accuracy had not been changed appreciably from that of the two previous experiments. This coincides with the results of Roffler and Butler.

Table VIII

Results of Experiment C - Band-pass Noise, 6.3K to 10K Hz

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
22	M	5.6	.96	2.64	1.68	1.52
23	R	4.4	.97	2.78	1.54	1.35

At this point, some of the other Roffler and Butler (1968a, 1968b) experiments are examined. One of their experiments was concerned with the accuracy of locating a single pure tone (Trimble 1934, Pratt 1930). The results of their tests showed that a pure tone is located at approximately the same level, regardless of where the actual source was located. Furthermore, higher-pitched tones were perceived as originating at a higher position than lower-pitched tones. The results of our early experiments conducted in the hard-wall room were found to agree with this. Roffler and Butler (1968b) went to some pains to demonstrate that this was true even for children who were apparently unaware of the use of the words "high" and "low" as applied to pitch.

Experiment D

Since Roffler and Butler found that pure tones were located according to their pitch, while noise was accurately located, it was desired to determine how complex a sound must be to be well localized. Hence, an experiment was devised using three mixed tones: 5.5K, 7.5K, and 13.5K Hz. The reason for selecting these frequencies will be made clear later. The results, listed in Table IX, show a definite degradation in accuracy from the high-pass noise. The large changes are in the square root of the sum of variances and in R, rather than in the information transmitted. The overall accuracy, however, is fair.

Table IX

Results of Experiment D - Mixed Tones, 5.5K, 7.5K, 13.5K Hz

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
28	M	12.5	.75	2.57	1.75	1.51

The result of this experiment leaves a puzzling question of why the accuracy of locating pure tones is poor and is placed in accordance to pitch, while, in contrast, the ability to locate three mixed tones gives better accuracy, and high-pass noise gives the best accuracy. This question led to performing a second group of experiments with a stationary speaker, reported in the next chapter.

CHAPTER VII

EXPERIMENTS ON LOCALIZATION OF A PHANTOM SOUND

Since it was concluded that binaural differences gave no cues to vertical localization, it being dependent upon some quality in the sound, it seemed likely that a phantom sound for the vertical could be presented by a single speaker rather than with two speakers necessary for phantom sounds in the horizontal. The creation of phantom vertical sound was the final goal of the experimentation since the auditory display system would be designed with stationary speakers. Hence, in this group of experiments, the judgment of the vertical position of the sound source was dependent on changes of the quality of sound - the sound source remaining in one position.

In the experiments reported by Roffler and Butler on localization of tonal stimuli, they found that vertical localization was poor with pure tones and that pure tones were generally located according to pitch. This pitch-height relationship was also noted by Trimble (1934, p. 332) who felt that "This phenomenon . . . may prove important in the study of localization in the vertical dimension." For this reason, we first performed several experiments with pure tones, obtaining values for comparison with those subsequent experiments which attempted to improve upon the basic pitch-height correlation. A brief summary of the experiments of this chapter is listed in Table X. The first experiment on this table, test 24, was performed with pure tones to give us the range over which the best pitch-height relationship exists. Experiment F gave the maximum possible transmission values for placing high tones high and low tones low. This was accomplished by instructing the subjects to deliberately place high pitches high and low pitches lower. Next, the results from Shaw and Teranishi (1968) were utilized to produce the phantom vertical sound. Shaw and Teranishi made spectral measurements at the entrance of the ear canal of sound pressure versus frequency at different angles of incidence. Each of the following experiments took some fundamental feature(s) from the sound spectra measured by Shaw and Teranishi and represented it in the form of mixed pure tones or as broad-band noise. The first of these experiments (Experiment G) abstracted the mode feature of the sound spectrum. Since two modes were present in the spectrum, two pure tones were used to represent these modes. The results were negative. In experiment H the proper relative amplitudes were imposed on to the stimuli of the previous experiment. Here the results were good. Using the same stimuli, experiment I used an earplug-phone in an attempt to improve on the phantom sound. Since the earplug-phone would place the sound at the same location as the Shaw and Teranishi measurements were made, it was felt that both correlation and transmission would increase. The results showed an increase in correlation. Experiment J attempted to represent the sound spectrum with three pure tones. The effort failed. The final experiment, experiment K, abstracted the notch features of the sound spectrum. A notch in broad-band noise was presented and showed good results in correlation.

Table X

Summary of Experiments on Localization of Phantom Sound Source

Experiment	Test No.	Stimulus	Objective	Result
E	24	10 tones from 1.5K – 12.5K Hz	determine freq. range for good pitch-height relationship	Good correlation between 3.15K and 6.3K Hz
F	26–27	9 tones from 2.8K to 7.1K Hz	determine maximum possible transmission on pitch-height rel.	1.50 – 1.67 bits, R = .86, .87 w/o training
G	29–30	Two tones representing sound spectrum at ear	determine if two tones properly selected give phantom height position	Negative; bits good, no correlation
H	31,38–39	Same tones as above, but with selected db level	Same objective as above	Positive; bits = 1.56–1.90 R = .48–.64
I	40–42	Same stimuli as above except earplug-phone used	check for better results than above	R = .83–.90 bits = 1.49–1.59
J	32–37	Three tones representing sound spectrum at ear	determine if this combination gives phantom position	Negative; bits high but no correlation
K	43–45	Notch in broad-band noise representing sound spectrum at ear	determine if the notch gives phantom height	Positive; bits = .94–1.29 R = .57–.77

Experiment E

In our first experiment on phantom sound, the listener was encouraged to believe that the only difference between this experiment and previous experiments was that pure tones were used. To hide the fact that the speaker position was unchanging, the experimenter's aide behind the panel moved the speaker randomly after each stimulus and then returned it to the 12.5 level. Ten tones from a broad range of frequencies, ranging from 1.5K to 12.5K Hz at approximately 1/3 octave intervals, were presented. The first analysis of the results (Table XI, test 24) shows little or no correlation between height and pitch. However, further examination showed that the five tones between 3.15K and 6.3K Hz had better correlation; e.g., test 24-1 in Table XI.

Table XI

Results of Experiment E - Pure Tones, Stationary Speaker Unknown

Test No.	Subject	$\sqrt{\sum \sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
24	M	8.9	.02	1.30	2.02	2.32
24-1*	M	6.3	.49	1.06	1.27	2.26

*** Test 24 analyzed by using only the middle 5 stimuli.**

Experiment F

The next experiment used frequencies between 2.8K and 7.1K Hz, approximately the same frequency range which had good correlation between pitch and height in the previous experiment. Nine tones at approximately 1/6 octave intervals were presented. The added cue or dimension of loudness was eliminated by calibrating the loudness of each tone using the Loudness Analyzer. The presentations were made at 10 sones_G. The subjects were instructed to associate high tones with high levels and low tones with lower levels. It should be noted that this is the only experiment in which apparent sound position was not asked for. The results of the tests are listed in Table XII. The transmission of 1.67 and 1.50 bits agreed with work by Pollack (1952, 1953) where 1.59 and 1.30 bits per stimulus were transmitted on pitch. In his work, however, the subject did not match pitch with height, but only identified tones. Pollack also showed that by training the subjects, this transmission rate could be increased to 2.3 bits per stimulus. It is suspected that at least this transmission rate would be obtained on pitch matched with height if the subjects were trained to recognize tones. An interesting result is the range of response levels used by the subjects. R used levels 2 through 22, while M used a smaller range from 3 through 16. By coincidence or otherwise, this is the same range M used on test 24, when the speaker position was not known to be stationary.

Table XII

Results of Experiment F - Pitch, Stationary Speaker Known

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
26	R	9.1	.86	1.67	1.50	2.48
27	M	6.8	.87	1.50	1.67	1.55

Shaw and Teranishi Results

The subsequent experiments which attempted to improve on the basic pitch-height phenomenon could not have taken place had not the results by Shaw and Teranishi (1968) been reported. It had been intended to record vertically located sound through a human head replica and then replay the sound through earphones and see if the sensation of vertical movement was obtained. If it was, it would have been desirable to analyze the spectrum of the recorded sound placed at different levels.

Fortunately, before this task was undertaken, Shaw and Teranishi's work was noted. They reported on the comparison of an external-ear replica to the real human ear. Their report showed that good agreement was not obtained above 7K Hz. It was reported in the previous chapter that high frequency noise was necessary for vertical localization, in particular, above 7K Hz. Hence the use of an ear replica for the above task would probably end in failure. However, even more important, was their graph of pressure ratio (db) versus frequency measured at the entrance of the canal of a human ear with the meatus blocked. Measurements were made by Shaw and Teranishi for seven different angles of incidence of sound located in the vertical, ranging from 45° below, at 15° intervals as shown in Figure 2. Figure 3 is drawn from their results with the human ear. A similar graph for only the normal angle of incidence (0°) for another individual is shown in Figure 4. In this figure, curves for both the meatus-blocked and meatus-open (dashed line) are shown. The sharp minimum near 8K Hz is present in both curves. Shaw and Teranishi (1968, p. 248) report that "This prominent feature is relatively independent of the angle of incidence in the horizontal plane (front-back) but is strongly dependent on the angle in the

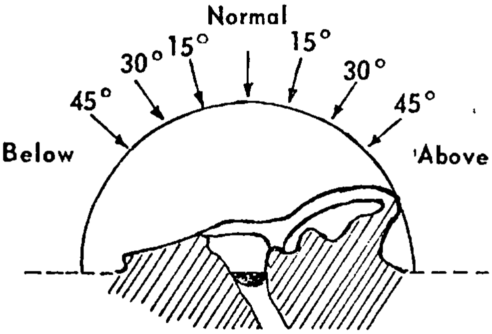


Figure 2. Angle of Incidence of Sound Source on the Ear

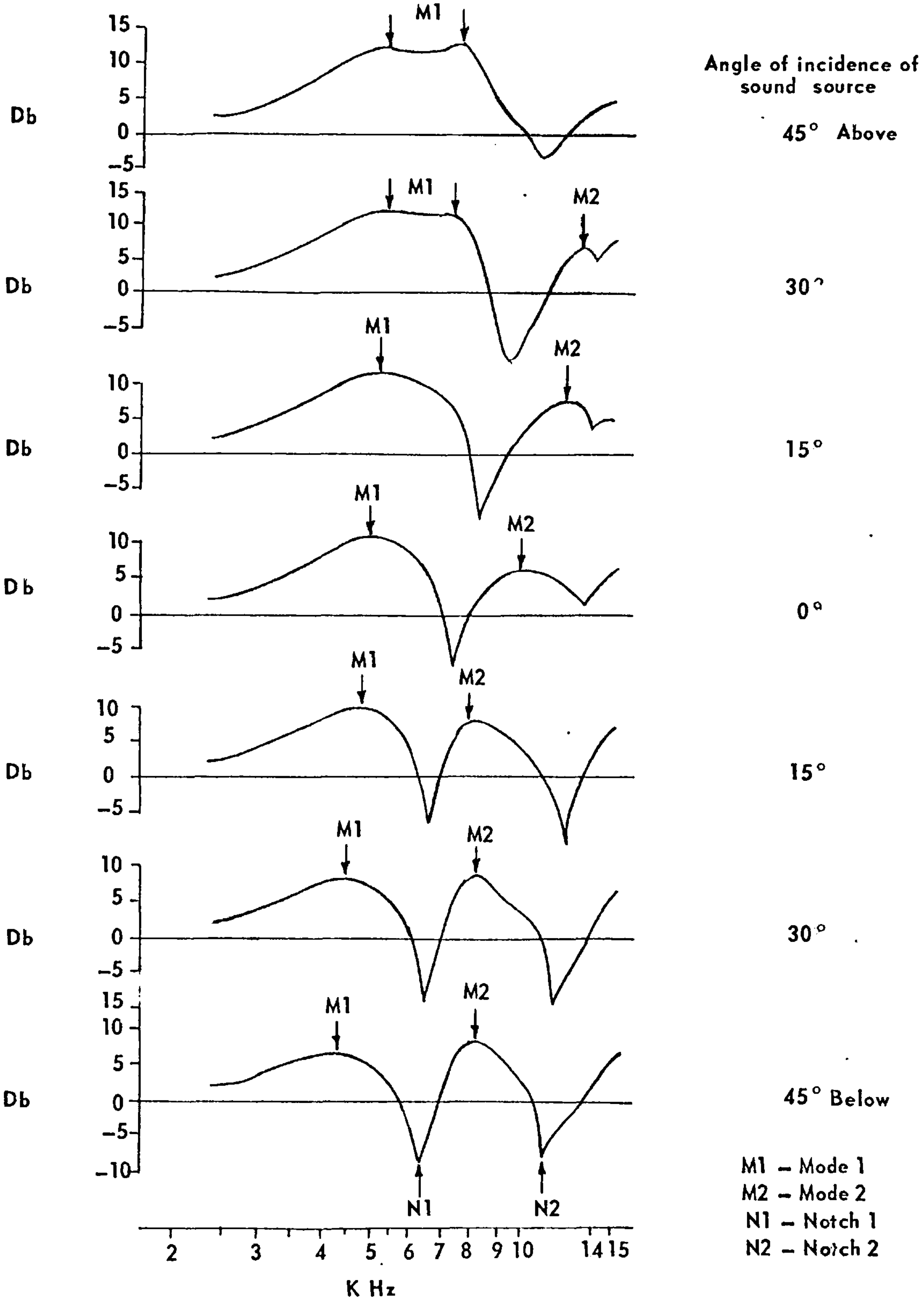


Figure 3. Pressure Ratio versus Frequency Measured at the Entrance of the Blocked Ear Canal

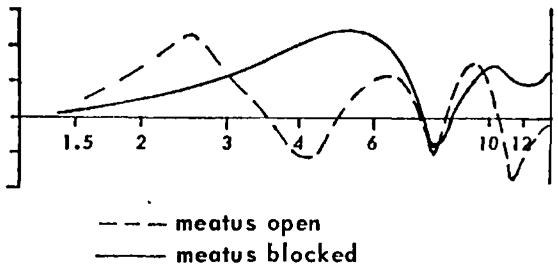


Figure 4. Pressure Ratio versus Frequency Measured at the Entrance of Ear Canal with Sound Source at Normal Angle of Incidence

vertical direction (above-below)." We also noted the peaks (or modes; i.e., the peak intensity at the high frequency end of the sound spectrum) at approximately 6K Hz and 9K Hz on both meatus-blocked and meatus-open curves. The high pressure ratio at 2.5K Hz in Figure 4 of the meatus-open curve is caused by the resonant frequency of the ear canal. It is, of course, not present in the meatus-blocked curve. In our examination of Figure 3, it was evident that the pressure ratio changes with angle of incidence.

In our analysis of Figure 3, plots were made of mode and notch frequencies as a function of angle of incidence of sound. The result, Figure 5, demonstrates that both the modes and notches shift to higher frequencies with higher angles of incidence. We then reasoned that if the dominant frequencies of the spectrum could be represented by the two modes, then two pure tones representing the modes might correlate with height. Furthermore, if this does occur, it would be reasonable to explain the pitch-height phenomenon by this same correlation.

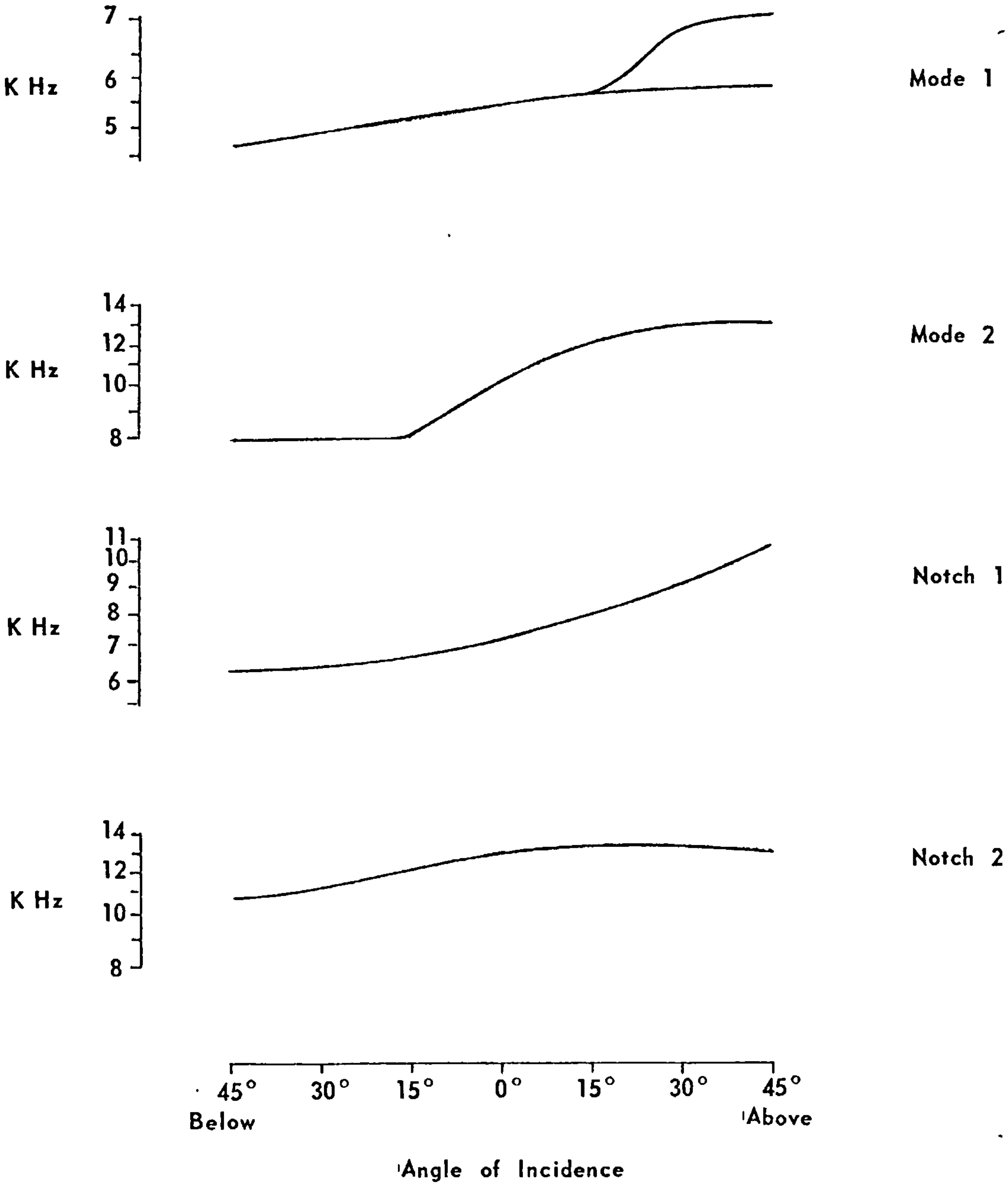


Figure 5. Frequency versus Angle of Incidence of Modes and Notches

Experiment G

To test this a new experiment was set up in which the two mode frequencies, for each angle of incidence, were presented as a single stimulus. The listeners were asked to respond to the apparent position of the stimulus. They were not told to associate pitch with height, although they had done so in previous experiments. Test 29 used 7 sets of stimuli, each representing an angle of incidence from the original Shaw and Teranishi graph. Test 30 used 13 sets of stimuli, using in addition, 6 interpolated values. The results of these tests are listed in Table XIII. Although it is hard to compare the two tests because of the different number of stimuli, the results are obviously poor, since in both cases, the correlation was not significant.

Table XIII

Results of Experiment G - Mode Tones

Test No.	Subject	$\sqrt{\sum \sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
29	M	4.0	-.11	1.47	1.33	1.82
30	R	14.2	.01	1.68	2.02	2.28

Experiment H

Again the Shaw and Teranishi graphs were examined. This time, amplitude (pressure ratio in db) at the modes and notches was plotted versus angle of incidence, as shown in Figure 6, to determine the pattern of db change of the modes and notches with angle of incidence. The experiment was then repeated with 13 stimuli corrected for the proper pressure ratios. The Harmonic Wave Analyzer was used to perform this

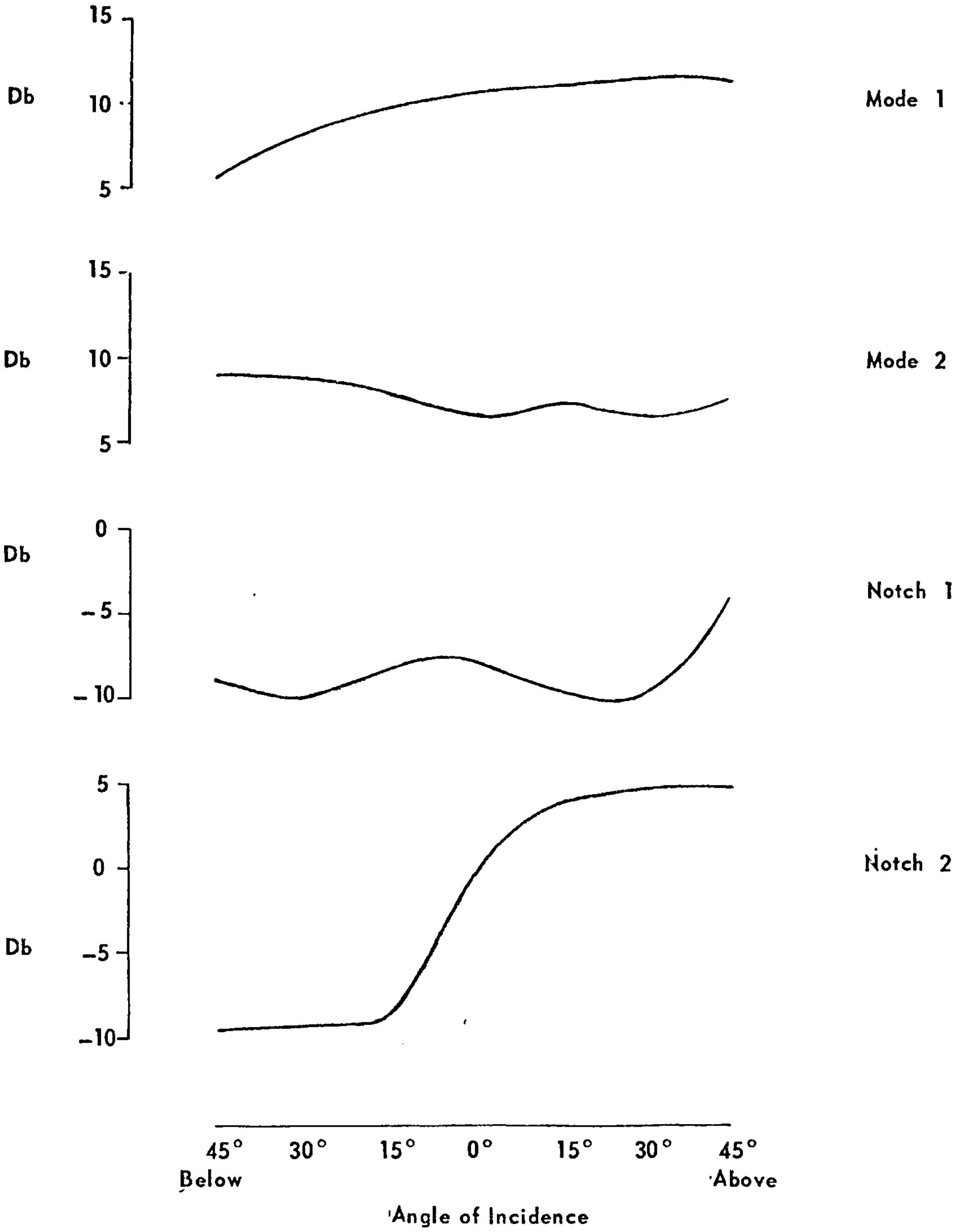


Figure 6. Pressure Ratio versus Angle of Incidence of Modes and Notches

calibration. The results of these tests are listed in Table XIV. In all these tests, their correlations were significant. The mode tones and pressure ratios are slightly different in tests 38 and 39 from that of test 31. Tests 38 and 39 applied the higher frequencies of the Mode 1 curve while test 31 used the lower frequencies (see Figure 5).

The difference demonstrates the two Mode 1's appearing in the Shaw and Teranishi graph for sound at 30° and 45° angle of incidence above the ear (see Figure 3). Test 39 might have been slightly degraded by R's cold. Again it is of interest to note the range of M's responses to be between 3 and 14, while R's responses are between 3 and 22, and 1 and 23, respectively.

Table XIV

Results of Experiment H - Mode Tones, Calibrated

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
31	R	10.0	.64	1.90	1.74	1.71
38	M	8.3	.50	1.73	1.97	1.69
39	R	17.1	.48	1.56	2.14	1.90

Experiment I

In an attempt to improve on the result of the previous experiment, the tests were repeated using the same stimuli as in tests 38 and 39, however, instead of the speaker being held stationary at the 12.5 level, an earplug-phone was employed. Hence the sound source was placed at approximately the same location that the Shaw and Teranishi measurements were made. The result is listed in Table XV. It shows a

Table XV

Results of Experiment I - Mode Tones, Calibrated, Earplug-phone

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
40	M	4.8	.90	1.59	2.11	1.29
41	M	4.5	.83	1.49	2.21	1.42
42	R	7.7	.85	1.52	2.18	1.55

definite increase in correlation over the previous experiment (listed in Table XIV). There was, however, a probable drop in bits transmitted per stimulus. The differences can be accounted for by two points: First, the earplug-phone placed the sound source at the same point of measurement made by Shaw and Teranishi. This probably accounts for the increase in correlation. Second, the loss of recognition of as many stimuli, or drop in bits transmitted, is probably due to the distortion introduced by the poor quality of the earplug-phone.

Also note the increase of equivocation over the previous experiment. Equivocation shows a lack of distinction between inputs or stimuli; thus the distortion proposition. Noise decreased, somewhat, indicating better output distinction. This better output distinction is in better correlation.

Experiment J

An experiment to increase bits transmitted and correlation was devised by selecting three frequencies at points halfway between the modes and the notches. Since the pressure ratios were nearly constant for each frequency with angle of incidence, no calibrations were made on most of these tests. The results are listed in Table XVI. Again, slightly different stimuli were used in tests 33, 34, and 36 from those in tests 32 and 37. In all but test 32, the correlation was not significant. It should be noted that several weeks passed between test 32 and the others. There seems to be no reason for the discrepancy. Because the results of the first test could not be duplicated, the attempt was considered a failure.

Table XVI

Results of Experiment J - Mid-tones

Test No.	Subject	$\sqrt{\Sigma \sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
32	M	7.3	.70	2.01	1.69	1.63
33*	M	7.3	-.22	1.42	2.28	2.10
34*	M	9.3	-.19	1.52	2.18	1.63
35	M	8.7	-.33	1.82	1.88	1.86
36	R	13.9	.26	1.89	1.81	2.18
37	M	9.5	-.35	1.86	1.84	1.86

*Calibrated

Experiment K

The special pattern changes being recognized for vertical localization were expected to be more complex than just the dominant frequencies and their pressure ratios. It was felt that the attenuation of the other frequencies also added to the pattern for localization. Hence, an experiment on the recognition of notches in broad-band noise and on the degree of association of these notches with height would determine if the attenuation of certain frequencies was another cue of the complex pattern of recognition for localization. The experiment attempted to shape broad-band noise corresponding to the low frequency notch (Notch 1 of Figure 3) from the Shaw and Teranishi graph. A lower frequency cutoff at 3.4K Hz and an upper cutoff at 17K Hz were used on the broad-band noise. The amplitudes of Figure 3 were not calibrated, but the notches were formed at approximately the correct frequencies. Table XVII lists the notch cutoffs for the 24 db/octave filters. Two tests were performed with 7 notches, one with a stationary speaker and the other with an earplug-phone. A final test was performed with a stationary speaker and the lower notch cutoff evenly spaced, as shown in Table XVIII. Note that these notches do not represent the Shaw and Teranishi graph, however, they are spaced over the same range of frequencies. The results of the three tests are listed

Table XVII

Notch Cutoffs for Tests 43, 44

Stimulus No.	Lower Cutoff	Upper Cutoff
1	6.35K Hz	16.1K Hz
2	4.80	15.4
3	4.28	13.7
4	4.08	11.5
5	3.70	10.9
6	3.63	11.1
7	3.82	10.7

Table XVIII

Notch Cutoffs for Test 45

Stimulus No.	Lower Cutoff	Upper Cutoff
1	6.5K Hz	16.1K Hz
2	6.0	15.0
3	5.5	12.4
4	5.0	11.25
5	4.5	11.1
6	4.0	10.0
7	3.5	7.9

in Table XIX. The results show significant correlation of notch position with height. Hence the proposition that the attenuation of certain frequencies is an added cue for localization is tentatively accepted. It is important to note that the stimuli only slightly represented the Shaw and Teranishi spectrums since only one notch was represented and pressure ratio had not been calibrated for the notch or either side of the notch. Pressure ratio was set equal for both sides of the notch for the 0° angle of incidence (Stimulus No. 4). The same pressure ratio was kept for the other angles of incidence. The notch calibration was not accomplished, however, on the earplug-phone.

Table XIX

Results of Experiment K - Broad-band Notched Noise

Test No.	Subject	$\sqrt{\Sigma \sigma_i^2}$	R	Information		
				Transmittal	Equivocation	Noise
43	M	3.8	.76	1.06	1.75	1.56
44	M	5.8	.57	.94	1.87	1.68
45	M	3.7	.77	1.29	1.52	1.82

Response Levels

In the experiment just described, M's responses are between levels 3-13, 2-11, and 3-11, respectively. This is about the same as reported in the other experiments. In contrast, R responded over a wider range, generally from 2-22. In spite of this difference in response choices, both subjects had about the same correlation coefficient and bits of information transmitted with the same experiment. Trimble (1934, p. 321) believed that "there is some evidence here and there throughout literature that localization in the anterior-posterior and vertical dimensions depends upon auditory habits or attitudes peculiar to the observer." He went on to propose that "If localization in the anterior-posterior and vertical dimensions depends on auditory habits peculiar to the observer, it should turn out that each observer favours a certain particular quadrant or inter-quadrant position in his localization" (p. 326). He concluded from his experiment that he was justified in this proposition. It may be that "auditory habits" are formed by each individual's pinna contour or formation and are responsible for the discrepancy between the response range of the two subjects.

Earplug-Phone versus Speaker

In experiment I and test 44 of experiment K, an earplug-phone was employed as the sound source. In all other tests, a speaker was placed directly in front of the subject. With the earplug-phone, the sound source was located approximately at the same position that Shaw and Teranishi measurements were made. The difference in sound placement was expected to cause large differences in the results; however, the difference can be best explained in terms of cascading filters. First, the sound source presented was basically a filtered sound - either mode tones or broad-band notched noise. With the earplug-phone, this sound was sent directly to the eardrum. However, with the speaker, it was again filtered by the pinna. The second filter produces our cascading filters. In these tests, the pinna's filter had a constant shape - that of 0° azimuth and 0° elevation. Fortunately, it had little effect. Examination of the Shaw and Teranishi graphs show little likelihood of the presented mode tones occurring at the same frequencies as a notch in the pinna's filter. Hence, the mode tones were heard at approximately the same intensity as presented by the speaker. As for the broad-band notched noise presented, the pinna's filter apparently added another notch or two. This apparently was not dominant enough to destroy the results. However, the results did have a lower bit transmission than that of mode tones.

CHAPTER VIII

EXPERIMENT AND RESEARCH SUMMARY

In 1901, Angell and Fite (1901a, p. 226) stated that the "difference in intensity and quality of the sound sensations perceived by the two ears (are) the fundamental factors in our localization." They went on to say that "examination of monaural hearing suggests, however, the extent to which one set of auditory symbols, i.e., qualitative peculiarities of sound, may serve as localizations" (p. 246). The presently reported experiments may have not determined the exact change in sound pattern used for localization, but they have given strong evidence for a "spectral recognition" theory. Furthermore, it appears that the cue for vertical localization or the cue not accounted for by differences in intensity and phase of the sound at the two ears for azimuth localization is in the recognition of the high frequency portion of the audio spectrum. The requirement for high frequencies was shown by Roffler and Butler (1968a) in experiments in which good vertical localization of broad-band noise was not impaired when the noise was high-pass filtered, even when the lower cutoff was as high as 7K Hz (36 db/octave attenuation).

For median plane vertical localization, the listener seems to be cognizant of at least the dominant frequencies and the respective pressure ratios in a complex sound. The pattern responded to is probably more complex than that and requires cognizance of both the dominant frequencies and the notches at their respective pressure ratios.

The recognition of dominant frequencies in vertical localization explains the phenomenon of pure tones being placed on a vertical scale in accordance to their pitch. It was shown in Figure 5 that both mode frequencies from the Shaw and Teranishi graphs increased as the angle of incidence increased. Thus, the "auditory habits" for localization tended to locate at a particular level the pure tone that had no other elements of information. Yet when other elements of information were added, such as in test 28 where three pure tones were mixed, localization was possible. (In this test, the tones were picked from the four extremes of the two modes, where the high extreme of the first mode and the low extreme of the second mode were the same).

The effects of the pinna have long been suspected as the means for localization. Experiments on pinna-less animals by Fynn and Elliott (1965, p. 105) led them to the conclusion that "The pinna presumably serves as a device for locating sound source and maximizing its reception." Now this can be extended to say that the pinna imposes a pattern of organization on the high frequencies of the sound being located. Furthermore, the pattern appears to be a shift of the dominant frequencies to the higher frequencies as the sound is placed higher. In addition, attenuation of the other frequencies and pressure ratios are important elements of the located sound.

This extension on the role of the pinna is based on the two types of experiments: mode tones and notched noise. In the experiment with mode tones (Tests 31, 38-42), there appeared to be an increase of the number of bits transmitted over that of the experiments of correlating pitch with height. Although this increase could be due to a learning process whereby the number of bits could increase, this was probably not the case. Too few tests were performed to expect this. Hence, the increase in the number of bits supports the proposition of the recognition of dominant frequencies and their pressure ratios. The experiment using notched noise (Tests 43-45) had a surprising but not unexpected result. Here, the notched noise represented only a portion of the Shaw and Teranishi spectrum, yet tended to be located on the vertical plane accordingly. Hence, the spectrum recognition proposition is supported.

It is interesting to note that Jongkees and Groden (1946) performed an experiment similar to that of Angell and Fite. While Angell and Fite had used a subject who was totally deaf in one ear since a child, Jongkees and Groden used a subject who had good hearing in both ears, but had his hearing blocked in one ear by means of cotton wool soaked in paraffin wax. They reported that "directional hearing was bad to very bad" (p. 503). They went on, however, to say that "some directional hearing remains in the vertical plane" (p. 503). Unfortunately, no definite conclusion was drawn from their experiment. Obviously, there exists a discrepancy between the Angell and Fite experiment and the Jongkees and Groden experiment. The discrepancy exists in the subjects. The two subjects did not have even similar auditory habits. While spectral recognition was important in all directions for the deaf subject, it was not for the other. For him, spectral recognition was very important in only the vertical plane.

The auditory habits appear to be responsible for the discrepancy between the range of responses of the two subjects. Undoubtly, if individual spectrum measurements were made and then presented, the range discrepancy between individuals would not be so apparent. However, the use of mixed mode tones or notched noise from the Shaw and Teranishi graph for localization purposes will require some training of the auditory habits to provide consistency among users. It should not be too difficult of a training task, however, since the natural tendency to locate these sounds vertically is already present.

Future studies should obtain complete Shaw and Teranishi data on the responses of the real ear. Individual variances should be examined closely to learn more about the range discrepancy between individuals. Also, optimum values for mode frequencies may be determined giving best results for the majority of individuals.

CHAPTER IX

THE PROPOSED AUDITORY DISPLAY

The auditory display proposed here is based on the results of the experiments on vertical localization and on the results of published experiments on equatorial localization. The objective of the display is one which has realism or naturalness in the localization. It is also intended that the display accurately aids the pilot in locating an aircraft with which he might collide.

The display will be much like the previous discussed auditory display reported by Vallerie (1968). Again the azimuth and elevation of the intruder are transformed into sound. However, in this display both azimuth and elevation will be based upon more of a natural localization, rather than a coding.

Azimuth Position

In defining the frequency for azimuth localization, several factors are taken into consideration. First, the frequency which gives the smallest detectable difference between azimuth angles. Results by Mills (1958) show that the smallest values are in the frequency range between 250 to 1000 Hz. A slightly higher minimum occurs between 3K and 6K Hz. If the frequency should be taken from the lower range, the 500 Hz will be picked. In a report by Katz et al. (1964, p. 7) a "lateral target location was coded in lateral source of the auditory signal. A low frequency (500 cps) tone was used . . . and it was interrupted 4 times per second to reduce habituation and increase discriminability of direction." The Dunlap Auditory Display reported by Vallerie used a 2500 Hz base tone. If a steady tone is to be utilized, then a tone from the higher range may be more desirable. Conclusions from Feddersen et al. (1957, p. 991) say "localization of high-frequency pure tones, where there is no cue provided by the onset of the tone, demands a difference of level at the two ears which can be provided by tones above about 5000 cps." However, Sandel et al. (1955, p. 852) reports that "a phantom source which lies between the two actual speakers at a position which can be predicted with reasonable accuracy for frequencies of 1200 cps and below. For higher frequencies the localization is subject to considerable individual and random influences." Based on these studies, it is proposed that a 500 Hz signal be employed for lateral localization. The number of speakers should be from 3 to 5. The placement of the speakers should be one in front, two on each side (less than 90° to left and right), and one or two behind. The reason for the speaker(s) behind the pilot is based on a report by Howell and Fisher (1957) whose title was "Overtaking, Not Head-On Approach Found to be Greatest Cause of Our Mid-Air Collisions." More studies, however, must be planned to determine the actual number of speakers. Stevens and Davis (1938, pp. 181-183) report on the use of three speakers as opposed to two in "The Stereophonic Effect." If earphones are utilized rather than speakers, then some problems would arise with head movement. However, Jeffress and Taylor (1961) report that the lateral localization task is essentially the same through earphones as through an external speaker. Confusion would exist, however, between front and back positions. This confusion, sometimes called the "cone of confusion", is caused by the same binaural loudness and phase differences representing two points in space, one in front and one in back. Using the speaker system would overcome this problem because of the additional cues provided by the pinna's modification of the sound spectrum.

Elevation Position

In defining the frequencies for vertical localization, more research should be performed; however, based on the data and results gathered so far, we can either use the mode frequencies from Figure 5 or shape high-pass noise to the spectra of Figure 3. The high-pass noise should have a sharp cutoff at approximately 3.2K Hz.

Apparatus

The apparatus for sound generation should transform the elevation information of the intruding aircraft into either the mode tones at the proper pressure ratios or into high-pass noise shaped into the proper spectrum. The 500 Hz tone should then be mixed for use of azimuth localization. In this process the azimuth of the intruding aircraft should transform the mixed tones so that the proper binaural loudness and phase differences are presented at the speaker combination or earphones. It is possible that the range of the intruding aircraft could be encoded into the interrupt rate of the stimulus. If the range is not encoded, then the stimulus should be interrupted at a constant rate of 4 to 6 times per second to reduce habituation and increase discriminability. If multiple intruders exist, then the apparatus should cycle through localizations on each intruder. Tests to determine the length of the cycle times would be necessary; however, results by Lockheed-California Company (1966) and Sperry Gyroscope Company (1963) lead us to believe the cycle time would be on the order of 5-10 seconds per intruder. Cycle times may also be devised as a function of range, allowing the closer intruders more time to be located.

Interfacing Problems

Further studies on the audio spectrum response of the human ear in vertical localization may show variations among individuals which consist of simple variations in mode and notch frequencies and, also, in pressure ratio of modes and notches. Controls on these variables may allow the pilot to adjust the apparatus for his individual variation. Simply, the pilot could adjust the apparatus by sequencing through a number of localization positions. At each position the pilot would adjust the controls for best sensation of the intended position.

Tests should be conducted on the distinction of the stimuli over background noise of aircraft. Additional studies on the auditory load of the pilot are necessary. Tests should also be made on the required hearing ability of the pilot for use of the system. The use of the system may require some training.

CHAPTER X

SUMMARY AND CONCLUSIONS

Experiments were made under laboratory conditions to determine the possibility of vertical localization from a stationary speaker for the purpose of providing a two-dimensional auditory display. The objective was to make azimuth and elevation localization as natural as possible to relieve the user of any decoding. Experiments indicate that this is possible, however, more experiments are necessary to determine the method for best results.

The use of the two-dimension auditory display appears to be feasible and possesses many advantages that should be considered in developing a cost effective system. Among these are relatively low cost, ease of retrofitting, high reliability, and simple maintenance requirements. The disadvantage of being temporal rather than spatial is not as severe as was first thought; as studies by Sperry Gyroscope Company (1963) report that optimum bearing angle information may be close to temporal accuracy. However, further research is required to assess its capabilities under environmental conditions.

APPENDIX A

METHOD FOR CALCULATION OF INFORMATION TRANSMITTED

Consider the information channel:

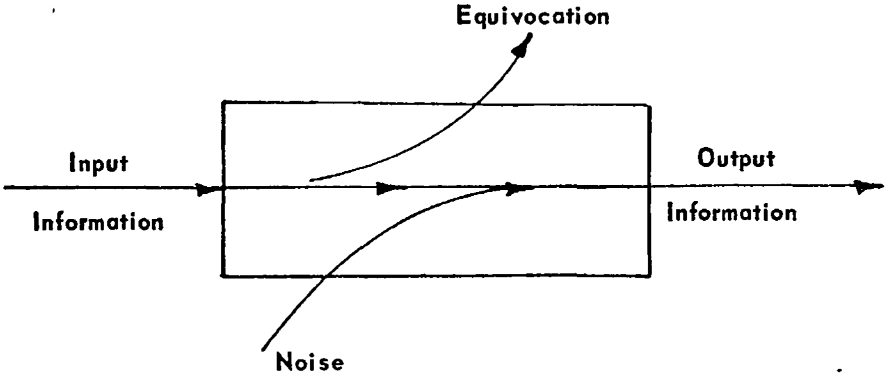


Figure 7. Information Channel

An experiment is made where input and output information is recorded. The recorded information is formed into a "contingency table as shown below:

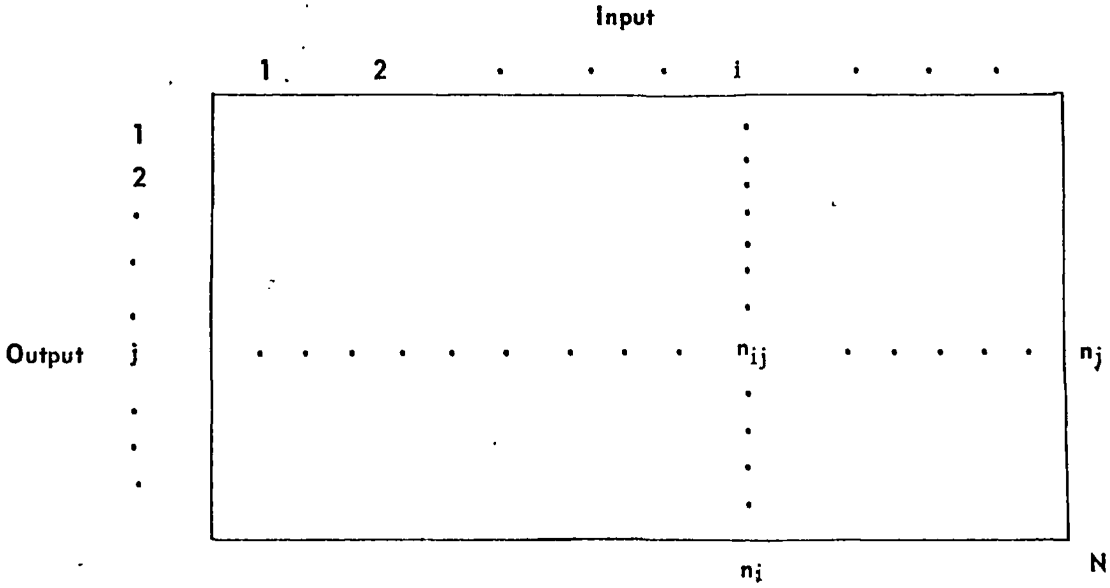


Figure 8. Contingency Table

n_{ij} = total number of responses (output) j for stimulus (input) i.

n_i = total number of input i.

n_j = total number of output j.

N = total number of inputs or outputs.

Define the following terms:

$H(x)$ = input information

$H(y)$ = output information

$H(x,y)$ = information in the input-output pair

$H(x|y)$ = equivocation

$H(y|x)$ = noise

$T(x,y)$ = transmitted information

The first three terms are estimated as follows:

$$\hat{H}(x) = \log_2 N - \frac{1}{2} \sum_i n_i \log_2 n_i$$

$$\hat{H}(y) = \log_2 N - \frac{1}{2} \sum_j n_j \log_2 n_j$$

$$\hat{H}(x,y) = \log_2 N - \frac{1}{2} \sum_{ij} n_{ij} \log_2 n_{ij}$$

The last three terms have the following relationship:

$$T(x,y) = H(x) + H(y) - H(x,y)$$

$$H(x|y) = H(x) - T(x,y)$$

$$H(y|x) = H(y) - T(x,y)$$

Further discussion of this topic may be found in Attneave (1959) and Sheridan and Ferrell (1966).

APPENDIX B

EXPERIMENT CONFIGURATION

List of Equipment and Tests

The equipment consisted of the following: two General Radio Random Noise Generators, Type 1390-B; two RCA Audio Generators, Model Wa-44C; one General Radio R-C Oscillator, Model 1210-C; two Federal Pacific Decade Resistors, Model RDB; one General Radio Decade Resistor, Type 1432-P; two Krohn-Hite Variable Band Pass Filters, Models 3100 and 310-AB; one Burr-Brown Operational Amplifier, Model 1503; one Hewlett-Packard DC Power Supply, Model Harisson 6200B; one Grass Precision State Audio Monitor (Audio Amplifier), Model AM5C; one Jenson 8-inch Woofer, Model W8-R8; one Jenson Compression Horn Tweeter, Model T-107; one Hewlett-Packard Loudness Analyzer, Model 8051 A; one Hewlett-Packard Condensor Microphone, Model 15109B; one Hewlett-Packard Harmonic Wave Analyzer, Model 300A; and one Japanese-made earplug-phone. The tests are listed in Table XX.

Table XX

List of Tests

Test No.	Subject	Experiment Code	Sound Generation Equipment Configuration Code	Calibration Equipment Configuration Code	Number of Presentations	Number of Different Stimuli or Locations	Sound Level (Sones$_G$)	Experiment Room
1	G	A	1	–	80	8	–	H
2	G	A	1	–	80	8	–	H
3	N	A	1	–	80	8	–	H
4	N	A	1	–	80	8	–	H
5	D	D	2	–	80	8	–	H
6	D	A	2	–	80	8	–	H
7	B	A	3	–	80	8	–	H
8	B	A	2	–	80	8	–	H
9	A	A	1	–	80	8	–	H
10	C	A	4	–	56	14	–	A
11	W	A	4	–	56	14	–	A
12	D	A	4	–	80	20	–	A
13	J	A	4	–	80	20	–	A
14	M	A	4	1	80	20	8 – 10	A
15	R	A	4	1	80	20	8 – 10	A
16	M	A	4	1	80	20	8 – 10	A
17	R	A	4	1	80	20	8 – 10	A
18	M	A	4	1	80	20	10	A
19	R	A	4	1	80	20	10	A
20	M	A	4	1	80	20	10	A
21	R	A	4	1	80	20	10	A
22	M	A	4	1	80	20	8 – 10	A
23	R	A	4	1	80	20	8 – 10	A
24	M	P	5	–	80	10	–	A
25	R	P	5	–	80	10	–	A
26	R	P	5	1	90	9	10	A
27	M	P	5	1	90	9	10	A
28	M	A	6	1	80	20	–	A
29	M	P	7	–	70	7	–	A
30	R	P	7	–	78	13	–	A
31	R	P	8	–	78	13	–	A
32	M	P	6	2	78	13	–	A
33	M	P	6	2	78	13	–	A
34	M	P	9	2	78	13	–	A
35	M	P	6	–	78	13	–	A
36	R	P	6	–	78	13	–	A
37	M	P	6	–	78	13	–	A

Table XX - Continued

Test No.	Subject	Experiment Code	Sound Generation Equipment Configuration Code	Calibration Equipment Configuration Code	Number of Presentations	Number of Different Stimuli or Locations	Sound Level (Sones$_G$)	Experiment Room
38	M	P	8	2	78	13	–	A
39	R	P	8	2	78	13	–	A
40	M	P	10	2	78	13	–	A
41	M	P	10	2	78	13	–	A
42	R	P	10	2	78	13	–	A
43	M	P	11	2	70	7	–	A
44	M	P	12	2	70	7	–	A
45	M	P	11	2	70	7	–	A

A actual location

P phantom location

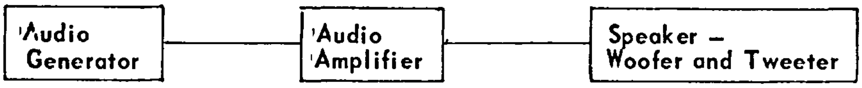
All tests in anechoic room made at the 8 – 10 Sones$_G$ range.

H hard–wall

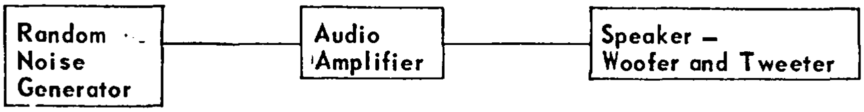
A anechoic

Sound Generation Equipment Configurations

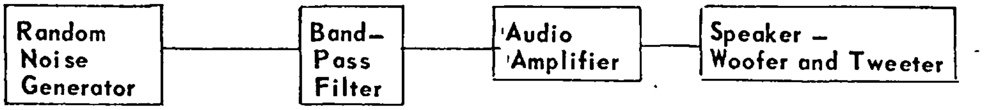
1.



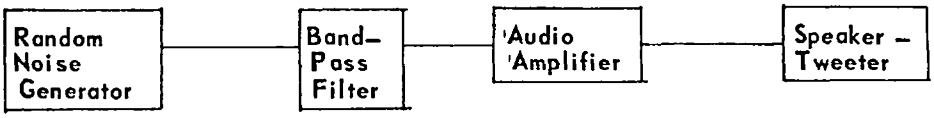
2.



3.

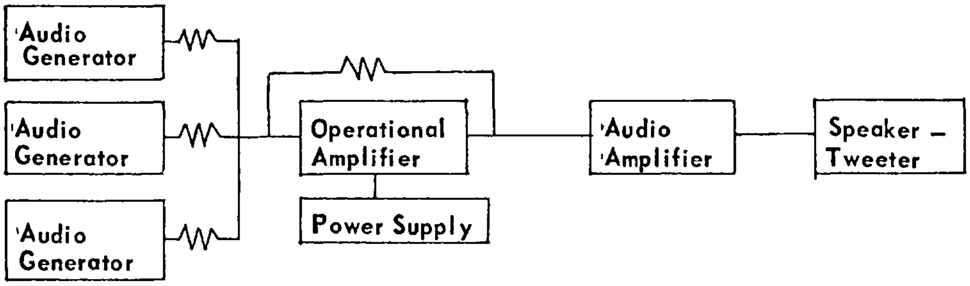


4.

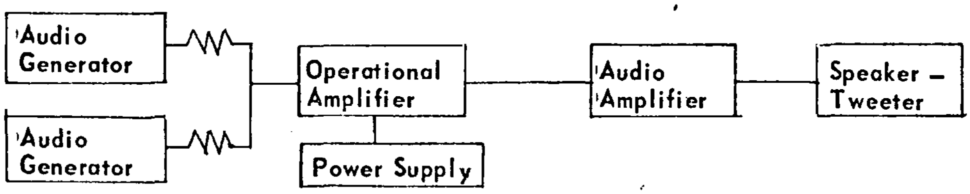


5.

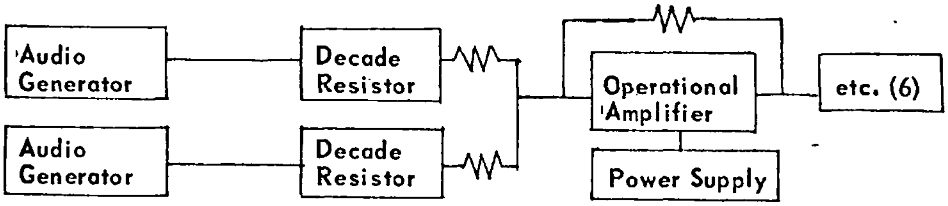
6.



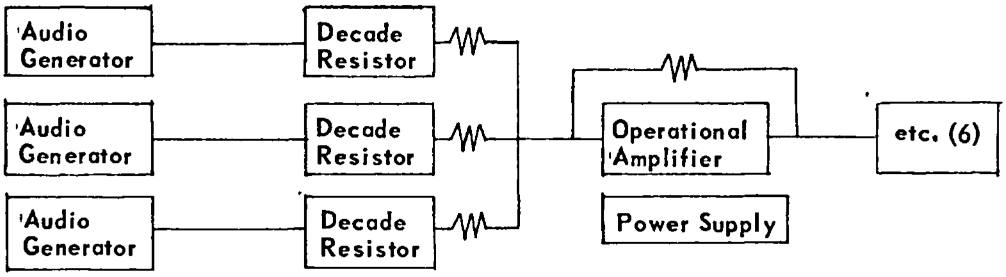
7.



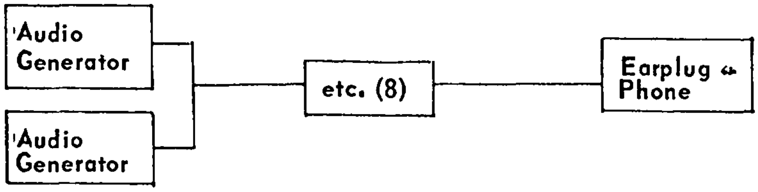
8.



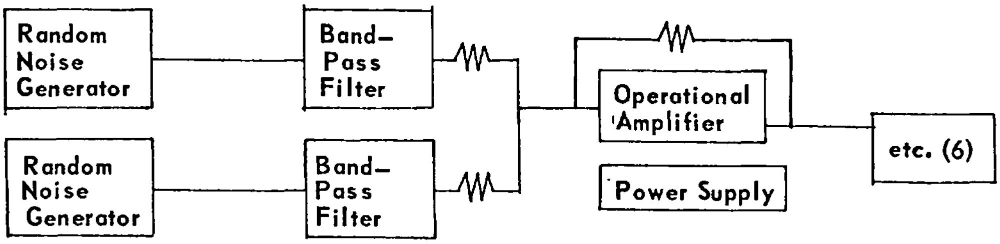
9.



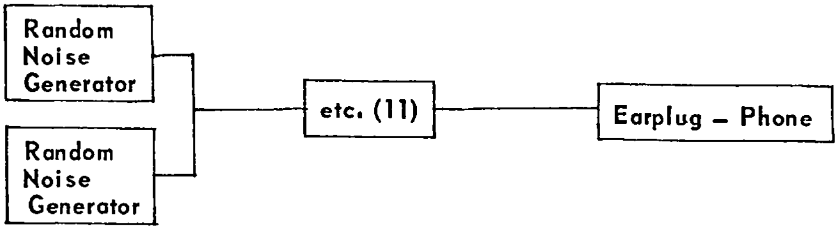
10.



11.



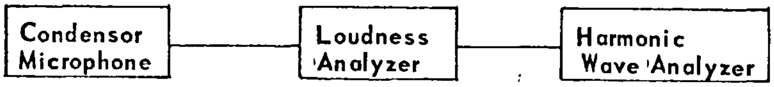
12.



Measuring and Calibration Equipment Configurations

1.

2.



APPENDIX C

ANGELL AND FITE RESULTS

Angell and Fite (1901a, 1901b) performed three experiments which were of interest. The first experiment was performed on a subject deaf in one ear. A spherical sound cage 4 feet in diameter was placed about him with his head in the center. The second experiment used a binaural subject. Again, his head was placed in the center of the sound cage. The third experiment again used the subject deaf in one ear. However, in this experiment the subject's ear was placed in the center of the sound cage. The spherical sound cage consisted of three horizontal planes; an equatorial circle whose plane passes through the center of the head, a circle 45° above the equatorial circle, and a third 45° below. A total of sixteen sound positions were used. Our analysis of the Angell and Fite experiments are listed in Table XXI. It should be noted that these were two dimensional experiments and should not be compared with the vertical localization experiments which are expected to have fewer bits transmitted. Of interest is the ability of the monaural subject to transmit as many bits as the binaural subject.

Table XXI

Angell and Fite Experiments

Test No.	Subject	$\sqrt{\Sigma\sigma_i^2}$	R	Information		
				Transmitted	Equivocation	Noise
I	Monaural	11.9	–	2.18	1.82	1.43
II	Binaural	4.9	–	3.01	.90	.79
III	Monaural	8.1	–	3.19	.81	.70

REFERENCES

Angell, J. R. and W. Fite (1901a), "The Monaural Localization of Sound," Psychol. Rev., Vol. 8, pp. 225-246.

Angell, J. R. and W. Fite (1901b), "Further Observations on the Monaural Localization of Sound," Psychol. Rev., Vol. 8, pp. 449-458.

Attneave, Fred (1959), Application of Information Theory To Psychology, Henry Holt and Company, Inc., New York.

Aviation Week (1969), "Aircraft Collision in 1968 Follow Pattern," Aviation Week, 91, pp. 107-109.

Brown, David R. (1967), "NASA Seeks Low-Cost Collision Warning," Aviation Week, 87, pp. 114-119.

FAA (1967), Proceedings of a Symposium on Pilot Warning Instruments, Federal Aviation Administration, AD 666122, 201 p.

Feddersen, W. E., T. T. Sandel, D. C. Teas, and L. A. Jeffress (1957), "Localization of High Frequency Tones," J. Acoust. Soc. Am., 29, pp. 988-991.

Fynn, William E. and D. N. Elliott (1965), "Role of Pinna in Hearing," J. Acoust. Soc. Am., 38, pp. 104-105.

Hewlett-Packard (1968), Acoustic Handbook, Application Note 100.

Howell, Wayne D. and R. B. Fisher (1957), "Overtaking, Not Head-On Approach, Found To Be Greatest Cause of Our Mid Air Collision," SAE J., 65, pp. 62-65.

Jeffress, L. A. and R. W. Taylor (1961), "Lateralization vs Localization," J. Acoust. Soc. Am., 33, pp. 482-483.

Jongkees, L. B. W. and J. J. Groden (1946), "On Directional Hearing," J. Larynogol. and Oto., 61, pp. 494-504.

Katz, Darryl, Jerry A. Emery, Richard Gabrie, and Alan A. Burrows (1964), Experimental Study of Acoustic Displays of Flight Parameters In A Simulated Aerospace Vehicle, Douglas Aircraft Company (Long Beach), NASA CR-509, 154 p.

Lockheed-California Company (1966), Collision Avoidance Visibility, Rept. No. LR 19790 - L/STR #1004 (SST), AD 807 685, 108 p.

Mills, W. W. (1958), "On Minimum Audible Angle," J. Acoust. Soc. Am., 30, pp. 237-246.

Nordlund, Berthil (1962), "Physical Factors In Angular Localization," Acta Oto-Laryngol., 54, pp. 75-93.

Pollack, Irwin (1952), "The Information of Elementary Displays," J. Acoust. Soc. Am., 24, pp. 745-749.

Pollack, Irwin (1953), "The Information of Elementary Displays II," J. Acoust. Soc. Am., 25, pp. 765-769.

Pratt, Carroll C. (1930), "The Spatial Character of High and Low Tones," J. Exptl. Psychol., 13, pp. 278-285.

Roffler, Suzanne K. and Robert A. Butler (1968a), "Factors That Influence The Localization of Sound in the Vertical Plane," J. Acoust. Soc. Am., 43, pp. 1255-1259.

Roffler, Suzanne K. and Robert A. Butler (1968b), "Localization of Tonal Stimuli In the Vertical Plane," J. Acoust. Soc. Am., 43, pp. 1260-1266.

Saltzman, Dorothy and W. R. Garner (1950), "Accuracy of Visual Estimation of Azimuth Position," J. Psychol., 29, pp. 453-467.

Sandel, T. T., D. C. Teas, W. E. Feddersen, and L. A. Jeffress (1955), "Localization of Sound from Single and Paired Sources," J. Acoust. Soc. Am., 27, pp. 842-852.

Shaw, E. A. G. and R. Teranishi (1968), "Sound Pressure Generated In An External-Ear Replica and Real Human Ears By A Nearby Point Source," J. Acoust. Soc. Am., 44, pp. 240-249.

Sheridan, T. B. and W. R. Ferrell (1966), "Notes for Course 2.18, Man-Machine Systems," Massachussetts Institute of Technology, Cambridge, Mass.

Sperry Gyroscope Company (1963), A Study of Requirements For A Pilot Warning Instrument for Visual Airborne Collision Avoidance, Sperry Report No. ER-5260-0390, AD 614 622, 116 p.

Stevens, Stanley Smith and Hallawell Davis (1938), Hearing: Its Psychology and Physiology, "Auditory Localization," Chapt. 6, pp. 167-183, John Wiley and Sons, Inc., New York.

Trimble, Otis C. (1934), "Localization Of Sound In The Anterior-Posterior and Vertical Dimensions Of 'Auditory' Space," Brit. J. Psychol., 24, pp. 320-334.

Vallerie, Leroy, L. (1968), "Human Factors Program For The Cooperative Pilot Warning Indicator System," Dunlap and Associates, Inc., BSD No. 68-689, N69 - 23893, 33 p.

Wulfeck, Joseph W., Alexander Weiz, and Margaret W. Raben (1958), Vision In Military Aviation, Wright Air Development Center, WADC Tech. Rept. 58-399, AD 207 780, 395 p.