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THE ASSOCIATION OF COLORS WITH PURE TONE FREQUENCIES AMONG MILI--ETC(U)

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THESIS

THE ASSOCIATION OF COLORS
WITH PURE TONE FREQUENCIES
AMONG MILITARY OFFICERS OF THREE NATIONALITIES

by

Henry A. Pyzdrowski, Jr.

March 1979

Thesis Advisor: J.K. Arima

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The Association of Colors With Pure Tone Frequencies Among Military Officers of Three Nationalities

by

Henry A. Pyzdrowski, Jr.
Captain, United States Marine Corps
B.S., United States Naval Academy, 1970

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

This experiment was designed to determine whether there was a natural association of color and pitch that was common among military officers of three nationalities. Fifty military officers were used as subjects. The analysis of experimental data was to produce additional evidence for information display design employing the senses of audition and vision in presenting redundant information. The data analysis indicated that the amount of transmitted information was less than one bit when the maximum possible was 2.32 bits. Three was a significant difference in the amount of transmitted information per nationality though no learning trends among nationalities were observed. The Korean subjects' average number of trials to criterion was significantly different from the Americans' but not from the Indonesians'. A significant association of selected color combinations and tones existed for the Indonesian and American subjects.

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I. INTRODUCTION

This experiment was designed to determine whether there was a natural association of color and pitch that was common among military officers of three nationalities. The experimental parameters were selected on the basis of human factors design criteria and the coding dimensions of audition and vision used in previous investigations. The analysis of experimental data was to provide additional evidence for information display design employing sensory modes of vision and audition in presenting redundant information.

The development of hardware and software technology, providing color graphics and computerized data displays, has placed additional burdens on operating personnel in receiving and correctly interpreting information. Operators and information display systems must function in harmony, but they often exist in an environment where penalties for wrong decisions are significant and performance consistency and safety are paramount. Sensory dimensions may be combined with redundant information coding in order to maintain operator efficiency and alertness.

This investigation was undertaken to explore the feasibility of combining a natural association of color and pitch with present man-machine signal design criteria in order to improve operator behavior and efficiency.

Several references cited in the bibliography provide a basic, though nonexhaustive, survey of investigative tests in this area. Sufficient experimental evidence indicates that there exists among children and adults a particular pattern of association of high- and low- pitched tones with light and dark hues, respectively. In addition, the experiment was to determine the amount of learning and information transmitted in the cross-modality matching and to ascertain whether these criteria were significantly affected by nationality.

II. THE ASSOCIATION OF LIGHT AND SOUND

A. GENERAL

There is a substantial amount of experimental literature investigating the association and psychological correspondences of light and sound. Marks (1974) discussed the equivalence of the psychological attributes of light and sound, i.e., the extent to which the visual dimensions translate into auditory dimensions and vice versa, and presented a brief historical synopsis of several experimental conclusions related to the cross-modality matching of light and sound. He noted that the two fundamental attributes of sense perception were subjective quality and intensity. The dimension of quality was considered to be represented by hue in vision and pitch in hearing. The dimension of intensity was represented by brightness in vision and loudness in hearing. The correlation between brightness and loudness and hue and pitch had been substantiated and found to be consistent and reliable (Simpson, Quinn & Ausubel, 1956; J. C. Stevens & Marks, 1965; Marks & J. C. Stevens, 1966). Marks (1974) investigated the cross-correlation between visual brightness and auditory pitch and reported the following results: the Subjects (Ss) matched pure tones to gray surfaces (using the Munsell System values); with loudness constant, the Ss mapped increasing pitch to increasing surface brightness and with pitch constant, most Ss matched increasing loudness to increasing brightness while some matched increasing loudness to increasing darkness. Wicker (1968) conducted experiments to determine hypothesized perceptual alignments of selected auditory and visual dimensions. Several perceptual alignments were obtained; however, the alignments of pitch-saturation, loudness-brightness and loudness-darkness, as witnessed in other studies, did not occur. In addition, earlier studies of visual and auditory synesthesia produced similar cross-correlations of brightness and pitch. Synesthesia was considered the phenomena in which stimuli reacted to by only one kind of receptor produced experiences or reactions supposedly specific to another sense (Howells, 1938; Riggs & Karowski, 1934; Karowski & Odbert, 1938; Karowski, Odbert & Osgood, 1942). These investigations involved people who claimed that visual sensations arose from auditory stimulation and almost always reported that brightness of these "secondary" visual sensations increased with an increase in pitch of the inducing sound (Marks, 1974). Despite the nonexistence of consistent cross-modality correlations as witnessed by Wicker (1968), sufficient experimental evidence strongly suggests that such correlations do exist. A significant amount of work was done by Stevens (1975) in developing scaling methods for relating these different perceptual dimensions. These scaling methods are discussed later.

B. THE ASSOCIATION OF COLOR AND PITCH

Simpson, Quinn, and Ausubel (1956) conducted an experiment with 995 elementary school children to determine the degree of association between six colors (yellow, orange, red, violet, blue, green) and six pure tone frequencies (125, 500, 1000, 4000, 8000, 12000 Hz). Systematic relationships between the colors and sounds were found as follows:

(1) Yellow and green were associated with the "high" pitched tones (8000, 12000 Hz);

(2) Red and orange were associated with the "middle" pitched tones (1000, 4000 Hz);

(3) Blue and violet were associated with the "low" pitched tones (125, 250 Hz);

(4) The color-tone relationships were not significantly or consistently related to sex or intensity variation;

(5) With the exception of specific color-pair relationships to tone frequency, no one-to-one spectral-tone frequency symmetry existed.

An additional, more subtle, interpretation of experimental results was made with regard to the influence of cultural conditioning. The children (grades three, four, five and six) were selected in order to minimize the influence of cultural conditioning on pitch-hue relationships. The authors pointed out that high and low-pitched notes in music were conventionally used in combination with other elements to produce or represent contrasting moods and that college students and adults, in a musical context, tended to associate light and dark hues with high- and low-pitched musical notes. It was their contention that cultural conditioning influenced the pattern of association among older subjects. Yet, because of the minimization of cultural influences among children, the formation of a similar association pattern would be the result of genetic predisposition. The authors stated:

> The findings of definite pitch-hue associations in children, apart from the musical context, is interpreted as lending support to the view that genetically determined predispositions exist for particular tones and hues to be perceived as selectively compatible with particular mood states, particular colors and tones become indirectly related to each other. (p. 103)

The genetic implications of these results are supported by a study done by S. S. Stevens (1975) in which adults and five-year-old children matched brightness to loudness. In this study Stevens concluded that age and prior learning did not affect the matching process. Also, a study by Walsh (1978) investigated how personality indices were compared to color preferences, which suggests that additional factors influence color-tone matching than cultural conditioning alone.

III. EXPERIMENTAL METHODOLOGY IN THE ASSOCIATION OF LIGHT AND SOUND

A. GENERAL

Several experimental methods used in sensory scaling and cross-modality experiments were reviewed in order to provide a foundation for the design of this study. Of the literature reviewed, the following experimental techniques and test apparatus were selected to provide a survey of previous testing methods involving the association of light and sound. Also, a brief synopsis of experimental results is included.

B. THE ASSOCIATION OF LIGHT AND SOUND USING BRIGHTNESS, PITCH AND SOUND

Marks (1974) investigated the psychological correspondences between light and sound using the dimensions of brightness, pitch and loudness. Several experiments were conducted in which combinations of these dimensions were matched in the following categories: pitch and brightness with loudness constant, loudness and brightness with pitch constant, pitch and loudness with brightness constant, and loudness to brightness at four different pitches (200, 500, 1000, 2000 Hz). The visual stimuli were gray squares of different Munsell values viewed against a black background and then against a white background and illuminated by an incandescent lamp. The auditory stimuli were either pure tones or variable loudness levels generated by an oscillator, amplified and fed through a "sone" potentiometer to earphones. The Experimenter (E) controlled the position-switch for varying the pitch and loudness. In these experiments the Subject (S) was to indicate to the E when a match had been obtained with the auditory stimuli as the observer viewed the visual stimuli. The Ss were not told to match increasing pitch or loudness to increasing brightness and could proceed in whatever way seemed natural to the observer. Several graphical plots of the matching interactions were obtained and used to outline the experimental results. The Ss repeatedly set increasing pitch to increasing brightness. Some observers set increasing loudness to increasing brightness while others set increasing loudness to increasing darkness. When brightness was held constant, increasing pitch was matched to decreasing loudness.

C. CROSS-MODALITY MATCHING OF BRIGHTNESS AND LOUDNESS

J. C. Stevens and Marks (1966) used the method of cross-modality matching to demonstrate that subjective magnitude grows as a power function of stimulus intensity.

Two experiments (with two sessions each) were conducted in which Ss had to adjust sound to match light or adjust light to match sound. In the first session, eight luminance levels between 50 and 100 dB (re 10^{-10}L) were used as visual stimuli and the observer rotated a "sone" potentiometer permitting a 100 dB variation in the level of noise in matching the sound to the light. In the second session, the observers adjusted the light to match the eight levels of sound between 45 and 95 dB (re 0.0002 dyne/cm^2). This scaling experiment demonstrated that the cross-modality matching of brightness and loudness had the form of the "psychophysical power law of sensory magnitude," i.e., that subjective magnitude of brightness grows as a power function of loudness intensity and vice versa. This technique was developed by S. S. Stevens (1975) in order to provide an experimental method for cross-modality matches of different sensory continua.

D. THE ASSOCIATION OF COLORS WITH PURE TONE FREQUENCIES

Simpson, Quinn and Ausubel (1956) conducted an experiment with 995 elementary schools children in groups of 20 in studying the association of spectral colors with pure tone frequencies. The procedure followed in this experiment was to present the Ss with a series of six pure tones (125, 250, 1000, 4000, 8000, 12000 Hz). The subjects responded by indicating which of the six colors (yellow, orange, red, violet, blue, green) they thought of immediately after hearing each tone. The auditory stimuli were generated by an audiometer and passed through earphones to each S. The visual stimuli were six colors on one inch cards with a letter below each card corresponding to the color. The cards were mounted on a rectangular strip of light-tan, manila paper. The Ss responded by writing down the color letter they felt went with the auditory stimulus. The result indicated that yellow and green were associated with high level pitches (8000, 12000 Hz), that red and orange were associated with the middle range pitches (1000, 4000 Hz), and blue and violet were associated with low-pitch tones (125, 250 Hz). These authors referenced a study in which similar results using adult subjects were obtained.

E. SCALING OF SATURATION AND HUE

Indow and S. S. Stevens (1966) conducted a series of scaling experiments on the saturation of aperture colors using the hues red, yellow, green, blue, orange and yellowish-green. Similar experiments were conducted on changes in saturation using various colors. The colors were mixed by means of a rotating prism and presented through five apertures. In each aperture the mixing ratio of two colors were varied continuously and independently without affecting luminance. The principle of the apparatus is illustrated in the paper by Indow and Stevens. The study investigated the relation of saturation to colorimetric purity and luminance of aperture colors viewed in a dark surround. The saturation of the hues was found to increase as a power function of colorimetric purity. Direct hetero-chromatic matching of saturation to saturation led to the construction of families of saturation scales. The authors stated that the scales generated in this experiment were not necessarily useful for practical purposes but served the purpose of quantifying perceptive continua of hue and saturation. Also, during the heterochromatic matchings of saturation, using the colors, red, blue, green and yellow, the authors reported that the observers were unanimous in pointing out that yellow looked brighter than blue, and that in the saturation matches a difference in brightness levels was not particularly disturbing. This article provided a very comprehensive discussion of scaling techniques and color matching methods.

F. HUMAN INFORMATION TRANSMISSION AS A FUNCTION OF SELECTED VISUAL AND AUDITORY STIMULUS DIMENSIONS

Buckner and Harabedian (1961) conducted an exploratory study to investigate information transmission as a function of combinations of selected visual and auditory stimuli. The visual stimuli were three primary hues; red, yellow and green. The auditory stimuli were three pure tones 400, 1000, and 1950 Hz. The visual dimensions were hue and brightness and the auditory dimensions were pitch and loudness. The test apparatus consisted of a response panel containing nine toggle switches and feedback lights in three rows and three columns. A speaker and stimulus aperture were located above the switches. The auditory stimuli were presented through an eight inch speaker and visual stimuli were presented through 1/2 inch aperture. A combination of an auditory and visual stimulus could be produced, but multiple simultaneous stimuli could not. The equipment was designed so that stimuli could be produced at three absolutely discriminable levels for each dimension. There were three levels of hue, brightness, pitch and loudness. Each value of the quantitative stimulus dimensions (loudness and brightness) corresponded to one of three rows and each value of the qualitative stimulus dimensions (pitch and hue) corresponded to one of the three columns. Nine groups of four Ss received a different combination of stimulus dimensions. Thus, for each group, there were nine quantitative-qualitative stimulus combinations. Each S's task was to respond as accurately and as rapidly as he could by moving the toggle switch that represented an appropriate match with the stimulus. The accuracy scores were transformed into information transmission values (bits/stimulus).

The authors presented a brief summary of studies performed on human channel capacity using different types of auditory and visual stimuli. The following studies and results were mentioned: Pollack (1952) found that the channel capacity for absolute judgments of pitch to be 2.5 bits; Garner (1953) using from four to twenty different loudness levels found a channel capacity for absolute loudness judgments to be 2.3 bits; Pollack (1953) found a channel capacity of 3.1 bits for pitch and loudness together, and Eriksen (1954) obtained 3.1 bits for hue and 2.1 bits for brightness. Buckner and Harabedian (1961) differed from these studies in that the amount of input and output information was held constant in order that variations in the amount of information transmitted could be observed. The results were stated as follows:

> Hue produced higher transmission scores and faster reaction times than pitch regardless of whether either was combined with loudness or brightness. Both brightness and loudness yielded higher transmission scores and faster reaction times when they were combined with hue than when they were combined with pitch. (p. 22)

In addition, transmission performance of stimulus redundancy was complicated by the difficulty of discriminating among combined stimulus dimensions. The authors noted that the equality of discrimination which existed when subjects were exposed to single dimensions ceased to exist when exposed to two or more dimensions simultaneously. The results obtained by Buckner and Harabedian (1961) regarding the decrease of transmitted information when stimulus dimensions were increased may have been attributable to the set of experimental conditions used in their study. Egeth and Pachella (1969) and Pollack (1953) stated that in absolute judgment tasks, total information transmitted about a set of stimuli increased as the dimensionality of the stimuli increased but as the number of dimensions increased, information about each component decreased. Egeth and Pachella (1969) cited four factors, acting singly or in combination, that influence multistimulus identification and may have contributed to this decrement: stimulus duration, distraction, interstimulus interference, and stimulus complexity. The influence of these factors may affect the amount of information transmitted in a multidimensional stimulus identification. Alluisi (1957), Buckner and Harabedian (1961), McCormick (1976), and Miller (1956) contain detailed information on discrimination of various sense modalities.

G. THE INFLUENCE OF PRACTICE AND PITCH-DISTANCE BETWEEN TONES ON THE ABSOLUTE IDENTIFICATION OF PITCH

Hartman (1954) investigated several factors influencing absolute judgment using pitch. The following relationships about the role of pitch in absolute judgment tasks were investigated: the effect of pitch separations on accuracy of judgments; the amount of information transmitted as a function of pitch-distance between tones; the relationship of pitch separation and practice on absolute judgment tasks. Four series of nine pure tones, separated by 50, 100, 200, and 300 mels, were recorded at constant intensity and placed discretely on a record to permit individual presentation. Each tone was two seconds in duration and was preceded by a six second burst of white noise, i.e., the following sequence was presented every 30 seconds: a burst of white noise was given to wash out the preservative effects of preceding stimuli (six seconds), an interval of silence (one second), and a pure tone for two seconds. The tones were presented in a predetermined order and in such a way that each tone followed every other tone an equal number of times. The sounds were presented to each S over earphones. The E presented one of the tones and the S had to decide which tone was being presented. The S recorded his response on a chart containing nine circles numbered one to nine (low to high) in order to assist him in picturing the position of the tones. Three four member groups were used and two experimental sessions per week for eight weeks were conducted. Two months after completion of the experiment, each S was given an additional experiment to determine how much information was lost regarding the previous experiment. Hartman (1954) presented a detailed discussion of the experimental results. The significant conclusions were as follows: (1) the smaller the pitch distance between tones, the smaller was the average error of judgment; (2) the wider the pitch distance beteween tones the more the average error was reduced by practice; (3) the learning curves for the 200 and 300 mel groups dropped sharply to asymptotes in about four weeks, while those for the 50 and 100 mel groups were gradual, indicating the learning was still occurring at the end of training; (4) the amount of transmitted information varied directly with the size of the pitch separation of the tones, i.e. varying the separation by a factor of six (300/50 mels) increased the efficiency of information transfer from 40 to 70% at the end of training.

The significant outcome of this experiment was that with wider pitch separation learning was rapid and complete within a few weeks which was not the case with relatively small pitch separations.

IV. PSYCHOLOGICAL SCALES OF LOUDNESS, PITCH AND BRIGHTNESS

During the experimental design, several distinctions regarding the relationships of loudness, pitch, and visual brightness had to be made. These relationships had to be fully understood in order to comprehend the psychological processes occurring in the cross-modality matching and to better interpret the experimental data. In addition, the knowledge of these relationships influenced the selection of the colors, range of frequencies, and loudness levels used in the study.

The terms loudness, pitch and visual brightness are terms that represent the psychological percepts of intensity, frequency and luminance. Human observers do not judge loudness, pitch, and luminance on a purely physical basis; i.e., they are not judged solely on the physical magnitude of a stimulus. S. S. Stevens (1975) has done a considerable amount of work in developing quantitative methods that relate stimulus magnitude to subjective sensation. Stimulus magnitude and several perceptual continua can be related by a linear function when plotted on logarithmic coordinates. For example, loudness magnitude is a linear function of sound pressure level (dB) when plotted in log--log coordinates, i.e., perceived loudness approximates a power function of stimulus intensity (Richards, 1976). This power function for loudness is one instance of what S. S. Stevens (1975) has called the general "psychophysical law." Visual brightness scales, magnitude scales of saturation, and scales for matching brightness and loudness have been developed based on this general "psychophysical law." These power functions are useful because numbers may be matched to sensations (magnitude estimation); loudness scales may be represented as a power function of stimulus intensity. However, psychophysical scales of pitch (Mel scales, relating subjective pitch to frequency), do not behave according to this "psychophysical law." The Mel scale is represented by a curvilinear form. Graphs of pitch (in Mels) versus frequency (in Hz) appear in S. S. Stevens (1966b, p. 1003) and Richards (1976, p. 110). Stevens provides the following graphical interpretation of the Mel scale: subjective pitch increases less and less rapidly as stimulus frequency is increased linearly; subjective pitch increases more and more rapidly as stimulus frequency is increased logarithmically.

The existence of linear and curvilinear magnitude scales show a fundamental difference in perceptual continua. S. S. Stevens (1975) noted that perceptual continua divide themselves into two categories, prothetic and metathetic continua. A prothetic continua represents sensations that have degrees of quantity and magnitude, and are power functions of stimulus magnitude, i.e., agree with the general "psychophysical law." Examples of prothetic continua are loudness, brightness, saturation, and hue. Metathetic continua represent sensations that are qualitative, and change because of differences in the locality of the stimulus. Examples of metathetic continua are pitch and apparent position, i.e., pitch varies from high to low and in a sense has a kind of position. Visual saturation and hue were once thought to be metathetic but Indow and S. S. Stevens (1966) suggest they behave as prothetic continua. Stevens (1975) attempts to clarify these distinctions between prothetic and metathetic continua by the following statement:

> No formula can capture all the richness of the daily sights and sounds and tastes and smells which our sense organs admit to us. Nevertheless, once we make a few basic distinctions, there emerge some principles that relate specific aspects of sensation to certain properties of stimulus forces. A chief distinction is the one between quantity and quality, or magnitude and kind, or size and sort. No pair of common words quite fits the distinction; but what it means concretely is that sweet is different from sour, although both may vary from strong to weak. (p. 12)

The importance of the work of Stevens (1975) in magnitude estimation and cross-modality matching is that it provided a means by which any perceptual continuum could be matched to any other continuum (Indow and Stevens, 1966; Richards, 1976; S. S. Stevens and Marks, 1965; S. S. Stevens, 1975).

V. PARAMETER SELECTION

A. GENERAL

The parameters for this experiment were selected on the basis of human factors design criteria and the visual and auditory coding dimensions used in previous experiments.

According to McCormick (1976) there are three types of human functions involved in the reception of visual and/or auditory signals. These functions are relative discrimination, absolute identification, i.e., a particular signal of some class, when only one is presented; and, specific task requirements of an operator, a general term, which includes various tasks required of an operator, i.e., signal detection, target location and identification, visual scanning, control selection and adjustment and "decision making." Sheridan and Ferrell (1974) state that many judgments people make of size, duration, or velocity are absolute judgments and instead of comparing two observations, people judge observations against a remembered standard. Absolute judgments are expected to be precise, but people commonly make comparative judgments when precision is required. Thus, the difference between absolute and relative discrimination is often times very small.

There are three sets of variables that impose demands for information presentation and data display. These demands were developed by Henneman and Long (1954) when considering the choice between the eyes and ears as sense channels for presentation of information. These sets of demands were: (1) demands imposed by operator variables (e.g., fatigue, motivation, personal habits, expectancy); (2) demands imposed by response variables (e.g., fine quantitative comparison, absolute discrimination, target location and identification, signal detection); (3) demands imposed by special environmental conditions (e.g., ambient noise, change in illumination, masking). A later study cited that the degree of familiarity, meaning and difficulty of material influenced the comprehension of information (Day & Beach, 1959).

The selection of information dimensions is largely a function of these variables that cover a broad range of demands on the operator and his or her workspace environment. These considerations, though somewhat general, provide a basis for selecting color and sound as coding dimensions.

Several references are devoted to the comparison of the auditory and visual senses as information channels (Cheatam, 1959; Henneman & Long, 1954; McCormick, 1976; Mowbray & Gebhard, 1958; Mudd, 1961).

B. COLOR AS A CODING VARIABLE

Advances in hardware technology have made color a highly feasible coding dimension. The use of multicolored CRT displays, operational display panels, and additional decision making aids has placed new burdens on the operator. Christ (1976) points out that the ultimate criterion for deciding whether or not to introduce a change in the design of the display is not how "nice" it looks or how technologically sound it is but how much it will enhance total system performance subject to the limiting objective performance of the operator. The esthetic value of the use of color is well established but a review of literature by Christ (1975) showed that even when operators preferred color displays and were convinced color aided performance, subjective operator reports were not consistent with the objective data regarding color effectiveness.

Experiments have been conducted with one and two dimensional displays and with relatively simple single tasks (choice reaction, search and locate, multiple-target identification). The conclusions stated that color was most likely to benefit performance in any task if the operator was to deal with complex, multiple stimuli and had to distinguish one class of stimuli from another. The results also stated that it appeared color assisted the subjects in organizing inputs from the display (Christ, 1976; Jones, 1962).

Color is not suited for situations demanding rapid and precise identification but it is suited for search and location, recognition and verification tasks. As a coding dimension, hue-brightness dimensions are better suited than size-brightness for accuracy and speed. Ericksen (1952) reported that scanning a group of visual objects in order to locate or count are better performed with color codes than a variety of other codes. Furthermore, color seems to be an important determinant of location speed with dense visual displays. If colored lights are to be used for coding and if color-blind people will have to use the color code, only certain colors (red, green, and blue) are recommended for use. The Air Force Systems Command Design Handbook for Personnel Subsystems, DH 1-3 (1972) states that these colors should meet standard military requirements (MIL-C-25050) because there are many red, green and blue hues that color-blind people cannot correctly identify. These colors should be used at moderate distances because at great distances blue is often confused with green. The USAF Systems Command Design Handbook, DH 1-3 (1972), Handbook of Human Engineering Data (1952), McCormick (1976) and Woodson and Conover (1964) contain additional information on the visual capabilities and limitations to make decisions concerning man's capacity to perform system functions.

In terms of information transmission measures, the capacity for absolute judgments of visual stimuli in a single dimension varies between 2.1 and 3.1 bits. Typically man can discriminate on an absolute basis about five brightnesses of lights and ten colors. Yet for normal operational use only three to five colors are employed. The Human Engineering Guide to Design Criteria for Military Systems Equipment and Facilities (MIL-STD-1478B) suggests the following color coding scheme for information displays:

Color	State	Result
Flashing Red	Emergency	Immediate operator action
Red	Alert	Corrective/override action must be taken
Yellow	Advise	Caution recheck as necessary
Blue	Advisory	Should be avoided
Green	Proceed	Condition Satisfactory

In this present study five Kodak Gelatin Wratten Filters were used as the colored stimuli. The color specifications are listed below. The blue color was the standard color because it allowed for the minimum passage of the brightness when all colors were set at maximum photometric brightness.

Color	Wratten No.	Wavelength (in nm.)
Blue (B)	45A	477
Green (G)	61	536
Yellow (Y)	15	579
Orange (O)	22	595
Red (R)	29	631

Barker and Krebs (1977) provide an annotated bibliography of abstracts and references for 78 studies which are concerned with one or more aspects of color effects on human performance with emphasis on color as a coding dimension in various tasks. A brief comparison of color and sound and the conditions in which each is more effective is provided in Appendix B.

C. PITCH AS A CODING VARIABLE

Several auditory coding methods exist but frequency and intensity are the more commonly used dimensions. It appears that the capacity for absolute judgments of auditory stimuli in a single dimension (e.g., pitch) is approximately 2.3 bits, or about four to seven categories of pitch may be employed in absolute-judgment tasks (McCormick, 1976).

In a noisy operating environment signal intensity has to be set at a level far above the ambient noise level in order to be detected. If several "meanings" are attached to a set of intensity levels (four to eight) of a pure tone, then the range of single intensities is rather restrictive, approximately 60 to 100 dB ; the range of intensity levels is a function of signal detectability among ambient noise and comfortable operator thresholds. On the other hand, four to sevel low frequencies at an approximate equal intensity setting above an ambient noise level are better suited for relative and absolute discrimination tasks. McCormick (1976) provides some guidelines for the selection or design of warning and alarm signals. These design recommendations are as follows:

1. Signals to be discriminated on the basis of frequency should be between 500 and 1000 Hz, though the ear is most sensitive to the range of frequencies 200 - 3000 Hz.

2. When signals have to travel long distances (1000 feet) frequencies below 1000 Hz should be used.

3. When signals have to "bend around" major obstacles or pass through partitions, frequencies below 500 Hz should be used.

4. If different warning signals are used to represent different conditions, each should be discriminable from the other.

5. In order to minimize masking, signals with frequencies different from those that dominate background noise should be used.

6. High intensity, sudden on-set signals should be used to alert an operator.

In addition to these considerations, the frequencies used in this study were selected based on experimental results related to information transmission. Hartman (1954) studied the influence of long training on pitch judgment as a function of the range of stimulus frequency. Sheridan and Ferrell (1974) explained Hartman's results as follows:

> There was at first little difference among groups in information transmitted. After seven weeks of practice all the groups of subjects had improved, but those with greater stimulus range and a wider pitch separation (in mels) between tones, showed greater improvement. The absolute difference between tones may govern their ultimate discriminability, so that practice tends to increase the normally slight dependence of transmission on stimulus range and spacing. (p. 102)

The frequency specifications used in this study are listed below. The reference tone was 1500 Hz at a loudness level of approximately 80 phons (80 dB SPL re 0.00002 dyne/cm^2). The average pitch separation for this study was approximately 200 mels. The pitch values were extrapolated from the psychophysical Mel scale for pitch perception referenced in Richards (1976).

Frequency (Hz)	Pitch (Mels)	Separation (Mels)
375	500	150
500	650	250
750	850	150
1000	1000	300
1500	1300	

Additional auditory selection criteria are discussed in Appendix B.

D. MATCHING CRITERIA

In order to investigate the association of color and pitch, the attributes of brightness and saturation in color and loudness in sound had to be isolated and adjusted in order that the colors appeared subjectively equal in brightness and the sounds appeared subjectively equal in loudness to each S. Therefore, five different colors had to be simultaneously adjusted (controlled) for brightness and saturation in order to isolate the hue aspect. It was assumed that saturation was correlated with brightness within a broad control region of brightness (Indow & S. S. Stevens, 1966). Also, the five different sounds had to be simultaneously adjusted for loudness in order to isolate the pitch aspect.

The matching criteria of loudness and brightness was based on a property common to all human senses, i.e., a person can distinguish a condition of equality with very good precision, the eye being particularly good at this. The estimation of the relative brightness of two lights of the same quality seen adjacent to each other is exceedingly precise. Also louder and softer are easy comparative decisions (Mowbray & Gebhard, 1958). Thus, the S made matching judgments that required him to isolate in his mind one aspect or particular quality, in the appearance of the test stimuli, when other aspects were present in different degrees. Wyszecki and Stiles (1967) provide matching criteria for brightness by the direct comparison method wherein the test stimuli may differ in saturation, hue, or both. The assumptions made in using this technique are that the light patches are homogeneous in appearance over the whole viewing area, at least with respect to the quality being judged, the test stimuli must be geometrically similar, and matched on the same retinal area. A parallel matching criteria was established for the loudness matching.

However, for this present study, the criteria provided by Wyszecki and Stiles (1967) was slightly modified. Five lights (tones) were matched for brightness (loudness) vice two. A preliminary (exploratory) brightness matching experiment using different colors in pairs was conducted before the present experiment was designed. Two colored lights were matched for brightness using the comparison by slow alternating method described by Wyszecki and Stiles (1967). The experiment was to determine if group brightness levels could be established. However, the degree of variability using this direct comparison technique was so large it was decided to allow each S in this present experiment to adjust and establish his own subjective brightness settings. Also, although different frequencies may be equal in acoustic (physical) intensity, an observer may perceive the loudness level of each frequency to be different. Therefore each S "adjusted" each frequency until each tone was equal in subjective loudness.

E. INFORMATION TRANSMISSION USING THE COMBINED DIMENSIONS OF COLOR AND PITCH

A sizeable amount of experimental work has been done supporting the concept of man as a limited information channel. Garner and Hake (1951) applied information measures to man's ability to discriminate stimuli, and Miller (1956) stated that the number of categories into which stimuli could be assigned is near seven. The number of stimulus categories (per sense modality) to be used in absolute judgment tasks is specified in several human engineering design handbooks. For instance, it is recommended that no more than eight categories be used for hue and five for sounds in absolute judgment tasks. McCormick (1976) recommends specific frequency ranges to be used in warning signal design, about 500 - 1000 Hz. These specifications are recommended guidelines, however. But stimulus categories and discriminability are not the only factors affecting man's information transmission abilities.

The use of multidimensional coding redundancy and extended practice contribute to the efficiency of man as a limited information channel, as well. But, just as these factors influence information transmission efficiency, other factors, namely, observation time, stimuli range and spacing of stimuli along a dimension, apparently do not significantly affect efficiency. Sheridan and Ferrell (1974) state that much of the significance of the limited capacity of absolute judgments to transmit information about a single stimulus dimension stems from man's insensitivity to these important factors. Observation time of a stimulus, unless it is very short, has only a slight effect on information transmitted. Sheridan and Ferrell (1974) state that absolute separation along a continuum is not a criterion for discriminability among stimuli judged on an absolute basis. By increasing the separation between stimuli and hence the range for a given number of stimuli, the confusion between stimuli is reduced. By increasing the range, the amount of information transmitted is increased, but only up to a point. The spacing of stimuli within a range has a relatively slight effect on judgments provided the spacing is generous (Erickson & Hake, 1955; Pollack, 1952; Sheridan & Ferrell, 1974). For example, Pollack (1952), as noted by Sheridan and Ferrell (1974), compared judgments of pitch of eight tones logarithmically spaced between 100 and 8000 Hz with judgments of four tones in the range of 100 to 250 Hz and four tones in the range 2000 - 8000 Hz and found essentially no difference for the two cases. Buckner and Harabedian (1961) investigated information as a function of selected visual and auditory stimulus dimensions (hue and brightness and pitch and loudness, respectively) as described in Section IV, Paragraph F, above. The equivalent settings in mels of 500, 1000, 1500 were selected because of the equal discriminability of the frequencies that corresponded to the pitches. These authors contended that the equal discriminability of pitches 500 mels apart could be easily discriminated as the hues. They reported no significance in discriminability among the hues and pitches in terms of number of errors or reaction times. Furthermore, the number of dimensions and number of bits per dimension contribute to the information of a stimulus set, and operators can distinguish among different dimensions better than they can among variations along a single dimension. Multiple dimensions can be used to create redundant coding in which the same information may be presented more reliably. The selection of the frequency range (375 - 1500 Hz) and octave spacing within frequencies was based upon the signal design criteria as referenced in McCormick (1976), though previous experimental work involved frequencies between 250 and 12000 Hz (Simpson, Quinn & Ausubel, 1956) and 400 to 1950 Hz (Buckner & Harabedian, 1961). The information measurement procedures used to calculate experimental information transmission data are explained in Appendix C.

F. EQUAL LOUDNESS CONTOURS

In order to maintain a reliable degree of auditory standardization throughout the study, the reference tone (1500 Hz) was held constant at 80 dB Spl (80 phons); the loudness levels of the four frequencies (375, 500, 700, 1000 Hz) were subjectively matched by each S to the standard loudness level of the reference tone. The loudness level (in phons) over the frequency range (375 - 1500 Hz) is approximately linear. The significance of this is that the subjective loudness of each tone (over the range 375 - 1500 Hz) is approximately equal at 80 dB Spl (McCormick, 1976; Richards, 1976). Sound level measurements were recorded for each S in order to determine the degree of variability among Ss with regard to this standard.

G. SUMMARY

The selection of a coding variable to symbolically represent different kinds of information depends on the way in which an operator will use the information presented to him. Except for the information conveyed by warning and/or emergency signals, information may be qualitative or quantitative in nature. A qualitative reading includes judgment of trends, rates of change, approximate values, etc. A quantitative reading includes an exact numerical reading of temperature, rpm, speed, etc. The scaling of quantitative codes is based on the lower and upper limits of the scale, the number of steps to be used in each scale and spacing of the scale to ensure uniform accuracy all along the scale (Garner & Hake, 1957). The factors discussed in this section were based on the demands of the operator, his performance, and work environment. The interaction of frequency and intensity, and the quantitative relationships among these auditory dimensions influenced the selection of tones, frequency range and reference standard.

VI. SOURCES OF VARIABILITY

A. GENERAL

In order to design test equipment and establish consistent experimental conditions several sources of variability had to be identified and accounted for. For instance, brightness matching for different colors is affected by stimulus color, background (surround), and the amount of ambient illumination. Loudness matching of different frequencies is affected by the amount of ambient noise, and the interaction of intensity and frequency. These are but a few factors that must be considered. The sources of variability that could affect this study were identified as follows: matching method in the brightness matching of *light sources*, stimulus intensity, surround, operators (Subjects), and nationality. These choices were not meant to be inclusive as additional factors are involved. Several authors have addressed the following additional areas as affecting variability in absolute judgment tasks: multidimensional discrimination (Lindsay, Taylor & Forbes, 1968), effects of discriminability and irrelevant information on absolute judgments (Morgan & Alluisi, 1967) and the effects of fatigue, age, practice, and proximity to a meal, on visual and auditory reaction times (Forbes, 1945).

Additional references cited in the bibliography address the information content and discrimination levels of lights and sounds. The significant point is that the systems widely applied in the military and industry employing lights and sounds (separately or in combinations) must be appropriate for the majority of laymen (Halsey, 1959) and must be designed to account for large variances in the operator population.

B. VARIABILITY OF VISUAL COMPARISON TECHNIQUES

There are well established inconsistencies between observers' judgments of equal brightness of several light sources under conditions of direct comparison. These discrepancies are especially large when lights differ markedly in color. This variability has been attributed to the unreliability of the direct visual comparison technique and from the confusion of saturation with brightness. A preliminary experiment to this study was conducted to investigate this variability. The method used was to match five different colors for brightness using slow alternating presentations of two colored lights until all five colors had been subjectively matched for brightness. The variability in the matching was so large that the method had to be discontinued. The effort, though time consuming, was insightful and necessitated a change in test equipment design to one in which five adjacently mounted lights were to be simultaneously adjusted for equal brightness by each S. Wyszecki and Stiles (1967) provide comprehensive technical explanations regarding the difficulty of brightness matching using direct comparison techniques.

C. INTENSITY

The lowering of brightness levels brings about noticeable decreases in color identification and consequently greater reduction in discrimination. A large increase of luminance may cause a hue to lose its color aspect and take on the appearance of a whitish glare. Reduction of sound intensity levels causes tones to become indistinguishable from ambient noise and other sounds used for signalling.

D. OPERATORS

Systems employing operators not trained for specific performance tasks must allow for marked individual differences (e.g., nutrition, expectancy, previously learned habits, sex and anatomical differences, visual and auditory acuity, training, age). Also, a percentage of the user population may be color and/or sound defective. Extended and periodic practice also affects an operator's ability to discriminate and remember assigned information content of signalling devices.

E. SURROUND

Color identification and auditory discrimination are affected by adapting light and ambient noise, respectively (i.e., background). For example, red night lights completely negate refined surface color coding and auditory signals may be masked by ambient noise or similar signals. Colored lights are not so affected by the adapting illumination (i.e., red ready room lights) as are surface colors.

F. NATIONALITY

If cultural, as well as genetic factors, affect the association of particular colors with particular pitches, then differences in nationality should bring out this possible source of variability.

VII. METHOD

A. EXPERIMENTAL SETTING

The experiment took place in a semidark, soundproof cubicle with gray surround. The ambient light level was approximately one foot candle and the ambient noise level was negligible. The E and S sat next to each other for issuance of instructions and test execution. The S was seated directly in front of the apparatus that included the light stimuli and response buttons, and between two loudspeakers which were directly behind the S. The sound generating and amplifying equipment were located outside the cubicle.

B. EQUIPMENT

Each auditory stimulus was generated by one of five Hewlett Packard Audio Frequency Oscillators -- Model 204C. The oscillators were connected in series and each was preset to the desired frequency (Figure 1). The loudness level of each tone was adjusted by rotating the amplitude control knob located on each oscillator. The oscillators were connected to one of five sound buttons on the S's response console (the stimulus-response console will be discussed later). A single cable connection was fed into the accessory channel of a MAICO Dual-Channel Research and Diagnostic Oscillator--Model MA 24B. Figures 2 and 3 illustrate the components of the sound generating and amplification equipment.

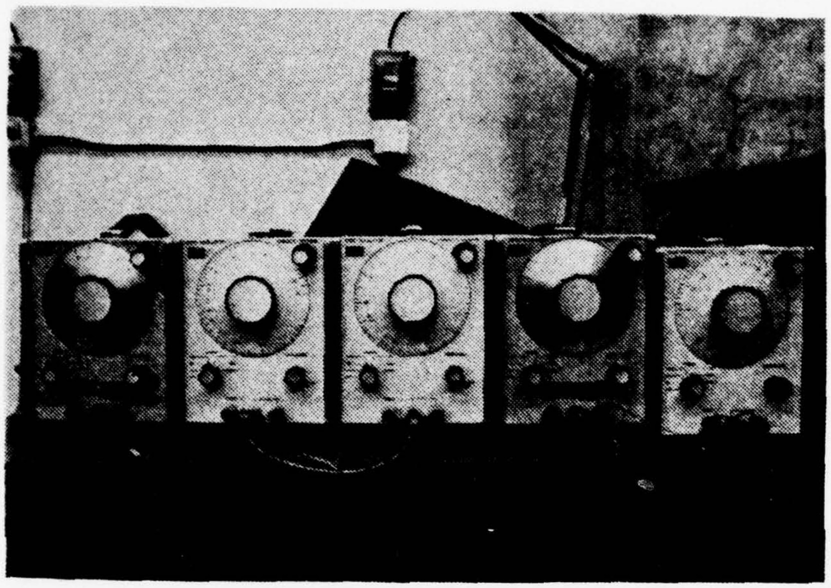


Figure 1. The Hewlett-Packard Audio-Frequency Oscillators (Model 204C)

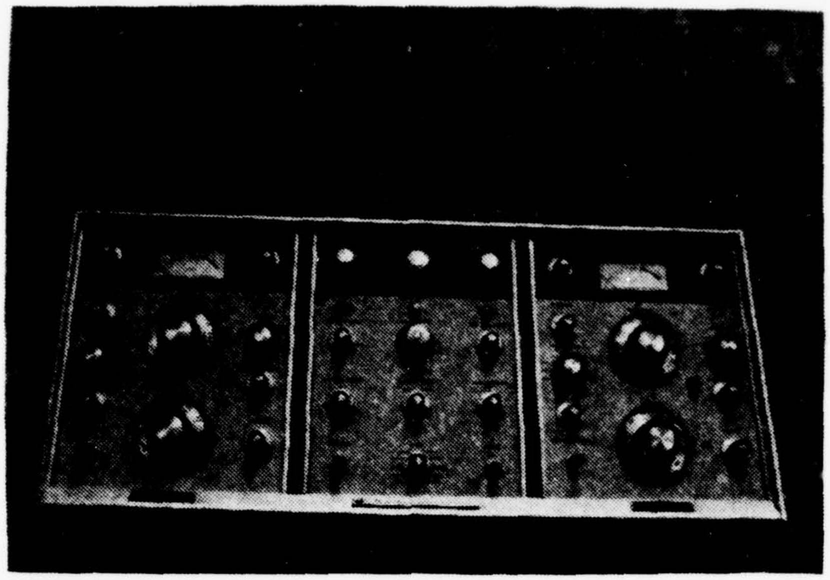


Figure 2. MAICO Dual Channel Audiometer (Model MA-24B)

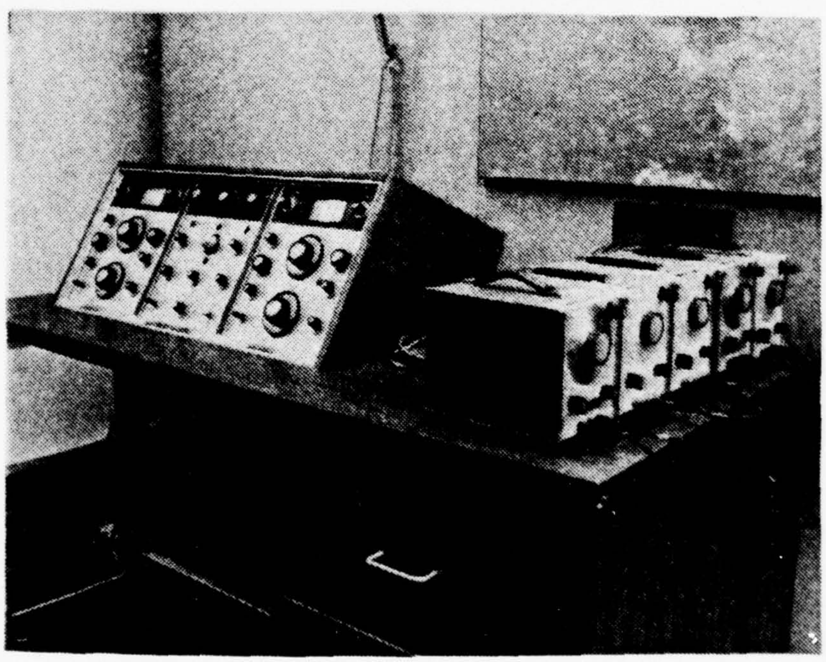
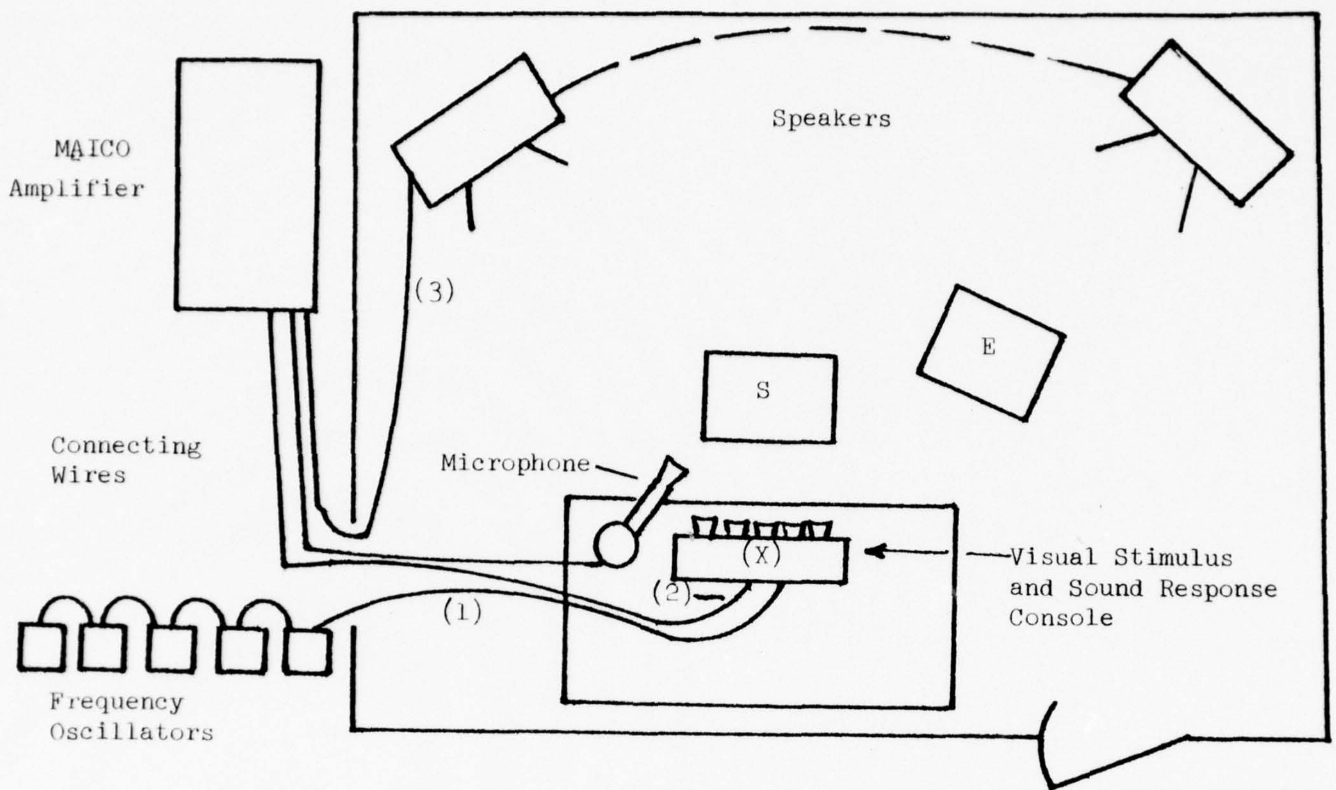


Figure 3. Set up of the MAICO Audiometer and Audio Frequency Oscillators Outside the Sound Booth

A block diagram of the functional relationship among the items is presented in Figure 4. Loudspeakers located inside the cubicle were connected to the MAICO as output channels. Therefore, by pressing one of the response console sound buttons, a sound signal (input) was fed into and amplified by the MAICO and was heard over the loudspeakers (output). The following MAICO accessory controls were preset at the following positions: (1) the output switch was set to "SPEAKER," (2) the test stimulus switch was set to "ACCESS,", the SPEAKER GAIN SWITCH was set at level "8", (3) the MIXER switch was set at "BOTH," (4) the -20 dB NORM control was set at "NORM," (5) the Hearing Threshold Level was set at "65 dB," (6) the Test Presentation switch was set to "ON," (7) the Talk-over Gain, Talk-back Gain, and Monitor Gain were set at level "2." In addition, during the first session of the experiment, the MAICO was used for two way communication between the E and S (in the cubicle).

C. VISUAL STIMULUS AND AUDITORY RESPONSE CONSOLE

The major components of the visual stimulus and auditory response console are illustrated in Figure 5. The console dimensions were 10 in. deep (at the base), 12 in. wide, and 18 in. high with the top, sides, and base being constructed from 1/2 inch plywood. Five 1 1/2-in. diameter projector lamps were adjacently mounted on a supportive aluminum strip. The lamps (and strip) were anchored to the top of



(1) Connecting wires presenting five frequencies to sound switches on console
(2) Connecting wire from sound switches to MAICO for amplification
(3) Connecting wire feeding amplified sound signal from MAICO to output speakers

Figure 4. Diagram of the Functional Relationship of Equipment

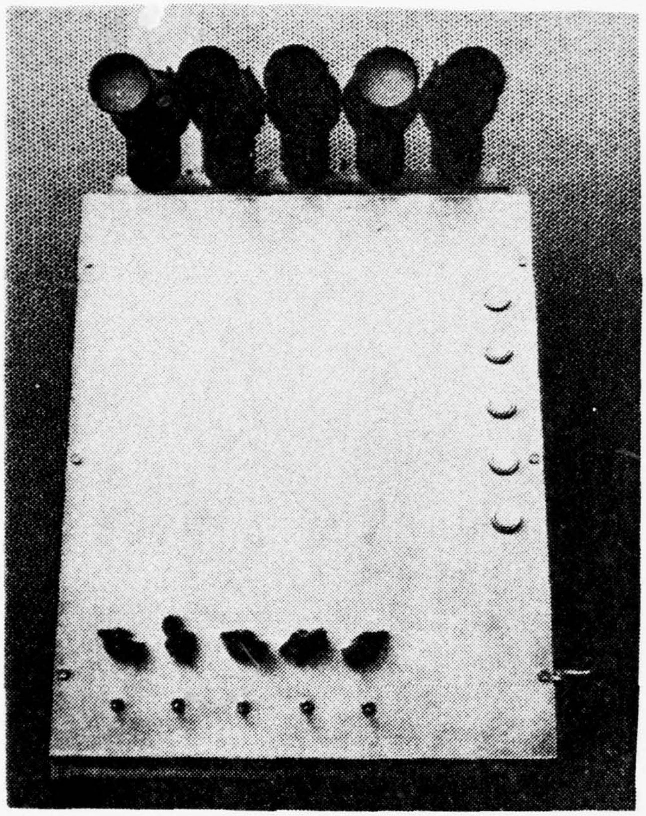


Figure 5. The Visual Stimulus and Response Console

the console. An aluminum plate (12 in. × 15 in., 1/16-in. thick) was attached to the front of the console on which a vertical row of five sound buttons (white push buttons) and a horizontal row of five brightness potentiometers (black knobs) were mounted. Located below each brightness control knob was a single pole, single throw toggle switch.

The vertical row of sound buttons corresponded, in a hierarchical ordering, to the highness and lowness of each pitch from top to bottom, i.e., the first (top) button was connected to 1500 Hz, the second button was connected to 1000 Hz, and so forth. This association remained fixed throughout the experiment. The sound buttons provided the means for responding to the light stimuli.

Each projector lamp consisted of a base and 5-in. tube extension, 1 1/2 in. in diameter. The length of the row of lights was 10 in. with about 1 in. separation between each lamp (Figures 5 and 6). A hollow cylinder containing the colored filter and diffuse filter was enclosed within the 5-in. outer, cylindrical sleeve of the projector lamp. The hollow inner cylinders could be easily removed and exchanged with the other lamp cylinders. One of the five gelatin, color filters was placed on the observer's side of the lamp and the diffuse filter was placed directly behind the color filter. Both filters were placed perpendicular to the line between the light bulb and the S (Figure 7). A lightweight box with gray interior was constructed and placed to enclose

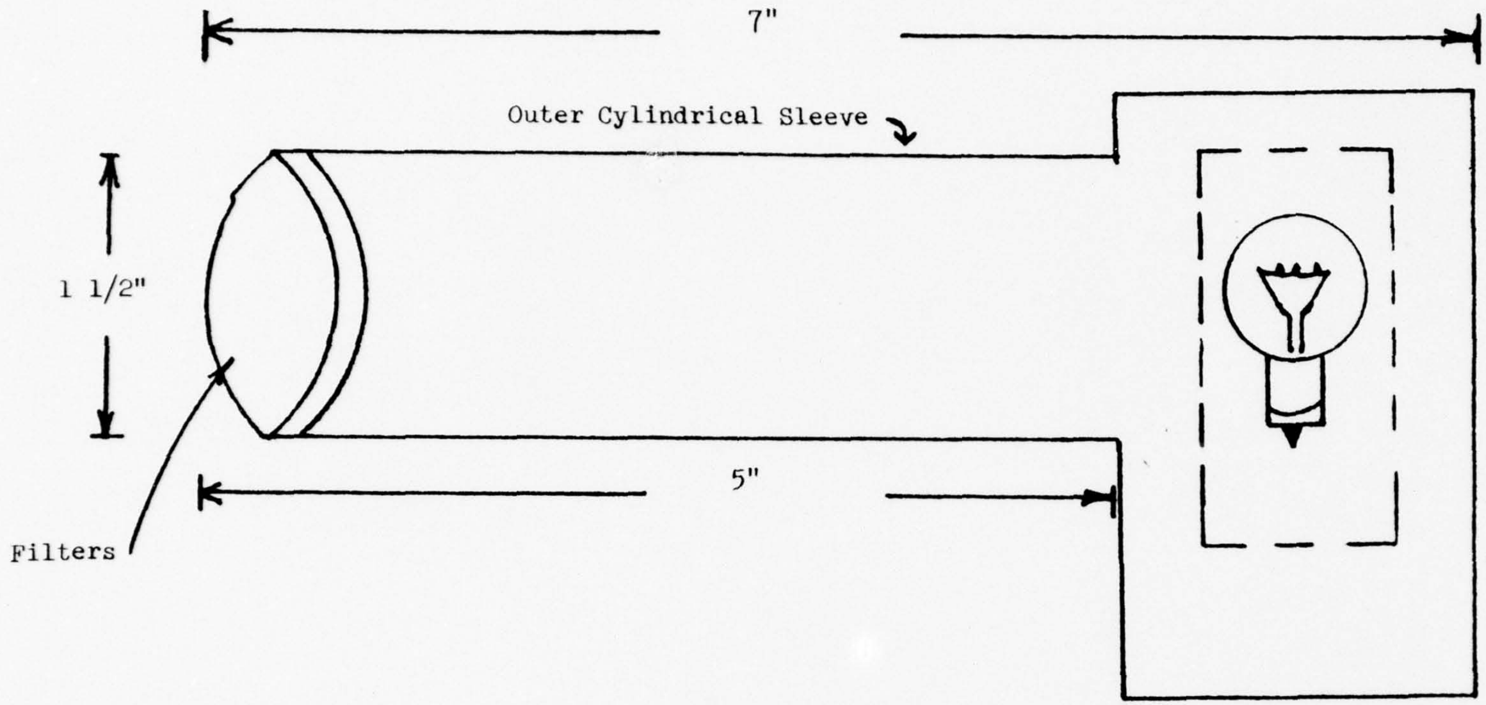


Figure 6. Projector Lamp

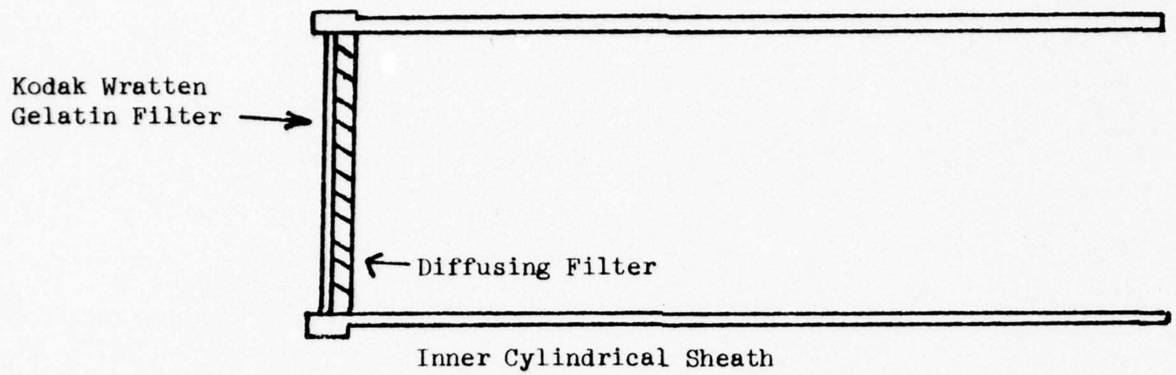


Figure 7. Inner Cylinder Housing the Light Filters

the entire row of projector lamps. In addition, it provided the means to offset the viewing distance (29 in.) between the projector lamp and the S. The dimensions of the box were 16 in. long, 12 in. wide and 4 in. high (Figure 8). Since the viewing area of each light was recessed in a dark surround within the box, each filter could not be discriminated in the ambient light until the selected lamp was turned on. Also the amount of light generated by one light did not provide a sufficient amount of light to illuminate neighboring lamps.

D. SUBJECTS

The Ss for the experiment were 50 male, military-officer students from the Naval Postgraduate School. Ss ranged in age from 27 to 41 years. They were divided into three groups according to nationality: 30 Americans (USA), 10 Indonesians, and 10 Koreans. During preliminary loudness matching and brightness matching sessions, the Ss remained naive as to the ultimate purpose of the experiment. The preliminary loudness matching session additionally served as a hearing test to determine if Ss could discriminate the auditory stimuli. All Ss volunteered for the experiment.

E. PROCEDURE

The basic procedure was to have Ss subjectively match each of five tones for loudness (reference 1500 Hz, 80 dB (SPL)), and then subjectively match all of the five colored lights for brightness (reference blue, set at

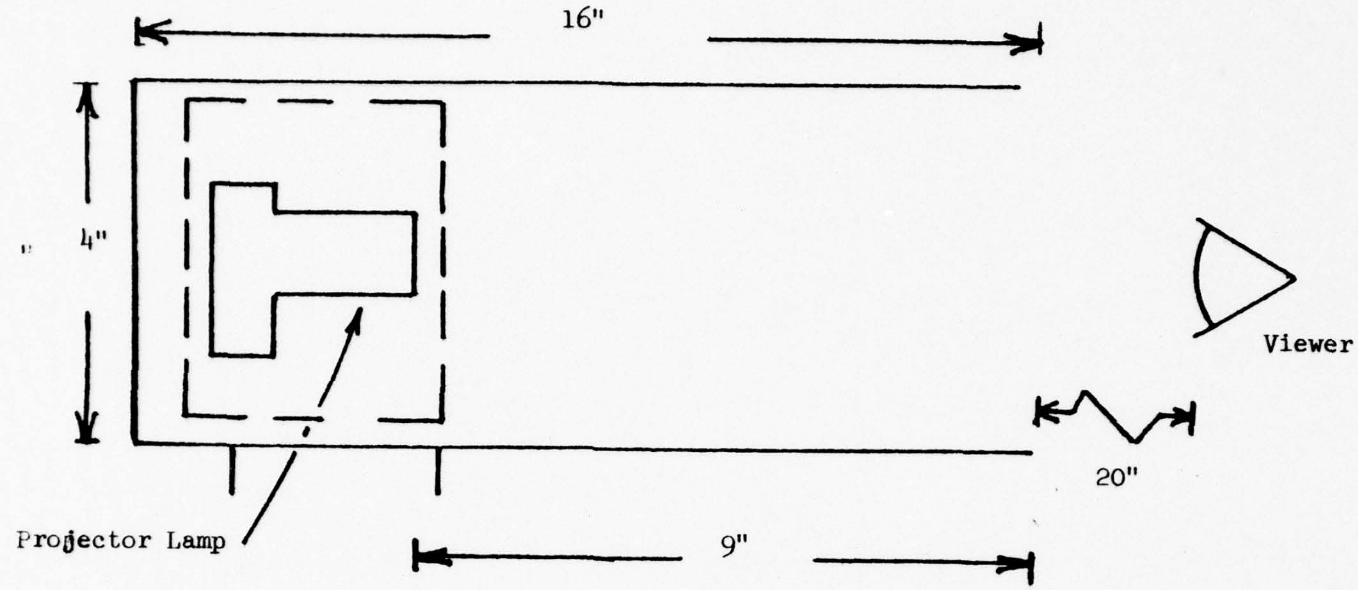


Figure 8. Lightweight Box Housing the Projector Lamps

maximum photometric brightness). The instructions (Appendix D) were orally issued but were standardized for the entire group. The instructions for the loudness and brightness matching made no reference to the ultimate purpose of the experiment. The description of loudness and brightness matching procedures was discussed in paragraphs F and H, below.

After the preliminary matching sessions were completed, each S was presented with a series of five colored lights, one at a time, and had to match a different tone to a different light. The lights were turned on, one at a time, in a random order to eliminate positional effects on the color-tone choices. Random positional arrangements of the five lights were also presented to each S. Any serial combination of R, Y, O was deliberately avoided, however, so as not to influence responses by such a close spectral association. The colors B and G were intentionally positioned to reduce such influence.

When a light was turned on by the E, the S was to respond by depressing a sound button which he "felt" should be matched with the colored light. After the response, the light was turned off and the response was recorded by E. Immediately thereafter, another light was turned on soliciting a response. The S was to match as quickly as possible though response time was not recorded. Each light was presented for approximately two seconds and the interval between light presentations was about one second. During the color-tone matching the Ss were not required to order the matches in any particular direction. They were told to perform the matches in whatever way felt natural or intuitive to them. Moreover, each S was also told that he could change his mind by changing a particular color and tone match but eventually a consistent matching pattern would be attained.

A trial was defined as one series of the five lights, each presented once. Therefore, when the S had been presented each light once and performed one color-tone match for each light, he had performed one trial. The experiment was stopped when the S performed consistent color-tone matches for two consecutive trials. After the two-trial criterion had been reached, the S was dismissed. The responses were tallied, the equal loudness and brightness levels (except for the standard color and tone) were reset. The colored filters were placed in a different random arrangement for the next S. This marked the termination of the experimental session.

F. LOUDNESS MATCHING PROCEDURE

During this phase each S was to match the five tones for loudness using the 1500 Hz, 80 dB tone as a reference. It was not feasible to give the S direct controls for adjusting loudness. Prior to matching the S was told to press each sound button once. This was done in order to assist him in identifying the difference in the loudness aspect when pitch changed. He was then explained the matching adjustment technique and he began by alternately pushing the top button (reference button) and then the second button in sequence. When the S wished the loudness of the second button to equal the loudness of the reference, he instructed the E (located outside the sound booth) to increase or decrease the amplitude of the tone. After the second button was adjusted, the S pushed the reference button and then the third button in the vertical row. Once the adjustments were made for this pair, the fourth and fifth buttons were adjusted similarly. Once the S had equally adjusted all the tones for loudness, he was instructed to push all buttons, one at a time, in any order, to insure he had attained a good loudness match. At the same time he was told to try to remember what each tone sounded like. Thus, he became acquainted with the different tones. After he had completed this final equal loudness check, the E immediately moved on to the brightness matching session.

G. LOUDNESS LEVEL MEASUREMENTS

Loudness level measurements were made with a Portable General Radio Sound Level Meter (Type 1565-B) and were recorded for each S after he had made is equal-loudness settings and completed his experimental trials. The Sound Level Meter was placed on top of the Stimulus-Response Console. The sound phone was pointed in a direction perpendicular to the noise path. The E's body was behind the sound phone out of the noise path. The Symbol "(X)" in Figure 4 marks the position at which the measurements were taken. The sound phone was facing in the direction of the frequency oscillator. Each sound button was pressed one at a time and the loudness level of the sound was measured and recorded. The C weighting scale was used based on the technical manual; i.e., the C scale was closely correlated with subjective estimates of loudness. After all loudness levels were recorded, the E reset the loudness level of each tone (except the reference tone) in preparation for the next S.

H. BRIGHTNESS MATCHING PROCEDURE

During this phase the S was to match five adjacently placed colored lights for brightness. All lights were simultaneously turned on. The S was instructed to make each light appear equal in brightness to the blue light by adjusting the potentiometers positioned below each light.

I. BRIGHTNESS LEVEL MEASUREMENTS

Brightness level measurements were made with a Weston Illumination Meter (No. 756-no filters) and were recorded for each S. The measurement procedure was conducted in the following manner. After the S exited the cubicle the brightness of each light was individually measured. Only one light was on at a time. The hand-held illumination meter was placed directly in front of each light in such a manner that only the light source was measured, uninfluenced by ambient light within the cubicle. The angle of incidence during measurement remained the same for each light from S to S. The observations were recorded after each measurement. After all lights were measured the colored filters were rearranged for the next S. The brightness levels (except for the blue color) were also reset.

VIII. RESULTS

A. COLOR-TONE PREFERENCES

The frequencies of color-tone matchings on the criterion trial for all 50 subjects are presented in Table 1.[1] The relative frequencies of choice (shown in parentheses) were calculated based on the occurrence of 250 color-tone matchings (event-pairs). Five subjects (all U. S. Officers) attained consistent color-tone matchings in two trials, suggesting a cognitive difference in matching strategy may have existed for these subjects. Accordingly, results for all 50 subjects were separated into the frequency of color-tone matchings for the 45 subjects who required more than two trials and the five U. S. subjects who completed the task in two trials. The data appears in Tables 2 and 3, respectively. Inspection of these results indicate that the color-tone frequencies of the five subjects do not reflect a consistent pattern that is different from the group results. Therefore, the results for these five are grouped with the results of the other 25 U. S. Officers for subsequent analyses. Table 4 contains the matchings on the criterion trial by nationality. The results in Table 4 suggest that a color-tone selection preference exists for certain colors and tones by nationality.

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[1] Results by trial showing choice, number of subjects and the amount of information transmitted per trial are displayed in a separate Data Appendix, Appendix E.

Table 1

Frequency of Color-Tone Matchings on the Criterion Trial for All Subjects
(Relative frequencies are shown in parentheses)

Colors	Tones					Row Sums
	375	500	750	1000	1500	
Red	7 (.028)	4 (.016)	10 (.04)	3 (.012)	26 (.104)	50 (.20)
Yellow	4 (.016)	6 (.024)	11 (.044)	14 (.056)	15 (.06)	50 (.20)
Orange	6 (.024)	7 (.028)	12 (.048)	21 (.084)	4 (.016)	50 (.20)
Green	8 (.032)	22 (.088)	13 (.052)	6 (.024)	1 (.004)	50 (.20)
Blue	25 (.10)	11 (.044)	4 (.016)	6 (.024)	4 (.016)	50 (.20)
(Column Sums)	50 (.20)	50 (.20)	50 (.20)	50 (.20)	50 (.20)	250 (1)

Table 2

Frequency of Color-Tone Matchings on the Criterion Trial for All Subjects Less Those Who Attained A Color-Tone Match in Two Trials (Relative frequencies are shown in parentheses)

Colors	Tones 375	500	750	1000	1500	Row Sums
Red	6 (.026)	3 (.013)	9 (.04)	3 (.013)	24 (.107)	45 (.20)
Yellow	3 (.013)	5 (.022)	10 (.044)	13 (.058)	14 (.062)	45 (.20)
Orange	6 (.026)	7 (.031)	11 (.049)	19 (.084)	2 (.008)	45 (.20)
Green	8 (.036)	20 (.089)	11 (.049)	5 (.022)	1 (.004)	45 (.20)
Blue	22 (.098)	10 (.044)	4 (.018)	5 (.022)	4 (.018)	45 (.20)
(Column Sums)	45 (.20)	45 (.20)	45 (.20)	45 (.20)	45 (.20)	225 (1)

Table 3

Frequency of Color-Tone Matchings on the Criterion Trial for Subjects Who Attained a Color-Tone Match in Two Trials
(Relative frequencies are shown in parentheses)

Colors	Tones					Row Sums
	375	500	750	1000	1500	
Red	1 (.04)	1 (.04)	1 (.04)	0 (.00)	2 (.08)	5 (.20)
Yellow	1 (.04)	1 (.04)	1 (.04)	1 (.04)	1 (.04)	5 (.20)
Orange	0 (.00)	0 (.00)	1 (.04)	2 (.08)	2 (.08)	5 (.20)
Green	0 (.00)	2 (.08)	2 (.08)	1 (.04)	0 (.00)	5 (.20)
Blue	3 (.12)	1 (.04)	0 (.00)	1 (.04)	0 (.00)	5 (.20)
(Column Sums)	5 (.20)	5 (.20)	5 (.20)	5 (.20)	5 (.20)	25 (1)

Table 4

Frequency of Color-Tone Matchings on the Criterion Trial by Nationality
(Relative frequencies are shown in paratheses)

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			U. S. Officers			
Red	5 (.033)	1 (.007)	7 (.047)	2 (.013)	15 (.10)	30 (.20)
Yellow	3 (.02)	2 (.013)	5 (.033)	9 (.06)	11 (.073)	30 (.20)
Orange	2 (.013)	5 (.033)	8 (.053)	12 (.08)	3 (.02)	30 (.20)
Green	4 (.027)	15 (.10)	8 (.053)	3 (.02)	0 (.00)	30 (.20)
Blue	16 (.107)	7 (.047)	2 (.013)	4 (.027)	1 (.007)	30 (.20)
(Column Sums)	30 (.20)	30 (.20)	30 (.20)	30 (.20)	30 (.20)	150 (1)
			Indonesians			
Red	0 (.00)	2 (.04)	2 (.04)	0 (.00)	6 (.12)	10 (.20)
Yellow	0 (.00)	0 (.00)	3 (.06)	3 (.06)	4 (.08)	10 (.20)
Orange	0 (.00)	1 (.02)	3 (.06)	6 (.12)	0 (.00)	10 (.20)
Green	3 (.06)	4 (.08)	2 (.04)	1 (.02)	0 (.00)	10 (.20)
Blue	7 (.14)	3 (.06)	0 (.00)	0 (.00)	0 (.00)	10 (.20)
(Column Sums)	10 (.20)	10 (.20)	10 (.20)	10 (.20)	10 (.20)	50 (1)

Table 4 Continued

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			Koreans			
Red	2 (.04)	1 (.02)	1 (.02)	1 (.02)	5 (.10)	10 (.20)
Yellow	1 (.02)	4 (.08)	3 (.06)	2 (.04)	0 (.00)	10 (.20)
Orange	4 (.08)	1 (.02)	1 (.02)	3 (.04)	1 (.02)	10 (.20)
Green	1 (.02)	3 (.06)	3 (.06)	2 (.04)	1 (.02)	10 (.20)
Blue	2 (.04)	1 (.02)	2 (.04)	2 (.04)	3 (.06)	10 (.20)
(Column Sums)	10 (.20)	10 (.20)	10 (.20)	10 (.20)	10 (.20)	50 (1)

The relative frequencies in Tables 1 and 4 were transformed to information measures in bits and used to calculate the information transmitted per trial for all subjects and by nationality. Table 5 contains the information quantities for the color-tone matchings on the criterion trial for all subjects and by nationality.[2] The following information measures are listed in Table 5: (1) input information, $H(X)$; (2) output information, $H(Y)$; (3) joint information, $H(X,Y)$; (4) transmitted information, $T(X,Y)$; (5) noise, $H(Y|X)$; and (6) equivocation, $H(X|Y)$. The amount of transmitted information was calculated by summing $H(X)$ and $H(Y)$ and subtracting $H(X,Y)$. Noise, $H(Y|X)$, was calculated by subtracting $T(X,Y)$ from $H(Y)$, and equivocation, $H(X|Y)$, was calculated by subtracting $T(X,Y)$ from $H(X)$. The amount of transmitted information was used as an index of consistency with which tones were matched to colors using subjects as a group, not as individuals. Perfect transmission would mean that knowledge of the response (i.e., tone selected) would yield knowledge of what color had been presented. The value of transmitted information in a perfect transmission task would be 2.32 bits. Analysis of the results in Table 5 indicated that the Indonesians had approximately twice as much transmitted information (.86 bits) as did the U. S. Officers (.40 bits) and approximately 3.5 times as much as the

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[2] A detailed discussion of information contingency tables and calculations appears in Appendix C.

Table 5

Information Transmission (in bits) in Color-Tone Matchings on the Criterion Trial for All Subjects and by Nationality

H(X)	H(Y)	H(X,Y)	T(X,Y)	H(X|Y)	H(Y|X)
		All Subjects			
2.32	2.32	4.13	.51	1.81	1.81
		U. S. Officers			
2.32	2.32	4.24	.40	1.92	1.92
		Indonesians			
2.32	2.32	3.78	.86	1.46	1.46
		Koreans			
2.32	2.32.	4.38	.26	2.06	2.06

Koreans (.26 bits). The results indicate different amounts of information transmitted by nationality, although all amounts were less than one bit.

In order to evaluate the sources of noise in the data, conditional response distributions were calculated for each color. Table 6 contains the noise source evaluation by color for all subjects and by nationality on the criterion trial. Each conditional probability was transformed to information in bits and these values were summed across each row to obtain the amount of noise (bits) per color. The occurrence of noise resulted from the tendency of a single stimulus to elicit several different responses. The amount of noise per color measured the variability in the responses not correlated with stimuli variability. The colors associated with the lower amounts of noise indicated that subjects tended to match tones more consistently for them, i.e., there was less variance. Colors associated with the larger noise values indicated that subjects were not consistent in their matching process. The frequencies associated with the conditional probabilities in Table 6 were used to perform a one-sample Chi-Square test (Siegel, 1956, pp. 42-46) in order to evaluate the statistical significance of the distributions. The Chi-Square values of the response (tone) distributions were evaluated against the hypotheses that expected tone responses would be evenly matched for any color. The expected frequencies per cell for the Indonesians and Koreans were less than five, but

Table 6

Noise Source Evaluation by Color for All Subjects and by Nationality on the Criterion Trial
(Conditional probabilities in rows)

Colors	Tones					Noise(bits)
	375	500	750	1000	1500	
			All Subjects			
Red	.14	.08	.20	.06	.52	1.89
Yellow	.08	.12	.22	.28	.30	2.17
Orange	.12	.14	.24	.42	.08	2.08
Green	.16	.44	.26	.12	.02	1.93
Blue	.50	.22	.08	.12	.08	1.93
			U. S. Officers			
Red	.17	.03	.23	.07	.50	1.84
Yellow	.10	.07	.17	.30	.37	2.09
Orange	.07	.17	.27	.40	.10	1.81
Green	.13	.50	.27	.10	.00	1.73
Blue	.53	.23	.07	.13	.03	1.78
			Indonesians			
Red	.00	.20	.20	.00	.60	1.37
Yellow	.00	.00	.30	.30	.40	1.57
Orange	.00	.10	.30	.60	.00	1.30
Green	.30	.40	.20	.10	.00	1.85
Blue	.70	.30	.00	.00	.00	.88
			Koreans			
Red	.20	.10	.10	.10	.50	1.96
Yellow	.10	.40	.30	.20	.00	1.85
Orange	.40	.10	.10	.30	.10	2.05
Green	.10	.30	.30	.20	.10	2.17
Blue	.20	.10	.20	.20	.30	2.25

the nature of the noise source evaluation did not allow for additional combinations of some of the classes to increase expected frequencies. Since, however, there were more than two degrees of freedom and the expected frequencies per cell were equal to two, Chi-square values were calculated for the Indonesians and Koreans as rough approximations (Walker and Lev, 1953, p. 107). Chi-square values greater than the critical value of 9.5 indicated a signficant departure from a uniform distribution of tones for those colors. In addition, the Chi-square values for the Americans and group (all 50 subjects) responses for the color yellow suggested a strong association of the color yellow and a particular sound did not exist. The results are listed in Table 7.

In order to assess the effects of reducing the noise source, the task was transformed to an information reduction task using only two categories, high (1000 and 1500 Hz) and low (375 and 500 Hz). The 750 Hz tone was excluded. The stimuli remained classified into five categories. Table 8 contains the results of this noise reduction analysis for all subjects and by nationality. The Chi-square independent, k-sample test (Siegel, 1956, pp. 175-179) was used to evaluate the noise reduction. Chi-square values for all 50 subjects and by nationality were computed. However, the expected frequencies for the Indonesians and Koreans were less than five but greater than two. The Chi-square values for these nationalities are their approximations. The contingency

Table 7

Chi-Square Values of Response (Tone) Distributions for Each Color by All Subjects and by Nationality

	Chi-Square			
Colors	Koreans	Indonesians	Americans	All Subjects
Red	6.0	12.0	20.6	35.0
Yellow	5.0	7.0	10.0	9.4
Orange	4.0	13.0	11.0	18.6
Green	2.0	5.0	16.3	25.4
Blue	1.0	13.0	13.67	31.4

Chi-Square at a .05 level with four degrees of freedom = 9.5

coefficient, (C) (Siegel, 1956, pp. 196-202), was computed for the appropriate Chi-square values in order to measure the degree of association between the variables of color and two sound categories. However, the contingency coefficient is not comparable to other correlation measures. With the exception of the Korean subjects, the results of the noise reduction were significant beyond the .001 level. The Chi-Square value for the Koreans (Chi-Square = 3.04) indicated that the color and tone combinations were independent. Some Chi-square values in Table 8 were larger than those values in Table 6 indicating that reduction of response categories increased the association of a particular color with a combination tone. This result was expected. A strong color-tone dependency existed except as noted above.

Analogous to the response (noise) reduction reported above, colors were combined to reduce the equivocation possible in the task using all five-tone categories, this, above, became a stimulus amplification task. Analyses of the response distribution for the combined color signals for all subjects and by nationality appear in Table 9. The one-sample Chi-square test was used to calculate Chi-square values of the response distribution. The Chi-square was evaluated against the expected hypothesis that tone choices would be evenly distributed for any color-combination. The expected frequencies for the Indonesians and Koreans was less than five (i.e., four); however, it was assumed that

Table 8

Noise Reduction by Reducing Responses to Two Categories (High, Low) for All Subjects and by Nationality[1]

Color	Tones: High (1000, 1500)	Tones: Low (375, 500)	Row Sums
All Subjects			
Red	29	11	40
Yellow	29	10	39
Orange	25	13	38
Green	7	30	37
Blue	10	36	46
(Column Sums)	100	100	200

Chi-Square = 50.4

Contingency Coefficient = .448

Color	Tones: High (1000, 1500)	Tones: Low (375, 500)	Row Sums
U. S. Officers			
Red	17	6	23
Yellow	20	5	25
Orange	15	7	22
Green	3	19	22
Blue	5	23	28
(Column Sums)	60	60	120

Chi-Square = 40.36

Contingency Coefficient = .502

Table 8 Continued

Colors	Tones High (1000, 1500)	Low (375, 500)	Row Sums
	Indonesian Officers		
Red	6	2	8
Yellow	7	-	7
Orange	6	1	7
Green	1	7	8
Blue	-	10	10
(Column Sums)	20	20	40

Chi-Square = 27.07

Contingency Coefficient = .635

Colors	High (1000, 1500)	Low (375, 500)	Row Sums
	Korean Officers		
Red	6	3	9
Yellow	2	5	7
Orange	4	5	9
Green	3	4	7
Blue	5	3	8
(Column Sums)	20	20	40

Chi-Square = 3.04

Contingency Coefficient = .265

1. The Chi-Square value at a .05 level with four degrees of freedom is 9.5

Table 9

Response Distribution for Combined Color Signals for All Subjects and by Nationality

Color Combinations	Tones					Row Sums
	375	500	750	1000	1500	
			All Subjects			
Red-Yellow	11	10	21	17	41	100
Red-Orange	13	11	22	24	30	100
Yellow-Orange	10	13	23	35	19	100
Red-Yellow-Orange	17	17	33	38	45	150
Green-Blue	33	33	17	12	5	100
(Column Sums)	84	84	116	126	140	
			U. S. Officers			
Red-Yellow	8	3	12	11	26	60
Red-Orange	7	6	15	14	18	60
Yellow-Orange	5	7	13	21	14	60
Red-Yellow-Orange	10	8	20	23	29	90
Green-Blue	20	22	10	7	1	60
(Column Sums)	50	46	70	76	88	

Table 9 Continued

Color Combinations	Tones					Row Sums
	375	500	750	1000	1500	
			Indonesian Officers			
Red-Yellow	0	2	5	3	10	20
Red-Orange	0	3	5	6	6	20
Yellow-Orange	0	1	6	9	4	20
Red-Yellow-Orange	0	3	8	9	10	30
Green-Blue	10	7	2	1	0	20
(Column Sums)	10	16	26	28	30	
			Korean Officers			
Red-Yellow	3	5	4	3	5	20
Red-Orange	6	2	2	4	6	20
Yellow-Orange	5	5	4	5	1	20
Red-Yellow-Orange	7	6	5	6	6	30
Green-Blue	3	4	5	4	4	20
(Column Sums)	24	22	20	22	22	

these cell frequencies would yield good Chi-square approximations. These results (Table 10) show that the dependency of combined colors on tone responses is less than the dependency of some single colors and tone responses (Table 7).

An equivocation analysis was conducted using color combinations red-yellow-orange and green-blue. The occurrence of equivocation results from the tendency of subjects to make the same response to several different stimuli. Thus to analyze equivocation reduction, the number of color stimuli were reduced by grouping them according to the commonalities seen in the preceding analyses.

The 5 × 2 contingency matrices were evaluated using Chi-square and the results were highly significant for all subjects and each nationality except for the Koreans (Chi-square = .833). Contingency coefficients were computed to provide an index of association between color combinations and tone responses. The row frequency data were transformed to bits using their relative frequencies. The information values were summed across each row providing a measure for the amount of equivocation in bits. The equivocation measured the tendency among subjects for several stimuli to elicit one response. The high equivocation values (close to one bit) indicated the existence of considerable uncertainty in matching a certain sound to particular color combinations, but there was considerable variability among tones and nationalities. The equivocation

Table 10

Chi-Square Values for the Association of Color Combinations and Tones for All Subjects and by Nationality

Chi-Square[1]

Color Combinations	Koreans	Indonesians	U. S. Officers	All Subjects
Red-Yellow	1.0	14.5	24.5	31.6
Red-Orange	4.0	6.5	9.16	12.5
Yellow-Orange	3.0	13.5	13.3	19.2
Red-Yellow-Orange	.333	12.3	17.4	21.2
Green-Blue	.50	18.5	26.2	31.8

1. Chi-Square was evaluated against the expected hypotheses that tone choices would be evenly distributed for any color combination. The critical Chi-Square value with four degrees of freedom at the .05 level was 9.5.

values were largest for the Korean subjects which provided an additional indicator of the lack of agreement present in the matching process for these subjects. The low equivocation values for the U. S. Officers and particulary the Indonesian Officers indicated consistent matchings existed for particular color combinations and tone responses. Equivocation results are provided in Table 11.

An optimal grouping of color combinations and tone combinations for all subjects and by nationality was obtained by selecting the color combinations and tone combinations with the larger Chi-square values computed in previous analyses (Tables 8 and 10). These optimal groupings are listed in Table 12. Chi-square and contingency coefficient values for these optimal color and tone combinations are summarized in Table 13. The results indicate highly significant dependence among color and tone combinations for the U. S. and Indonesian subjects. The grouping for the Korean subjects (Chi-square = .477) indicated that the color and tone combinations were highly independent. Figures 12 through 15 contain graphical representations of highly significant tone choices for red-yellow and green-blue color combinations for all subjects and by nationality listed in Table 10.

B. TRIALS TO CRITERION

The frequency distribution of trials to criterion for all subjects and by nationality is shown in Table 14. A fixed effects, one way analysis of variance for unequal

Table 11

Equivocation Reduction by Combining Color Signals for All Subjects and by Nationality

Tones	Color Combinations		Equivocation (bits)	Row Sums
	Red-Yellow-Orange	Green-Blue		
		All Subjects		
375	17	33	.925	50
500	17	33	.925	50
750	33	17	.925	50
1000	38	12	.795	50
1500	45	5	.469	50
(Column Sums)	150	100		

Chi-Square = 53

Contingency Coefficient = .418

Tones	Red-Yellow-Orange	Green-Blue	Equivocation (bits)	Row Sums
		U. S. Officers		
375	10	20	.915	30
500	8	22	.841	30
750	20	10	.915	30
1000	23	7	.778	30
1500	29	1	.194	30
(Column Sums)	90	60		

Chi-Square = 43.6

Contingency Coefficient = .475

Table 11 Continued

Tones	Color Combinations: Red-Yellow-Orange	Color Combinations: Green-Blue	Equivocation (bits)	Row Sums
		Indonesians		
375	0	10	0	10
500	3	7	.881	10
750	8	2	.722	10
1000	9	1	.469	10
1500	10	0	0	10
(Column Sums)	30	20		

Chi-Square = 30.83

Contingency Coefficient = .617

Tones	Color Combinations: Red-Yellow-Orange	Color Combinations: Green-Blue	Equivocation (bits)	Row Sums
		Koreans		
375	7	3	.889	10
500	6	4	.971	10
750	5	5	1.000	10
1000	6	4	.971	10
1500	6	4	.971	10
(Column Sums)	30	20		

Chi-Square = .833

Contingency Coefficient = .128

Table 12

Optimal Grouping of Color-Combinations and Tone Combination for All Subjects and by Nationality

Color Combination	Tones High (1000, 1500)	Tones Low (375,500)	Row Sums
		All Subjects	
Red-Yellow	58	21	79
Green-Blue	17	66	83
(Column Sums)	75	87	
		U. S. Officers	
Red-Yellow	37	11	48
Green-Blue	8	42	50
(Column Sums)	45	53	
		Indonesians	
Red-Yellow	13	2	15
Yellow-Orange	13	0	13
Green-Blue	1	17	18
(Column Sums)	27	19	
		Koreans	
Red-Orange	10	8	18
Yellow-Orange	6	10	16
(Column Sums)	16	18	

Table 13

Chi-Square and Contingency Coefficient Values for the Optimal Grouping of Color Combination and Tone Combination for All Subjects and by Nationality

Subjects	Chi-Square[1]	Contingency Coefficient[3]
All Subjects	43.48	.46
U. S. Officers	34.38	.51
Indonesians[2]	34.93	.66
Koreans	.477	.103

1. The critical Chi-Square value with one degree of freedom at the .001 level is 10.38.
2. The critical Chi-Square value with two degrees of freedom at the .001 level is 13.82.
3. The upper limits of the contingency coefficient for a 2x2 and 3x3 contingency table are .707 and .816 respectively.

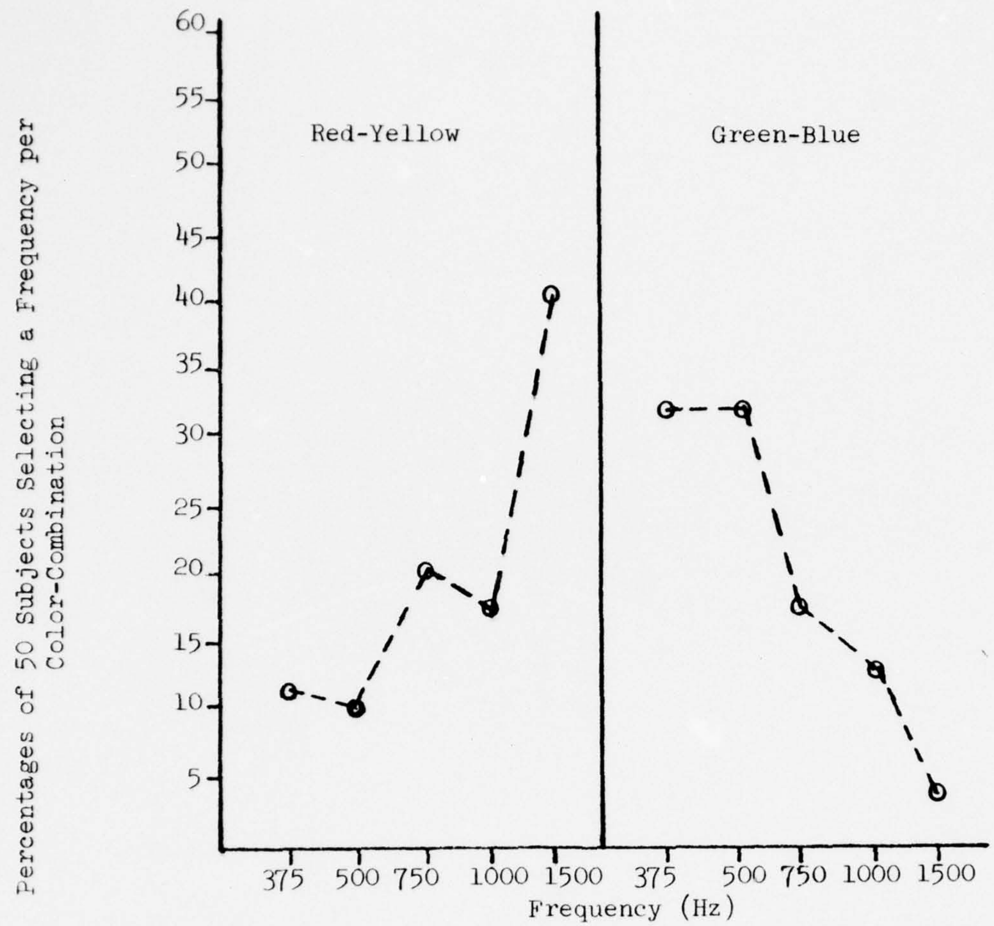

Figure 12. Graphical Representation of Tone Choices for Red-Yellow, and Green-Blue Color Combinations for All Subjects

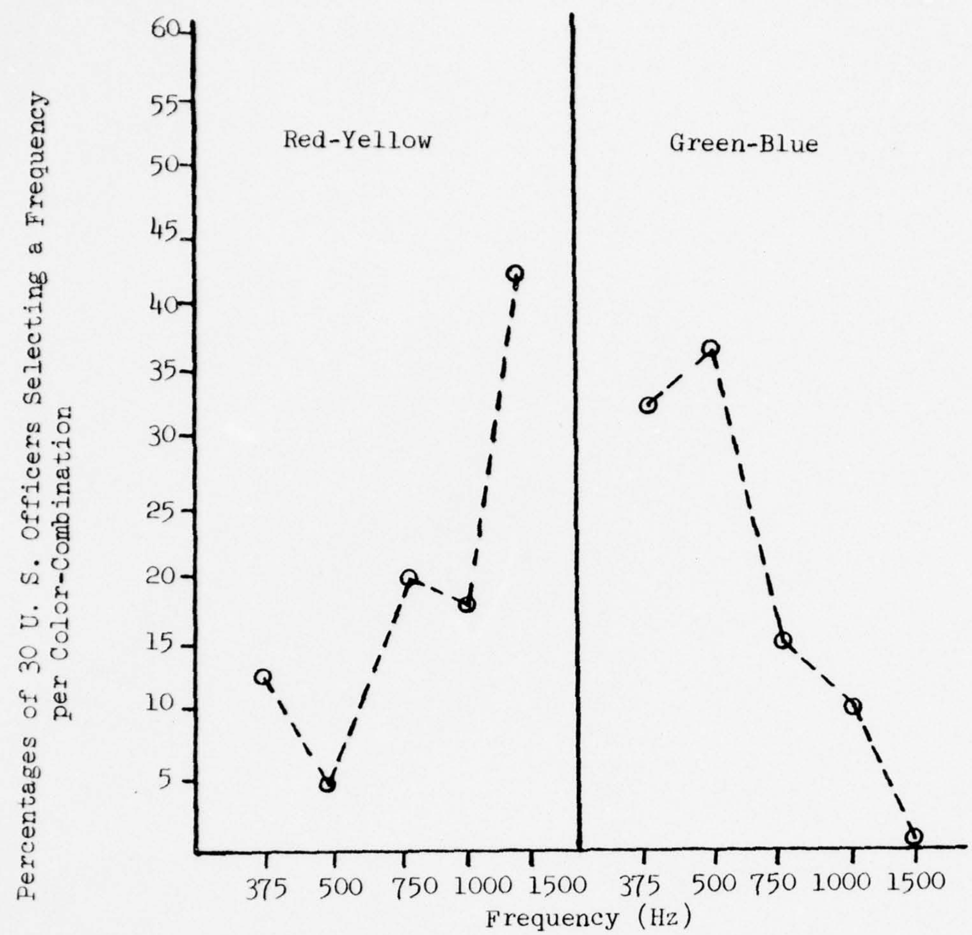

Figure 13. Graphical Representation of Tone Choices for Red-Yellow, and Green-Blue Color Combinations for U. S. Officers

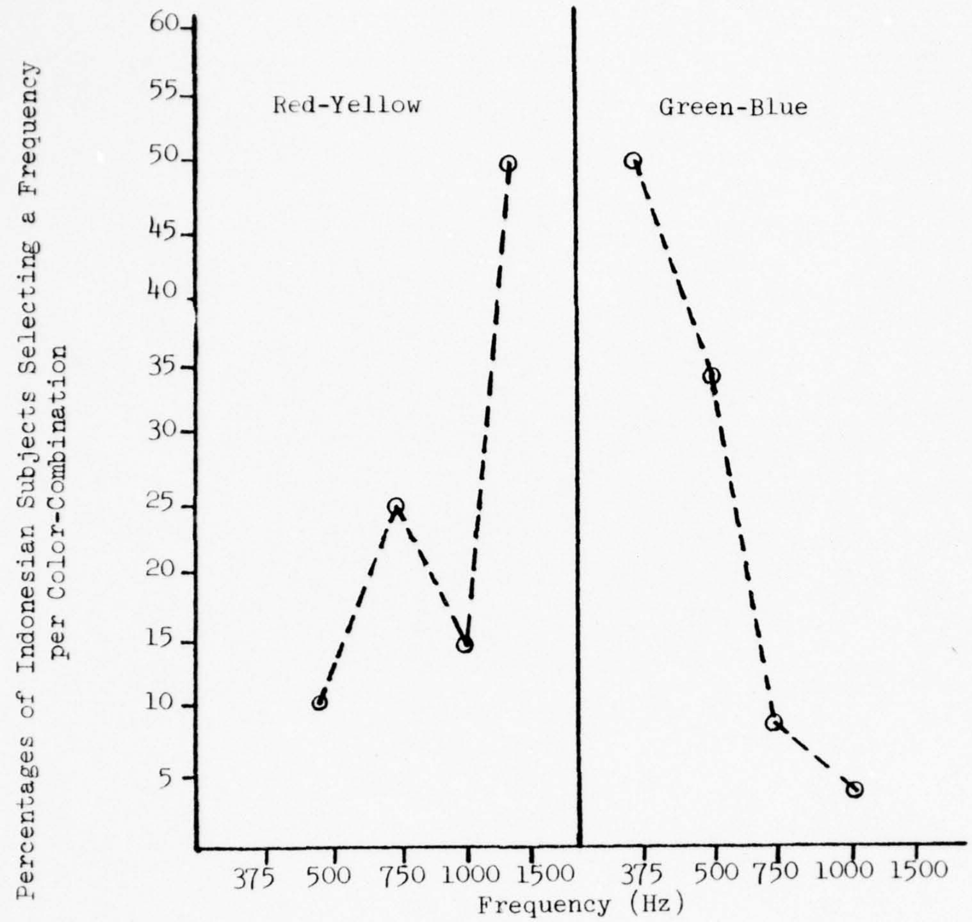

Figure 14. Graphical Representation of Tone Choices for Red-Yellow and Green-Blue Color Combinations for Indonesian Subjects

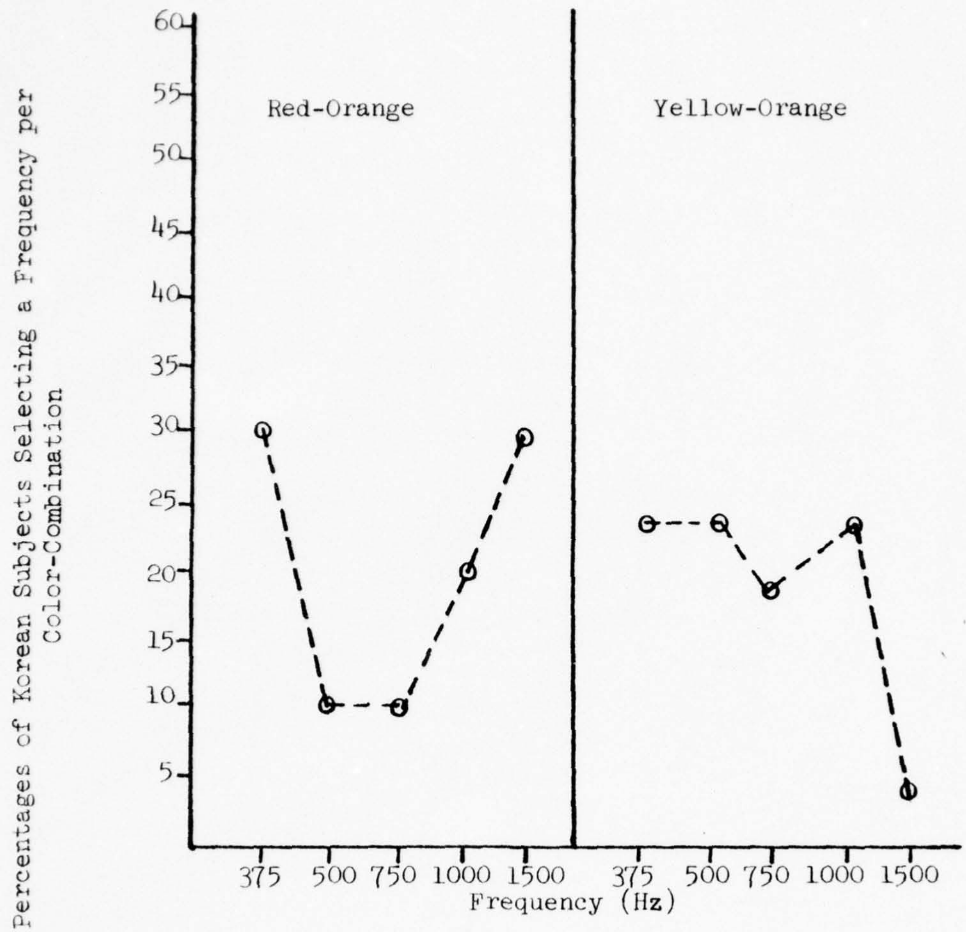

Figure 15. Graphical Representation of Tone Choices for Red-Orange and Yellow-Orange Color Combinations for Korean Subjects

Table 14

Frequency Distribution of Trials-to-Criterion by Nationality and by All Subjects

No. of Trials	Indonesians	Koreans	U. S. Officers	All Subjects
2	0	0	5	5
3	1	0	5	6
4	2	0	8	10
5	1	2	6	9
6	2	3	2	7
7	1	0	0	1
8	1	1	2	4
9	2	2	0	4
10	0	0	2	2
11	0	1	0	1
12	0	1	0	1
Mean Number of Trials to Criterion:	6.1	7.7	4.5	6.1
Variance of Number of Trials to Criterion:	4.54	6.23	4.67	30.21

sample sizes (Winer, 1971, pp. 210-215), was used to determine if significant differences in trials to criterion existed based on differences in nationality. The fixed effects model was used as military officers were assumed to be of a particular select group of the population of military officers of each nationality. Analysis of variance results are listed in Table 15 and indicated a significant difference in trials to criterion based on a difference in nationality. Contrasts of treatment means indicated that the Korean subjects' average number of trials to criterion were different from the U. S. officers' average numbers of trials to criterion but not from the Indonesians'.

C. LOUDNESS AND BRIGHTNESS SETTINGS

The means and standard deviations of loudness level settings per frequency appear in Table 16. The results indicated that the variability of reference tone of 1500 Hz (at 80 dB SPL) due to inherent equipment and measurement error was not extreme and that the subjects' subjective loudness settings were consistent and reliably close to the equal loudness contour of 80 phons over the frequency range 375-1500 Hz at a 80 dB loudness level.

The means and standard deviations of photometric brightness settings for each color are summarized in Table 17. There is considerable variability within the observed mean values. The colors yellow and orange were matched for brightness across a large range of values whereas the

Table 15

Analysis of Varinace of Trials-to-Criterion by Nationality and Contrasts
Contrasts of Treatment Means[1]

Source	df	SS	MS	F
Nationality	2	81.92	40.96	8.27
Error	47	232.5	4.95	

$F_{critical}$ (2, 47) at a .05 level = 3.20

Contrasts of Treatment Means	SS_c	F	$F_{critical}$
1 vs 2	12.8	2.59	4.05
1 vs 3	19.25	3.89	
2 vs 3	76.8	15.5	

$F_{critical}$ (1,47) at a .05 level = 4.05

1. Treatment 1: Indonesians
2: Koreans
3: U. S. Officers

Table 16

Means and Standard Deviations of Loudness Level Settings per Frequency

Frequency (Hz)	Average (dB)	Standard Deviation (dB)
375	72.62	5.04
500	72.48	6.70
750	74.46	6.30
1000	72.84	5.63
1500	79.46	1.13
Mean	74.37	4.96
Std. Dev.	2.95	2.23

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Table 17

Means and Standard Deviations Photometric Brightness Settings for Each Color

Color	Mean (fc)	Standard Deviation (fc)
Red	7.07	1.67
Yellow	4.10	4.47
Orange	3.78	5.02
Green	.527	.377
Blue	1.85	.0913
Mean	3.46	2.32
Std Dev.	2.49	2.30

colors red and green were matched for brightness across a much smaller range. Except for the standard color blue this suggests that differences in saturation do not influence the degree to which colors are considered equally bright, i.e., colors orange and yellow appear brighter than red and green regardless of differences in saturation. The color red had the largest photometric brightness mean value and a relatively small standard deviation as compared to the respective values for the other colors, i.e., yellow and orange. This indicated that the color red required the largest amount of intensity to make it appear equally bright to the other colors.

IX. DISCUSSION

The interpretation of information measures calculated in this experiment was based on information theory terminology for a discrete bivariate information channel described in Sheridan and Ferrell (1974). Interpretation of the information matrices for this study indicated a general lack of consistency and lack of perfect transmission in the presence of large amounts of noise and equivocation. Analysis of the information measures indicated that on the criterion trial the Indonesian subjects transmitted twice the amount of information as did the Americans and about 3.5 times the amount of the Korean subjects. Significant learning trends based on information analysis were non-existent yet analysis of variance results indicated the number of trials to criterion were affected by a difference in nationality. The Korean subjects' average number of trials to criterion were significantly different from the American subjects' but not the Indonesian subjects'.

Results of one-sample and independent sample Chi-square tests indicated dependent associations of color and tones (singly and in combination) existed and were affected by differences in nationality. The colors yellow and red were frequently grouped with the tones 1000 and 1500 Hz as were the colors blue and green with tones 375 and 500 Hz. No significant dependence existed for the Korean subjects.

Contingency coefficients were computed to provide an index of association between color and sound although this coefficient is not comparable to other measures of correlation.

The noise and equivocation analysis provided a method by which the amount of inconsistency in the matching process could be analyzed. Noise measured the tendency of a single stimulus giving rise to different responses, i.e. noise measured the variability in responses not correlated with the variability in stimuli. Equivocation (lost information) measured the tendency for a single response to result from several stimuli, i.e., it provided a measure of the variability in the stimuli which did not correlate with the variability in the responses.

The lack of consistency observed in this study is best explained as follows: the objective of this experiment was to determine if there was a natural association of color and pitch common among military officers of three nationalities. The objective was not to have subjects response to stimuli as if specific color-pitch associations had been learned and reinforced by practice sessions. The number of color stimuli and response tones was well within the recommended number of levels used in absolute judgment tasks using the dimensions of color and pitch. The selection of the five colors and five tones, over the frequency range 375 - 1500 Hz, with octave spacing within the frequency range was based on human factors design criteria, previous experimental investigations and the degree discriminability among the selected stimuli and responses. The mechanics of the matching response was not difficult yet the particular association of color and sound used in this study may have been unfamiliar and confusing to many subjects. In addition, the subjective nature of the association and individual cognitive processes were considered to influence the variability in matching technique from subject to subject. Also, the results indicated that differences existed due to differences in nationality. The additional variable of cultural conditioning, influenced the results. However, no quantitative criterion other than a difference in nationality, was used to measure the degree of influence of this variable. Some subjects may have had strong backgrounds in which colors and/or sounds were frequently used (i.e., art, photography, music, etc.) and these differences may have contributed significantly to dependent color-sound associations.

During the issuance of instructions the Korean subjects (as a group) took the longest time to instruct. They had difficulty understanding the subjective meanings of the terms "feel," "intuitive," and "natural." They appeared uncomfortable in understanding nonstructured terminology within the setting of this experiment.

The E questioned each S after each experimental session to determine what reasoning was used in forming the color-sound matches. Five Ss stated that they made the match by associating the spectral wavelength frequency with the tonal frequency. The majority of the Ss stated that the colors green and blue were mellow, calmer colors and associated these colors with the lower "mellow" pitches. Most Ss matched red with the frequency 1500 Hz, based on an operational exposure to the association of a red emergency light with a high attention getting sound. Also, these same Ss stated that yellow and orange were subsequently matched with higher frequencies as they were close in spectral hue to the color red. Some Ss matched red with the middle frequency 750 Hz stating that the colors yellow and orange were lighter than blue and green and made the association of yellow and orange with the "lighter" sounds of the higher frequencies. In these cases the Ss stated the color red was used as a middle reference point. It was not surprising to find such a wide range of variation in subjective matching strategies.

The loudness level observations for each of the five frequencies indicated that each subject's was consistent with respect to the reference tone 1500 Hz. The F_{max} statistic (Winer, 1971, pp. 206-207) was used to test for the homogeneity of group variances and the results were not significant ($p > .05$). The results of the t-tests of differences (Winer, 1971, pp. 27-35) comparing differences of the group mean loudness levels were not significant indicating that the group means (less 1500 Hz) were similar. The results of the photometric brightness observations indicated the variances were different for the colors. This variability was anticipated based on the comments by Wyszecki and Stiles (1967) regarding the degre of variability involved in direct visual brightness matching techniques using different colors.

Inspection of the results in Table 1 suggest an approximate one-to-one spectral tone correspondence existed in the matching process. The frequencies in each row were transformed to percentage values and the higher percentage values associated with a particular color-sound match indicated that the lower (higher) light frequencies were associated with the lower (higher) sound frequencies. These results are summarized as follows:

Color	Percentage of Ss Selecting a Frequency with a Designated Color	Wavelength (in nm)	Frequency (Hz)
Red	52	631	1500
Orange	42	595	1000
Yellow	30	579	1500
Yellow	38	579	1000
Green	44	536	500
Blue	70	477	375

This observed spectral-tone association resulted from the data, however, the objective of this study was not to investigate such an association.

The results obtained in this experiment differed from the results obtained by Simpson, Quinn and Ausubel (1956). These authors plotted percentages of Ss selecting six different frequencies for which color choices were made. The graphical representations of the percentage data computed in this study were quite dissimilar compared to the results of Simpson, Quinn and Ausubel (1956). However, among the relationships of color and sound, two were of particular interest with regard to this present study. These authors found a relationship of the color yellow with 8000 Hz and the color blue with 125 Hz. The results of this present study indicated the color yellow tended to be associated with the frequency range 1000 - 1500 Hz and the color blue with the frequency range 375 - 500 Hz. It appears that the spacing along the frequency dimension did not affect the color-sound associations using the colors yellow and blue. It should be noted that Simpson, Quinn and Ausubel (1956) tested 995 children using sound as the stimuli and color as the response and the frequency range was 125 - 12000 Hz. The percentage of Ss selecting colors for designated sounds was much smaller than the percentages values and range of percentages obtained in this present study. This comparison is illustrated below:

Color	Range of Percentage Points	Difference in Percentage Points
Red	13-21	8
Orange	14-20	6
Yellow	9-25	16
Green	12-19	7
Blue	10-28	18
Violet	12-23	11

Differences in percentage points for 50 Ss in this study were as follows:

Color	Range of Percentage Points	Difference in Percentage Points
Red	6-52	46
Yellow	8-30	22
Orange	8-42	34
Green	2-44	42
Blue	8-50	42

These differences may be partly attributable to the differences in stimuli presentation, sample size and specific experimental conditions between these investigations.

The experimental results of this study indicated that certain sounds were associated more frequently with certain colors than with other colors. The amount of information transmitted in this task was minimal. Analysis of the data suggested that this association of color and sound may be combined with functional requirements in an information display environment to promote redundancy coding and improve operator performance behavior. These auditory and visual dimensions could be used as supplemental coding variables in increasing the degree of accuracy in identification and location tasks and could be combined to enable the operator to process more information, once the consistent association of color and pitch had been learned and reinforced with practice sessions. A universal natural association of color and sound may not exist but within the specific experimental conditions of this study certain color-sound associations existed among two of three nationalities. Knowledge of these results may improve training techniques in teaching operators to associate these coding dimensions and subsequently improve operator efficiency in information processing.

Suggestions for further experimental investigations would be to evaluate the information transmission performance and reaction times using the dimensions of color and pitch singly and in combination, based on a learned association of these auditory and visual dimensions. In addition to using pure tone frequencies, warbling tones masked in white noise could be used as sound stimulus or responses simulating sound signal transmitted in an operational environment.

X. CONCLUSIONS

This experiment was designed to determine if there was a natural association of color and pitch among military officers of three nationalities. The analyses of the experimental data indicated that the amount of transmitted information was less than one bit when the maximum possible was 2.32 bits for all nationalities yet there was a significant difference in the amount of information transmitted per nationality. The Indonesians transmitted .86 bits, the Americans transmitted .40 bits and the Koreans transmitted .26 bits. The Korean subjects' average number of trials to criterion was significantly different from the American trials but not different from the Indonesian trials to criterion. The results of color combination and tone combination analyses indicated that significant association of color combination and tones existed for the American and Indonesian subjects, but did not exist for the Korean subjects. The color combinations red-yellow were associated with frequencies 1000 and 1500 Hz; the colors green-blue were associated with frequencies 375 and 500 Hz. Interpretation of the information matrices indicated a general lack of consistency and lack of perfect transmission in the presence of large amounts of noise and equivocation.

Within the conditions of this experiment there was a limited, natural association of color and sound for the Indonesian and American subjects.

APPENDIX A

DEFINITION OF TERMS

A. GENERAL

For the purposes of clarity and uniformity, the color and sound terminology used in this study conforms to a series of definitions provided by the Committee on Colorimetry of the Optical Society of America (1953), and referenced in Stevens (May, 1966) and Richards (1976).

Basic colorimetric concepts are expressed in psychological and psychophysical terms. Psychological concepts of color refer to color perceptions. The color terms which apply to these concepts enable an observer to describe his perceptions. Psychophysical concepts of color refer to the color-matching of one photometric field with another and to judgments of similarities and degree of differences between photometric fields. The following definitions are basic and of the most general use. The psychological and psychophysical distinction is not stated in each definition, however, it should be remembered in referring to these general concepts. A parallel distinction must be made with the auditory terms as well.

B. DEFINITIONS

1. Color: The relation between radiant energy and visual sensation is described by the OSA Colormetric Committee as "that aspect of radiant energy of which a

a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye." The physical characteristics of light which provide the basis for color are specified in terms of (a) photometric magnitude (luminance), (b) dominant wavelength, and (c) wave length purity. These physical characteristics correspond to the three primary attributes of visual sensation -- brightness, hue and saturation.

2. Brightness: Brightness is the quantitative aspect of the mental image and describes the image appearance in terms of its apparent amount. In a general way, brightness increases with the physical intensity of the light producing it. If a single spot of light appears in a field of view and it increases (decreases) in amount without changing its spectral energy distribution, it will appear brighter or dimmer.

3. Hue: Hue can be described as the main quality factor in color and permits colors to be described as red, blue, yellow, green, etc. It is the most noticeable factor that changes in the spectrum as the wavelength of light changes.

4. Saturation: Saturation is related to the amount of white a color appears to contain; the less white, the higher the saturation. Of the three color attributes, saturation and hue define what may be called the quality aspect of a mental image caused by light.

5. Chromatic and Achromatic Colors: Colors may also be divided generally into two distinct classes: chromatic and achromatic, depending on whether they do or do not exhibit a hue (e.g., black, gray or white are termed achromatic colors).

6. Color Mixture: The visual mechanism, unlike the ear, does not analyze light into its component frequencies. The fundamental concept upon which color specification is based, is that any given color can be matched by addition (subtraction) of a combination of three properly selected light sources of different wavelengths. The primary colors (red, green, blue (or violet)) are the three most often chosen reference lights by whose additive mixture nearly all other colors may be produced. Once these components are selected, the entire color spectrum can be produced by adjusting the relative amounts of the three components; the relative amounts of these primaries are called the tristimulus values of a color.

7. Dominant Wavelengths: The dominant wavelength of a color is the wavelength of the spectrum color. This correlates in an approximate way with what would be called the hue observed under every day conditions. In general, colors of a constant dominant wavelength perceived under similar conditions would be said to have the same hue. When dominant wavelengths are proportionately mixed (added) with a specified achromatic color, a match is produced with the color

being considered. Two colors are complementary when they can be mixed proportionately to produce an achromatic experience. Every color has a complement (e.g., red and green, blue and yellow).

8. <u>Specification of Chromaticity</u>: The specification of a color stimulus in terms of dominant wavelength and purity but not luminance is known as a specification of chromaticity. Chromaticity coordinates are the ratios of each tristimulus value of the color to their sum and plotting these coordinates yields a point on the diagram. A chromaticity diagram is one in which each point represents the chromaticity of a color independent of its luminance.

9. <u>Excitation Purity</u>: The excitation purity of any color possessing a dominant wavelength is an exactly defined ratio of distances in the chromaticity diagram, indicating how far the given color is displaced from the achromatic color towards the spectrum color. Excitation purity correlates loosely with saturation of a color observed under ordinary observing conditions.

An excellent color illustration of a chromaticity diagram is found in "Scientific American," September, 1968. Also, the color circle and color solid are abstractions that can be used to clarify statements and color attribute concepts schematically (Conover & Kraft, 1958; Evans, 1948; Jones, L., 1937; Judd & Wyszecki, 1975; Weintraub, 1966; Wyszecki & Stiles, 1967).

10. Methods of Specifying Color: Colors can be specified by means of colorimetry or comparison with established color standards.

a. Colorimetry: Instruments used for the direct measurement of light energy composition are called colorimeters. For making routine measurements the use of colorimeters has been superseded by indirect colorimetry, wherein the computation of tristimulus specifications is based upon photometric and psychological data.

b. Photometer: A physical photometer is a photosensitive surface which receives incident light and from which is drawn the electric current producing the instrument response. The response of a physical photometer is absolute and readings on different occasions are comparable. They are convenient to use and are built to give a high precision of measurement. Numerous photoelectric illuminance photometers of different designs can be obtained commercially. A major disadvantage is that the photocurrent generated for a given illuminance varies greatly with the angle of incidence of the light on the photosensitive surface (Wyszecki & Stiles, 1967).

c. Color Standards: Color standards are usually members of a systematically arranged set of pigmented or dyed surface (color patches) and are used for making visual comparisons with material whose color is to be specified. The Munsell System is representative of several specification methods using opaque, reflecting color standards. The International Committee on Illumination (CIE) color specifications have been published for typical sets of Munsell codes. Kodak Wratten Filters are used as well for a wide variety of photographic, scientific, and technical work. The standardization of each filter for color and spectral transmission have been calculated and is rigidly maintained. Several Kodak publications contain the applicable filter information. The Munsell Systems and Kodak Filters are widely accepted in industry, science and the military for use as color standards.

11. Sound: The basic concept for sound is that of pressure variation. Complex mechanical vibrations of air molecules transmit energy to the human ear and stimulate a sensation related to the physical sound. The simplest sound, a pure tone, consists of a single frequency of sinusoidal vibration; complex so-nds are called "noise" and come in a variety of forms. The most impure sound possible is called white noise. A pure tone has all its energy at one frequency, white noise has equal amounts of energy at all frequencies. White noise, like white light, can be separated into narrow bands and used to explore the properties of the ear (Fogel, 1963; Stevens, 1975).

12. Auditory Attributes: The auditory attributes of sound are pitch, loudness, volume, and density; these are dimensions of auditory experience and are all related to intensity and frequency. Yet distinctions between loudness

and intensity and between pitch and frequency have to be made. The intensity and frequency of a tone can be measured by an apparatus far removed from the listener; loudness and pitch are tonal attributes as heard and reacted to by a listener. Loudness and pitch are dimensions of an auditory experience, whereas, intensity and frequency are acoustic dimensions (Stevens, 1966). Pitch is the name given to the "highness" and "lowness" of tones; low (high) frequencies yield low (high) pitch tones as there is a rough correspondence between pitch and frequency. Loudness, in general, is determined by the physical intensity of a sound, or magnitude of an auditory sensation. The volume of a sound refers to the size of the sound or how large it appears to be. The density of a sound refers to the compactness, concentration, or hardness of a sound. The relationships of these attributes to intensity best understood by referring to numerous graphical presentations available in the literature. The important idea is that pitch and loudness are names for separate subjective aspects of auditory stimuli (Geldard, 1972; Stevens, 1966; Stevens, 1975).

13. <u>Ambient Noise</u>: Ambient noise is the background noise in a test environment. In most experiments dealing with audition, it should be kept to a minimum.

14. <u>Equal Loudness Contours</u>: Equal loudness contours are functions which relate equal loudness sensations (in dB SPL) for different frequency sounds; the reference frequency against which all other frequencies are compared

is 1000 Hz. The loudness level of the 1000 Hz tone is expressed in phons and is numerically equal to its sound pressure level (dB re 0.0002 dyne/cm^2) (Stevens, 1975).

15. Frequency: The frequency of pure tone represents the number of complete cycles (Hz) that the sound wave has passed through in a one-second time period.

16. Loudness: The loudness of a sound is the psychological percept of sound intensity.

17. Loudness Level: The loudness level (in phons) of any frequency tone is equivalent to the sound pressure level (dB re 0.0002 dyne/cm^2) of a 1000-Hz tone judged to be of equal loudness. A 100 Hz tone may have to be adjusted to a level of almost 70 dB SPL in order to equal the loudness of a 1000 Hz tone at a level of 60 dB SPL (Richards, 1976; Stevens, 1975).

18. Mel: The mel is an arbitrary unit used in the scaling of pitch sensation. A value of 1000 mels equals the apparent pitch of a 1000-Hz tone set to a loudness level of 55 phons (55 dB SPL). Mel scales relate pitch and frequency.

19. Octave: An octave is a 2:1 or a 1:2 frequency range; 250 Hz and 500 Hz are an octave apart, while the difference between 250 Hz and 1000 Hz is two octaves.

20. Pitch: The pitch of a tone represents the psychological percept of frequency; pitch is perceptual and frequency is physical.

21. Pure Tone: A pure tone is a sound wave which has a definite tonal quality; its wave form is sinusoidal.

22. Audio-frequency Oscillator: An audio-frequency oscillator generates sinusoidal wave outputs over the frequency range 20 - 20000 Hz. They are considered a basic audiometric instrument for acoustic research.

Additional terms used in psychoacoustic experimental environments are referenced in A. M. Richards, Basic Experimentation in Psychoacoustics, 1976.

APPENDIX B

DESIGN PRINCIPLES FOR WARNING SIGNALS AND AUDIO-VISUAL PRESENTATION

The following design principles for warning signals and audio-visual presentation are discussed to support and validate the selection of the parameters of color and pitch used in this study. These principles supplement those mentioned in the main body; they are some of the significant principles extracted from the several references listed at the end of this Appendix. The principles are listed according to typical demands for audio-visual presentation, warning signal design, principles of vision and auditory presentation.

A. TYPICAL DEMANDS FOR AUDIO-VISUAL PRESENTATION

For certain kinds of responses, especially for urgent or critical situations, or unusual environmental conditions, simultaneous presentation of information through the eyes and ears would provide better control of operator behavior. These categories are listed as follows:

1. Where great redundancy is desired: redundancy is sometimes essential to combat excessive noise. The greater degree of uncertainty, or more complex the information, the greater redundancy is necessary to maintain the efficiency of operator response. When faulty selection or

manipulation carries heavy command and/or operational penalties, redundancy coding to promote early warning and accuracy should be provided.

2. For emergency warning: simultaneous stimulation through both sense channels may provide a greater overall effect upon behavior where it is urgent to attract attention to a new situation or incoming message.

3. Where environmental conditions handicap data presentation through either sense channel alone.

These are some typical demands for dual sensory presentation. However, a logical projection would be that dual presentation may also enhance reaction time, in responding to a display panel and assist the operator in his decision making abilities. In addition, all of the sources consulted concluded that the combination of visual and auditory presentation is more efficient than either sense alone.

B. WARNING SIGNAL DESIGN

A good warning device should break through and get the attention of a preoccupied or bored operator; it should tell him what is wrong or what action to take and allow continued attention to other duties if necessary. In order to help the operator know what is wrong, signal lights can be grouped in patterns (i.e., arranged in sequence). In selecting a signal for a particular application, the urgency of the situation, other operator duties and other warning devices must be considered as the operator may become confused, neglect critical signals or be bothered by unimportant ones. Signal lights may also tell an operator what to do by their location, color, or labelling; he must be looking in their general direction, however, to properly react to their stimulation. These lights may be used to signal minor failures that do not demand immediate attention or can be used to indicate operational status. These latter points consider that the operator would be less attentive than he would be for an emergency.

C. AUDITORY PRESENTATION

Hearing is omnidirectional and cannot be involuntarily shut off; auditory signals are better for calling attention to imminent danger or potentially dangerous situations. The auditory channel should be used as follows:

1. To supplement overloaded vision when additional visual displays would be undesirable.

2. When vision is limited or impossible, as working in the dark or under low illumination and when maximum visual sensitivity is required.

3. When signals must be distinguished from noise, the ear is a very effective frequency analyzer.

4. When information must be presented independently of the orientation of the head, a person's duties may require him to move about or turn the head, whereas, visually presented information may be missed.

5. Auditory warnings are excellent "break through" devices for getting the attention of a busy, bored, or fatigued operator.

6. Tonal signals could be used under the following conditions:

a. The listener has special training in determining the meaning of a modulated signal.

b. The signal calls for immediate action.

c. The signal (message) is extremely simple.

d. Security of the message is important as speech is easily understood by unintended listeners.

7. Operators cannot correctly identify more than a few (3-5 categories) of different intensities or pitches in absolute judgment tasks.

8. Intermittent or repeated changes should be used in a signal rather than a single change followed by a continuous signal as the ear is much more likely to detect a change occurring every few seconds.

9. Pitch differences represent high or low (up or down) as people speak of high or low pitch.

D. VISUAL PRESENTATION

Visual presentation should be used as follows:

1. If the task requires simultaneous comparison, quick selection from a large number of alternatives, or scanning (maps, displays, etc.).

2. When the operator remains in a relatively stationary position.

3. When the receiving location is too "noisy."

4. When the number of display lights should be no more than eight for absolute discrimination.

5. When brightness levels are used as coding dimensions the levels should be three to five times brighter than surrounding lights.

6. When hue is used it is a more easily identified dimension and location time is short for coding purposes. For brightness, poor contrast will reduce visibility of weaker signals.

7. Colored lights may always be referred to over time; whereas, continuous sounds may become quite annoying to an operator.

8. A flashing light has a higher attention value but is more disturbing to a viewer; these types should be used for urgent warnings.

The choice of the most effective signal color in a specific situation is largely a function of background contrast, amount of ambient illumination and stimulus color. Personal preference for certain colors have to be considered as well. As Jones (1962) noted, blue-green colors seem to produce great identification variability; yet, most people prefer hues in the blue-green region in an operating environment. These principles and design considerations are a synopsis of those principles referenced in the literature consulted for this study (Barker & Krebs, 1977, USAF Design Handbook DH 1-3, 1972; Cheatam, 1950; Christ, 1975; Henneman & Long, 1958; Jones, 1972; McCormick, 1976; Morgan & Cook, 1963; Mowbray and Gebhard, 1958; Mudd, 1961; Reynolds & White, 1972).

APPENDIX C

INFORMATION MEASUREMENT TECHNIQUES
USED TO EVALUATE EXPERIMENTAL DATA

A. GENERAL

One of the objectives of this experiment was to explore the information measures associated with the cross-modality match of hue and pitch, and to ascertain if transmitted information was significantly affected by a difference in nationality. The conceptual model used to record and display the statistical relationships of input and output is discussed in Sheridan and Ferrell (1974) and Fitts and Posner (1967). The model characterizes the input-output relationships as bivariate discrete information channels. This concept is particularly useful in studying stimulus-response behavior as it refers only to the statistical association of input and output, and not to the perceptual mechanisms that relate them. A common method of analyzing bivariate channels is to use a contingency table. In this experiment the rows corresponded to the input and columns to the output. The cell elements are probabilities indicative of the input-output association. In addition to experimentally evaluating the input-output relationship, the information measures of transmission, noise and equivocation will be discussed.

B. INFORMATION MEASURES ASSOCIATED WITH A BIVARIATE DISCRETE INFORMATION CHANNEL

In this section the information measures used to evaluate the consistency of input-output (color-frequency) associated will be discussed. During this experiment each S was presented each of five colors (stimulus), X_i (i = 1,2,3,4,5). For each presentation the S responded in one of five possible ways by matching a sound (response), Y_j (j = 1,2,3,4,5) to the presented color. Each color was presented N times until a consistent matching of two consecutive trials was obtained (Section VII contains a description of the experimental procedure). The experimental data was represented in a contingency table illustrated in Figure 9. The number n_{ij} was the number of event pairs in which X_i was the input and Y_j the output. The number N was the total of N event pairs which was observed. The probabilities required for the calculation of information measures were based on sample relative frequencies entered into the contingency table and used to calculate the following information measures: input information, output information, transmitted information, noise, and equivocation. A brief description of these measures follows:

1. The average of the transmitted information associated with the occurrences of an event was computed as follows:

$$H(z) = p_i \log_2 \frac{1}{p_i}, \quad i = 1, \ldots, n.$$

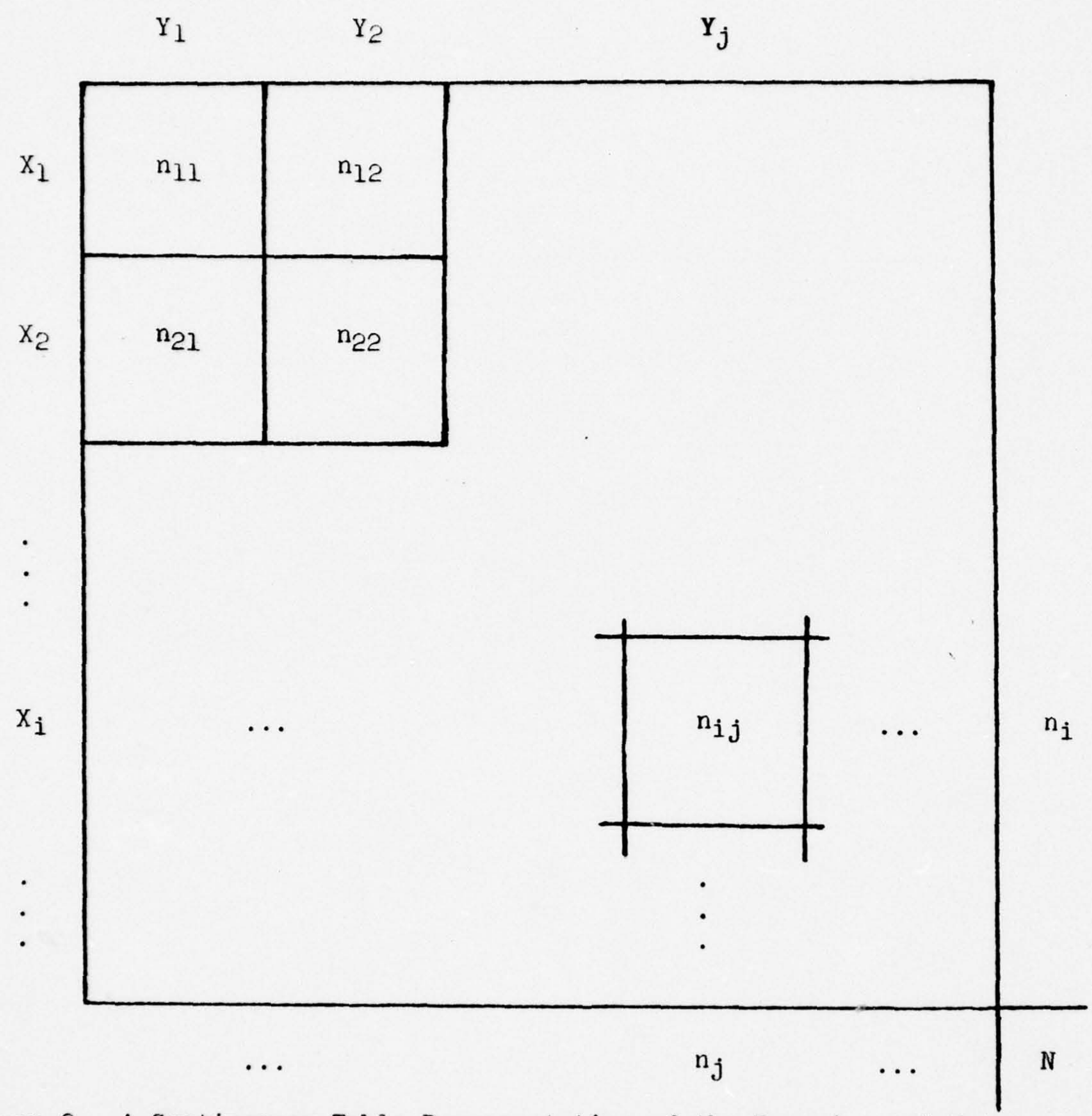

Figure 9. A Contingency Table Representation of the Experimental Data

The measure H(z) was called the information content of set z, i.e., the information conveyed on the average when a number of set z was specified; p_i is the probability associated with the occurrence of the event in set z.

2. The input (stimulus) information as determined by the E was defined as H(x). The probability associated with the event x_i was expressed by the following relative frequency:

$$p(x_i) = \frac{n_{i.}}{N} = \sum_j \frac{n_{ij}}{N}$$

The amount of input information was obtained by adding the contingency table (matrix) row marginals.

3. The output (response) information as determined by the S was defined as H(y). The probability associated with the event y_j was expressed by the following relative frequency:

$$p(y_j) = \frac{n_{.j}}{N} = \sum_i \frac{n_{ij}}{N}$$

The amount of output information was obtained by adding the matrix column marginals.

4. The information associated with the joint occurrence of the input and the output or the number of times each response occurred for each stimulus was defined as H(x,y).

This information measure was obtained from the matrix cell values. The probability associated with this joint occurrence of events x_i and y_j was expressed as the following relative frequency:

$$p(x_i, y_j) = \frac{n_{ij}}{N}$$

5. The amount of information transmitted was defined as T(x,y) and calulated as follows:

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

When the input information is equal to the transmitted information which is in turn equal to the output information, the information channel is perfect. For example, if an S responded as instructed, making no mistakes, the S acted as a perfect channel, i.e., given the S's response, the E can be certain of the stimulus that elicited it. However, an S can make mistakes by pairing his response with stimuli differently from the manner required of him and still transmit all the information. In this case, the results are insensitive to "correctness" of responses and are a function only of the consistency with which responses are paired with stimuli. Furthermore, input and output information may be equal, but information measures of equivocation and noise may exist.

6. The equivocation is the information about the input set x that might have been transmitted but was not. When many different inputs tend to result in a single output there is a loss of information and the input is equivocal (lost information). The amount of equivocation was defined as $H(x|y)$ and expressed as follows:

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

7. When the same input leads to different outputs on different occasions there is a variability in the output which does not correspond to the variability in the input, this is noise. Noise is something other than the input which is added to the transmitted information. The amount of noise was defined as $H(y|x)$ and expressed as follows:

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

Sheridan and Ferrell (1974) provide matrix examples and schematic illustrations to explain each of these information measures. Figure 10 illustrates the relationship of all the information measures associated with a bivariate discrete information channel.

C. CALCULATION OF INFORMATION MEASURES

The following sample of information measures calculations is provided to describe the computations used in this

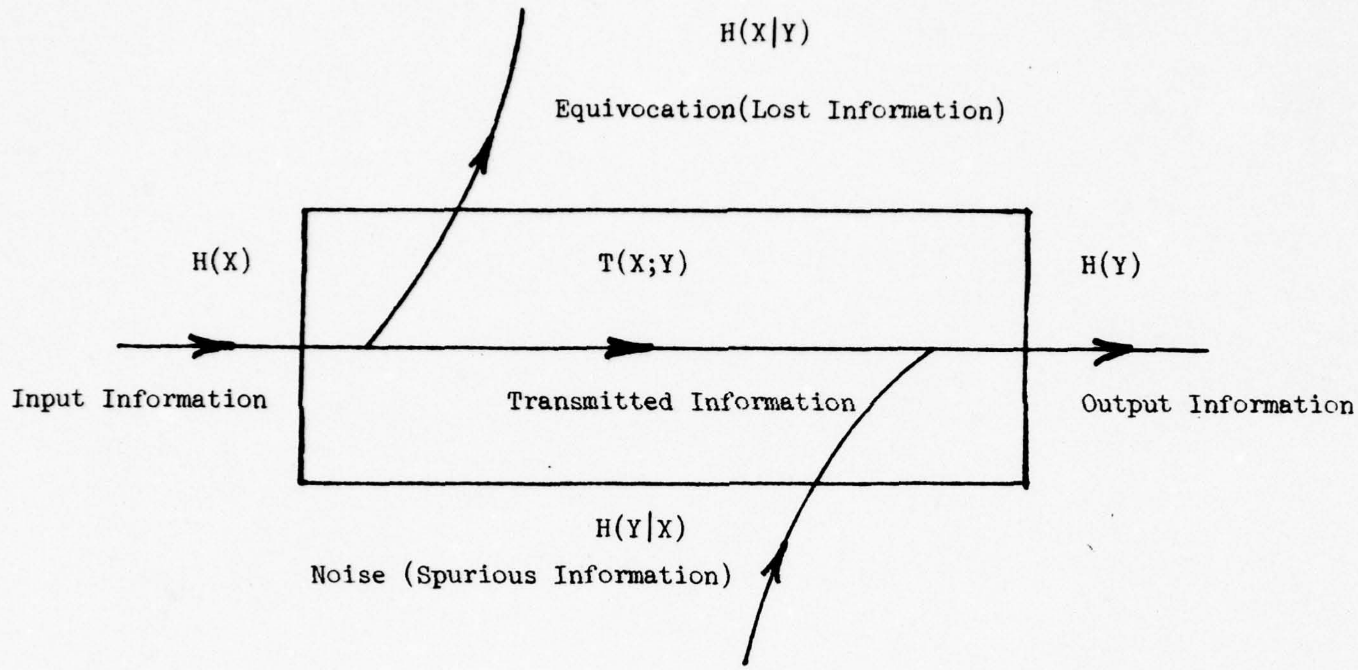

Figure 10. Information Measures Associated with a Bivariate Discrete Channel

study. The data were obtained from two pilot test Ss. Individual data results have been combined to calculate the information transmissions associated with this two-man group. Figure 11 illustrates the contingency table representation of the experimental data. The cell entries are the total number of responses the Ss made in matching the five colored lights to the five pitches. The data entries in parentheses are the relative frequencies of H(x), H(y), and H(x,y). The experimental data has been calculated and is shown below:

a. Input (stimulus) Information:

$$H(x) = 5(.2 \log_2(1/.2)) = 2.32 \text{ bits}$$

b. Output (response) Information:

$$H(y) = 2(.1714 \log_2(1/.1714)) + 2(.2286 \log_2(1/.2286)) + (1/2 \log_2(1/.2))$$

$$= 2(.43) + 2(.49) + (.46) = 2.30 \text{ bits}$$

c. Information of the joint occurrence of input and outout:

$$H(x,y) = (.1428 \log_2(1/.1428)) + 2(.057 \log_2(1/.057))$$

$$+ 2(.0286 \log_2(1/.0286)) + (.1714 \log_2(1/.1714))$$

$$+ 2(.1143 \log_2(1/.1143)) + (.086 \log_2(1/.086)$$

$$+ (.2 \log_2(1/.2))$$

$$= (.41) + 2(.24) + 2(.15) + (.43) + 2(.35)$$

$$+ (.31) + (.46) = 3.09 \text{ bits}$$

d. The amount of information transmitted for two S in matching five sounds to five colors:

$$T(x,y) = H(x) + H(y) - H(x,y) = 2.32 + 2.3 - 3.09$$

$$= 1.53 \text{ bits}$$

e. The amount of equivocation:

$$H(x|y) = H(x) - T(x,y) = 2.32 - 1.53 = 0.79 \text{ bits}$$

f. The amount of noise:

$$H(y|x) = H(y) - T(x,y) = 2.3 - 1.53 = 0.77 \text{ bits}$$

Response H(Y)
Frequency (Hz)

Stimulus H(X) Color	375	500	750	1000	1500	$p(x_i) = n_i/N$
Red			5 (.143)	2 (.057)		7 (.20)
Yellow					7	7 (.20)
Orange			1 (.028)	6 (.1714)		7 (.20)
Green	2 (.057)	4 (.1143)				7 (.20)
Blue	4 (.1143)	3 (.086)				7 (.20)
$p(y_j) = n_j/N$	6 (.1714)	7 (.20)	6 (.1714)	8 (.2286)	8 (.2286)	N = 35 (1)

Figure 11. Information Contingency Table of Experimental Data for the Two Pilot Test Subjects

APPENDIX D

EXPERIMENT INSTRUCTIONS

The following instructions were orally given to each S and corresponded to the different sessions involved in the experiment: Session 1 - Loudness matching; Session 2 - Brightness matching and Session 3 - Color-tone matching. The instructions were brief in order to keep the S naive as to the ultimate purpose of the experiment. The instructions in the following paragraphs are listed as they were presented to each S, i.e., in the first person.

A. SESSION 1 - INSTRUCTIONS

The first thing I want you to do is to press each white button from top to bottom. Notice that each has a different tone and some tones are louder than others. I want you to concentrate on the loudness aspect. If you wish you can identify the buttons by number from top to bottom as one, two, three, four, and five. The top button is the reference or standard tone. I will be outside the booth to make the necessary adjustments. You are to begin by alternately pressing buttons one and two as many times as you like, and tell me to "increase (up)" or decrease (down)" the loudness level of button two to make it sound equally loud to button one. When you think the tones sound equal in loudness, just say "equal". After the first two sounds are adjusted you are to go through the same matching process for buttons one and three, one and four, and one and five. Note: After the E reentered the booth, the S was instructed to press each button, one at a time, in any order, as a final check to ensure all buttons were equal in loudness. Also, the S was instructed to remember the sound of each tone.

B. SESSION 2 - INSTRUCTIONS

Prior to giving instructions to the S, the E turned on each light. Now what I want you to do is to adjust the brightness (intensity) level of each light so that each light appears equal in brightness to the blue light; the blut light is the reference light. You adjust the brightness level of each light by turning the black knob below each light.

As a final check the S was asked if each light appeared equal in brightness to the blue light.

C. SESSION 3 - INSTRUCTIONS

This is the last part of the experiment. I will turn on one light for about two seconds. While the light is on I want you to press a button that you feel should go with, or be matched with, the colored light. This matching should be done in whatever way seems natural to you. I will turn off the light and then turn on another light. You are to respond by pressing another button. The lights will be shown in random order. There is no association between the position of the buttons and the position of the lights. Do not worry about making mistakes; you will be shown each light several times and you may change your matching selection if you wish. But as you go along, you will learn to make consistent matching associations in which one different sound is matched to one different color. When I have seen that you have learned to do this, we will stop.

APPENDIX E

DATA APPENDIX

Tables E-1 through E-4 (Data Appendix E) contain the frequency data of the color-tone matchings by trial for all subjects and by nationality. Each row corresponds to a stimulus color and each column corresponds to a response tone. The cell entries contain the frequencies (choices) associated with the color-tone matchings. The relative sample frequency is listed in parentheses below each frequency count. The row and column marginals correspond to the summation of each row and column respectively. The relative sample frequencies were used to calculate the quantities of information measures. The notation associated with each trial is explained as follows: Trial N was the second to last trial of the two consecutively matched trials. The last two trials contained the same frequencies. Trial N-1 was the trial preceding Trial N and Trials N-2(N-3) were the trials preceding Trials N-1(N-2) respectively. Trial N-4 contained the pooled cell frequencies from the number of trials greater than or equal to the fourth trial preceding Trial N. The information matrices for Trial N are listed in Tables 1 through 4 and have been previously discussed. The information matrices for trials N-4, N-3, N-2, and N-1 for all subjects and by nationality are listed in Tables E-1 through E-4.

The detailed information analysis is contained in Table E-5. The information measures are summarized by trial, by number of subjects per trial, for all subjects and by nationality. The information matrices indicated a general lack of consistency and perfect transmission in the presence of large amounts of noise and equivocation. The information measures provide a means of identifying learning trends in the color-tone matchings. Inspection of the data for trials N-4 through N-1 indicates that learning was non-existent. The Indonesian subjects had larger amounts of transmitted information per trial. In all trials for the Korean subjects, the amount of transmitted information was less than .49 bits.

Tables E-6 and E-7 contain the loudness level and photometric brightness data for all 50 subjects, respectively.

Table E-1

Frequency of Color-Tone Matchings by Trial for All Subjects
(Relative frequencies are shown in parentheses)

Colors	Tones 375	500	750	1000	1500	Row Sums
			Trial N-4			
Red	10 (.033)	6 (.02)	6 (.02)	7 (.023)	31 (.103)	60 (.20)
Yellow	10 (.033)	15 (.05)	7 (.023)	12 (.04)	16 (.053)	60 (.20)
Orange	14 (.0467)	13 (.043)	12 (.04)	20 (.067)	6 (.02)	65 (.217)
Green	8 (.0267)	22 (.073)	18 (.06)	4 (.013)	4 (.013)	56 (.186)
Blue	15 (.05)	21 (.07)	9 (.03)	8 (.0267)	6 (.02)	59 (.197)
(Column Sums)	57 (.19)	77 (.257)	52 (.173)	51 (.17)	63 (.21)	300 (1)
			Trial N-3			
Red	3 (.0207)	6 (.0414)	3 (.0207)	2 (.014)	15 (.103)	29 (.20)
Yellow	3 (.0207)	7 (.0483)	8 (.055)	6 (.0414)	5 (.0345)	29 (.20)
Oran ge	7 (.0483)	7 (.0483)	5 (.0345)	9 (.062)	1 (.007)	29 (.20)
Green	7 (.0483)	8 (.055)	5 (.0345)	7 (.0483)	2 (.014)	29 (.20)
Blue	8 (.055)	7 (.0483)	5 (.0345)	6 (.0414)	3 (.0207)	29 (.20)
(Column Sums)	28 (.193)	35 (.242)	26 (.179)	30 (.207)	26 (.179)	145 (1)

Table E-1 Continued

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			Trial N-2			
Red	7 (.036)	5 (.026)	4 (.0205)	2 (.0103)	21 (.108)	39 (.20)
Yellow	3 (.0154)	6 (.031)	10 (.0513)	12 (.0615)	8 (.041)	39 (.20)
Orange	7 (.036)	11 (.0564)	7 (.036)	13 (.065)	1 (.005)	39 (.20)
Green	9 (.046)	15 (.077)	7 (.036)	5 (.026)	3 (.0154)	39 (.20)
Blue	11 (.0564)	10 (.0573)	5 (.026)	10 (.0513)	3 (.0154)	39 (.20)
(Column Sums)	37 (.19)	47 (.24)	33 (.17)	42 (.215)	36 (.185)	195 (1)
			Trial N-1			
Red	7 (.031)	7 (.031)	5 (.022)	2 (.008)	24 (.106)	45 (.20)
Yellow	5 (.022)	6 (.026)	9 (.04)	15 (.066)	10 (.044)	45 (.20)
Orange	6 (.026)	7 (.031)	9 (.04)	22 (.097)	1 (.004)	45 (.20)
Green	9 (.04)	15 (.067)	15 (.067)	4 (.017)	2 (.008)	45 (.20)
Blue	20 (.089)	9 (.04)	6 (.026)	6 (.026)	4 (.017)	45 (.20)
(Column Sums)	47 (.209)	44 (.195)	44 (.195(	49 (.219)	41 (.182)	225 (1)

Table E-2

Frequency of Color-Tone Matchings by Trial for 25 U. S. Officers
(Relative frequencies are shown in parentheses)

Colors	Tones 375	500	750	1000	1500	Row Sums
			Trial N-4			
Red	6 (.06)	0 (.00)	2 (.02)	0 (.00)	12 (.12)	20 (.20)
Yellow	6 (.06)	4 (.04)	2 (.02)	1 (.01)	7 (.07)	20 (.20)
Orange	0 (.00)	7 (.07)	7 (.07)	6 (.06)	0 (.00)	20 (.20)
Green	6 (.06)	12 (.12)	1 (.01)	1 (.01)	0 (.00)	20 (.20)
Blue	1 (.01)	12 (.12)	3 (.03)	4 (.04)	0 (.00)	20 (.20)
(Column Sums)	18 (.18)	35 (.35)	15 (.15)	13 (.13)	19 (.19)	20 (.20)
			Trial N-3			
Red	1 (.0167)	3 (.05)	1 (.0167)	0 (.00)	7 (.117)	12 (.20)
Yellow	1 (.0167)	3 (.05)	2 (.033)	3 (.05)	3 (.05)	12 (.20)
Orange	5 (.083)	3 (.05)	2 (.033)	2 (.033)	0 (.00)	12 (.20)
Green	2 (.033)	4 (.067)	2 (.033)	3 (.05)	1 (.0167)	12 (.20)
Blue	3 (.05)	3 (.05)	2 (.033)	3 (.05)	1 (.0167)	12 (.20)
(Column Sums)	12 (.20)	16 (.267)	9 (.15)	11 (.183)	12 (.20)	60 (1)

Table E-2 Continued

Colors	375	500	750	1000	1500	Row Sums
			Trial N-2			
Red	3 (.03)	1 (.01)	2 (.02)	1 (.01)	13 (.13)	20 (.20)
Yellow	3 (.03)	2 (.02)	4 (.04)	6 (.06)	5 (.05)	20 (.20)
Orange	2 (.02)	5 (.05)	3 (.03)	9 (.09)	1 (.01)	20 (.20)
Green	5 (.05)	10 (.10)	2 (.02)	1 (.01)	2 (.02)	20 (.20)
Blue	6 (.06)	5 (.05)	2 (.02)	5 (.05)	2 (.02)	20 (.20)
(Column Sums)	19 (.19)	23 (.23)	13 (.13)	22 (.22)	23 (.23)	100 (1)
			Trial N-1			
Red	5 (.04)	2 (.016)	3 (.024)	2 (.016)	13 (.104)	25 (.20)
Yellow	2 (.016)	3 (.024)	6 (.048)	7 (.056)	7 (.056)	25 (.20)
Orange	3 (.024)	4 (.032)	5 (.04)	12 (.096)	1 (.008)	25 (.20)
Green	5 (.04)	9 (.072)	7 (.056)	3 (.024)	1 (.008)	25 (.20)
Blue	12 (.096)	5 (.04)	3 (.024)	4 (.032)	1 (.008)	25 (.20)
(Column Sums)	27 (.216)	23 (.184)	24 (.192)	28 (.224)	23 (.184)	125 (1)

(Tones: 375, 500, 750, 1000, 1500)

Table E-3

Frequency of Color-Tone Matchings by Trial for the Indonesian Subjects
(Relative frequencies are shown in parentheses)

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			Trial N-4			
Red	0 (.00)	4 (.053)	1 (.013)	2 (.0267)	8 (.107)	15 (.20)
Yellow	3 (.04)	1 (.013)	1 (.013)	3 (.04)	7 (.093)	15 (.20)
Orange	1 (.013)	3 (.04)	2 (.0267)	7 (.093)	2 (.0267)	15 (.20)
Green	5 (.067)	3 (.04)	5 (.067)	0 (.00)	2 (.0267)	15 (.20)
Blue	5 (.067)	6 (.08)	3 (.04)	0 (.00)	1 (.013)	15 (.20)
(Column Sums)	14 (.187)	17 (.227)	12 (.16)	12 (.16)	20 (.267)	75 (1)
			Trial N-3			
Red	0 (.00)	1 (.0286)	2 (.057)	1 (.0286)	3 (.086)	7 (.20)
Yellow	0 (.00)	1 (.0286)	2 (.057)	2 (.057)	2 (.057)	7 (.20)
Orange	0 (.00)	0 (.00)	3 (.086)	3 (.086)	1 (.0286)	7 (.20)
Green	4 (.114)	2 (.057)	1 (.0286)	0 (.00)	0 (.00)	7 (.20)
Blue	2 (.057)	3 (.086)	1 (.0286)	1 (.0286)	0 (.00)	7 (.20)
(Column Sums)	6 (.1714)	7 (.20)	9 (.2572)	7 (.20)	6 (.1714)	35 (1)

Table E-3 Continued

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			Trial N-2			
Red	2 (.044)	2 (.044)	2 (.044)		3 (.0667)	9 (.20)
Yellow	0 (.00)	0 (.00)	3 (.0667)	3 (.0667)	3 (.0667)	9 (.20)
Orange	1 (.022)	4 (.088)	2 (.044)	2 (.044)	0 (.00)	9 (.20)
Green	3 (.0667)	3 (.0667)	2 (.044)	1 (.022)	0 (.00)	9 (.20)
Blue	3 (.0667)	3 (.0667)	2 (.044)	1 (.022)	0 (.00)	9 (.20)
(Column Sums)	9 (.20)	12 (.267)	11 (.244)	7 (.156)	6 (.133)	9 (.20)
			Trial N-1			
Red	0 (.00)	3 (.06)	1 (.02)	0 (.00)	6 (.12)	10 (.20)
Yellow	0 (.00)	1 (.02)	1 (.02)	5 (.10)	3 (.06)	10 (.20)
Orange	0 (.00)	0 (.00)	4 (.08)	6 (.12)	0 (.00)	10 (.20)
Green	3 (.06)	4 (.08)	2 (.04)	1 (.02)	0 (.00)	10 (.20)
Blue	6 (.12)	3 (.06)	1 (.02)	0 (.00)	0 (.00)	10 (.20)
(Column Sums)	9 (.18)	11 (.22)	9 (.18)	12 (.24)	9 (.18)	50 (.20)

Table E-4

Frequency of Color-Tone Matchings by Trial for the Korean Subjects
(Relative frequencies are shown in parentheses)

Colors	Tones					Row Sums
	375	500	750	1000	1500	
Red	4 (.032)	2 (.016)	3 (.024)	5 (.04)	11 (.088)	25 (.20)
Yellow	1 (.008)	10 (.08)	4 (.032)	8 (.064)	2 (.016)	25 (.20)
Orange	8 (.064)	3 (.024)	3 (.024)	7 (.056)	4 (.032)	25 (.20)
Green	2 (.016)	7 (.056)	12 (.096)	2 (.016)	2 (.016)	25 (.20)
Blue	10 (.08)	3 (.024)	3 (.024)	4 (.032)	5 (.04)	25 (.20)
(Column Sums)	25 (.20)	25 (.20)	25 (.20)	26 (.208)	24 (.192(	125 (1)

Trial N-3

Colors	375	500	750	1000	1500	Row Sums
Red	2 (.04)	2 (.04)	0 (.00)	1 (.02)	5 (.10)	10 (.20
Yellow	2 (.04)	3 (.06)	4 (.08)	1 (.02)	0 (.00)	10 (.20)
Orange	2 (.04)	4 (.08)	0 (.00)	4 (.08)	0 (.00)	10 (.20)
Green	1 (.02)	2 (.04)	2 (.04)	4 (.08)	1 (.02)	10 (.20)
Blue	3 (.06)	1 (.02)	2 (.04)	2 (.04)	2 (.04)	10 (.20)
(Column Sums)	10 (.20)	12 (.20)	8 (.20)	12 (.20)	8 (.20)	50 (1)

Table E-4 Continued

Colors	Tones					Row Sums
	375	500	750	1000	1500	
			Trial N-2			
Red	2 (.04)	2 (.04)	0 (.00)	1 (.02)	5 (.10)	10 (.20)
Yellow	0 (.00)	4 (.08)	3 (.06)	3 (.06)	0 (.00)	10 (.20)
Orange	4 (.08)	2 (.04)	2 (.04)	2 (.04)	0 (.00)	10 (.20)
Green	1 (.02)	2 (.04)	3 (.06)	3 (.06)	1 (.02)	10 (.20)
Blue	2 (.04)	2 (.04)	1 (.02)	4 (.08)	1 (.02)	10 (.20)
(Column Sums)	9 (.18)	12 (.24)	9 (.18)	13 (.26)	7 (.14)	50 (1)
			Trial N-1			
Red	2 (.04)	2 (.04)	1 (.02)	0 (.00)	5 (.10)	10 (.20)
Yellow	3 (.06)	2 (.04)	2 (.04)	3 (.06)	0 (.00)	10 (.20)
Orange	3 (.06)	3 (.06)	0 (.00)	4 (.08)	0 (.00)	10 (.20)
Green	1 (.02)	2 (.04)	6 (.12)	0 (.00)	1 (.02)	10 (.20)
Blue	2 (.04)	1 (.02)	2 (.04)	2 (.04)	3 (.06)	10 (.20)
(Column Sums)	11 (.22)	10 (.20)	11 (.22)	9 (.18)	9 (.18)	50 (1)

Table E-5

Information Transmission in Color-Tone Matchings by Trial for All Subjects by Nationality

Trial	No. of Ss.	H(X)	H(Y)	H(X,Y)	T(X,Y)	H(X|Y)	H(Y|X)
			All Subjects				
N-4	21	2.32	2.30	4.37	.26	2.06	2.04
N-3	29	2.32	2.31	4.44	.19	2.13	2.12
N-2	39	2.32	2.32	4.63	.01	2.31	2.31
N-1	45	2.32	2.33	4.36	.29	2.03	1.81
N	50	2.32	2.32	4.13	.51	1.81	1.81
			30 U. S. Officers				
N-4	6	2.32	2.22	3.915	.631	1.69	1.59
N-3	12	2.32	2.29	4.56	.052	2.268	2.238
N-2	20	2.32	2.29	4.29	.322	1.998	1.968
N-1	25	2.32	2.32	4.36	.27	2.05	2.04
N	30	2.32	2.32	4.24	.40	1.92	1.92

Table E-5 Continued

Trial	No. of Ss	H(X)	H(Y)	H(X,Y)	T(X,Y)	H(X|Y)	H(Y|X)
			10 Koreans				
N-4	8	2.32	2.32	4.38	.262	2.06	2.06
N-3	10	2.32	2.30	4.22	.40	1.92	1.90
N-2	10	2.32	2.29	4.23	.38	1.94	1.91
N-1	10	2.32	2.32	4.15	.49	1.83	1.83
N	10	2.32	2.32	4.38	.26	2.06	2.06
			10 Indonesians				
N-4	7	2.32	2.30	4.18	.442	1.88	1.86
N-3	7	2.32	2.30	4.12	.50	1.82	1.80
N-2	9	2.32	2.27	4.11	.482	1.84	1.79
N-1	10	2.32	2.31	3.74	.892	1.43	1.42
N	10	2.32	2.32	3.78	.86	1.46	1.46

Table E-6

Loudness Level Observations (in dB) for All Subjects for Each of Five Frequencies
(Reference Tone was 1500 Hz at 80 dB(SPL)

Subjects	Tones					Mean	Standard Deviation
	375	500	750	1000	1500		
S1	72	76	77	80	78	76.6	2.97
S2	72	78	76	79	78	76.6	2.79
S3	74	79	90	83	79	81	5.96
S4	72	76	84	77	78	77.4	4.34
S5	70	60	63	65	79	67.4	7.44
S6	73	60	62	60	79	66.8	8.70
S7	75	60	61	62	79	67.2	8.58
S8	78	68	72	66	[illegible]	72.4	5.55
S9	76	64	68	70	79	71.4	6.06
S10	78	65	69	70	80	72.4	6.35
S11	68	55	63	68	79	66.6	8.75
S12	66	72	74	72	78	72.4	4.33
S13	76	68	75	78	80	75.4	4.56
S14	70	65	74	75	78	72.4	5.03
S15	74	63	70	73	81	72.2	6.53
S16	71	70	76	87	80	76.8	6.98
S17	69	71	70	73	78	72.2	3.56
S18	67	74	68	76	78	72.6	4.88
S19	68	70	74	73	[illegible]	73	4.58
S20	64	74	72	70	[illegible]	72	5.83
S21	68	70	71	73	[illegible]	72.6	5.03
S22	70	76	76	72	[illegible]	75	4.24
S23	[illegible]	75	76	68	[illegible]	73.6	4.50
S24	70	70	74	72	79	73	3.74
S25	85	84	84	72	79	80.8	5.45
S26	68	75	73	69	75	72.6	4.16
S27	74	73	70	[illegible]	79	73.2	3.70

Table E-6 Continued

Subjects	Tones 375	500	750	1000	1500	Mean	Standard Deviation
S28	63	73	74	67	79	71.2	6.26
S29	67	72	73	68	80	7272	5.15
S30	70	68	71	70	80	71.8	4.71
S31	66	69	67	69	78	69.8	4.76
S32	71	69	73	66	79	71.6	4.88
S33	70	75	78	70	81	74.8	4.87
S34	71	79	79	67	78	74.8	5.50
S35	77	74	74	78	80	76.6	2.60
S36	74	72	76	70	80	74.4	3.85
S37	84	86	87	80	81	83.6	3.05
S38	72	74	73	75	79	74.6	2.70
S39	70	68	72	74	79	72.6	4.22
S40	80	82	82	79	82	81.0	1.41
S41	72	69	71	73	80	73.0	4.18
S42	79	75	79	74	81	77.6	2.97
S43	72	75	81	87	80	79	5.79
S44	76	78	87	72	81	78.8	5.63
S45	80	84	82	80	82	81.6	1.67
S46	68	74	70	77	79	73.6	4.61
S47	71	76	75	70	80	74.4	4.04
S48	77	78	78	76	79	77.6	1.14
S49	80	77	81	70	80	77.6	4.50
S50	83	86	78	77	80	80.8	3.70
Mean	72.62	72.48	74.46	72.84	79.46	74.37	4.74
Std Dev.	5.04	6.70	6.30	5.63	1.13	3.89	1.68

Table E-6 Continued

1. The mean value of the distribution of the average loudness levels per frequency: 74.37 dB.

2. The standard deviation of the distribution of the average loudness levels per frequency: 2.95 dB.

3. The mean value of the distribution of the standard deviation of loudness levels per frequency: 4.96 dB.

4. The standard deviation of the distribution of the standard deviations of loudness level per frequency: 2.23 dB.

5. The mean value for the distribution of each S's mean loudness level: 74.37 dB.

6. The standard deviation for the distribution of each S's mean loudness level: 3.89 dB.

7. The mean value of the distribution of each S's standard deviation loudness level: 4.74 dB.

8. The standard deviation of the distribution of each S's standard deviation loudness level: 1.68 dB.

Table E-7

Photometric Brightness Observation (in foot-candles) for All Subjects for Each of Five Colors
(Reference Color was Blue)

Subjects	Colors					Mean	Standard Deviation
	R	Y	O	G	B		
S1	3.10	9.00	3.80	1.00	1.8	3.58	3.28
S2	1.40	1.90	2.40	1.20	1.85	1.75	.47
S3	.70	.90	1.00	.25	1.90	.95	.604
S4	.75	1.20	.78	.25	1.90	.976	.616
S5	.90	1.50	2.10	.45	1.90	1.37	.689
S6	1.90	3.00	14.0	1.70	1.75	4.47	5.36
S7	2.30	12.0	2.25	.50	1.75	3.76	4.66
S8	2.95	4.85	1.70	.25	1.85	2.32	1.71
S9	1.00	3.00	1.25	.40	1.75	1.48	.979
S10	.70	1.00	1.25	.20	1.75	.98	.582
S11	.50	.75	1.00	.25	1.85	.87	.615
S12	.90	1.65	2.25	.25	1.95	1.40	.714
S13	2.00	13.0	3.00	.50	1.95	4.09	5.06
S14	3.60	4.40	25.0	1.20	1.75	7.19	10.04
S15	1.40	13.0	1.00	.25	1.70	3.47	5.35
S16	3.00	13.0	1.40	1.40	1.75	4.11	5.01
S17	.95	4.9	1.40	.25	1.90	1.88	1.80
S18	1.90	4.9	3.90	.50	2.00	2.64	1.75
S19	1.00	1.40	2.00	.25	1.95	1.32	.727
S20	1.20	2.45	2.60	.50	1.80	1.71	.876
S21	1.00	2.75	.65	.25	1.80	1.29	.996
S22	1.40	5.80	2.90	.25	1.75	2.42	2.11
S23	3.40	2.50	15.0	.65	1.75	4.66	5.87
S24	2.15	2.40	5.70	.25	1.70	2.44	2.00
S25	1.85	2.50	1.75	1.50	1.75	1.87	.375
S26	1.25	1.65	1.25	.6	1.75	1.30	.452
S27	.50	2.45	1.35	.5	1.90	1.34	.859

Table E-7 Continued

Subjects	Colors R	Y	O	G	B	Mean	Standard Deviation
S28	.95	.90	1.50	.3	1.85	1.10	.596
S29	1.00	.95	.90	.25	1.85	.99	.569
S30	.75	1.00	.75	.25	1.75	.90	.547
S31	1.20	3.00	1.95	.40	1.85	1.68	.963
S32	1.25	.85	.80	.40	1.80	1.02	.529
S33	2.40	22.0	15.0	1.35	1.85	8.52	.44
S34	.35	4.0	1.50	.20	1.80	1.57	1.52
S35	1.00	2.8	1.30	.30	1.90	1.46	.945
S36	1.50	1.00	1.75	.25	2.00	1.30	.694
S37	1.85	2.20	3.00	.75	2.00	1.96	.809
S38	1.30	1.70	1.30	.30	1.85	1.29	.604
S39	1.20	4.50	3.00	.25	1.90	2.17	1.64
S40	3.10	4.40	3.00	.75	1.90	2.63	1.37
S41	4.50	1.75	2.25	.40	2.00	2.18	1.48
S42	1.80	2.75	2.20	.50	1.95	1.84	.832
S43	2.75	2.30	1.80	.25	2.00	1.82	.948
S44	1.90	.75	1.65	.50	1.90	1.40	.713
S45	1.40	3.50	2.00	.35	1.90	1.83	1.14
S46	2.00	11.0	3.00	.90	2.00	3.78	4.11
S47	.60	2.0	2.25	.35	1.85	1.41	.870
S48	3.00	15.0	18.0	.75	1.75	7.70	8.14
S49	11.0	4.5	6.5	.40	1.70	4.82	4.19
S50	5.0	2.00	2.00	.65	1.75	2.28	1.62
Mean	7.07	4.10	3.78	.527	1.85	2.43	2.16
Std Dev.	1.67	4.47	5.02	.377	.0913	1.74	2.38

Table E-7 Continued

1. The mean value of the distribution of the average brightness levels per color: 3.46 fc.

2. The standard deviation of the distribution of the average brightness levels per color: 2.49 fc.

3. The mean value of the distribution of the standard deviation of brightness levels per color: 2.32 fc.

4. The standard deviation of the distribution of the standard deviations of brightness levels per color: 2.30 fc.

5. The mean value for the distribution of each S's mean brightness level: 2.43 fc.

6. The standard deviation for the distribution of each S's mean brightness level: 1.74 fc.

7. The mean value of the distribution of each S's standard deviation brightness level: 2.16.fc.

8. The standard deviation of the distribution of each S's standard deviation brightness level: 2.38 fc.

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