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# Virginia Polytechnic Institute and State University

Human Factors Laboratory
Industrial Engineering and Operations Research
BLACKSBURG, VIRGINIA 24061

⑧ LEVEL II

ANNUAL SUMMARY REPORT

# RESEARCH ON
# NEW ELECTRONIC DISPLAY TECHNOLOGIES

by

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14 December 1979

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This report summarizes the work performed during the first year, dealing with two tasks. The first task, entitled "Human Engineering Survey and Analysis," reviews the current flat panel display technologies, a summary of the human operator-critical characteristics of each technology, a technical summary of relevant human operator visual characteristics, and an evaluation of each technology by current visual display theoretical evaluation approaches. The second task, entitled "Hue/Luminance Contrast Tradeoffs," involved laboratory research designed to develop a metric by which luminance contrast and chrominance

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) contrast can be traded off in display design to provide a metric of total effective display contrast. Work to date on both these tasks is summarized in this report.

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# SECTION 1: TECHNICAL SUMMARY

This Annual Summary Report summarizes work performed to date under Contract N00014-78-C-0238, entitled "Research on New Electronic Display Technologies." The contract contains two separate, but related, tasks.

The first task, Human Engineering Survey and Analysis, provides for a comprehensive review of current flat panel display technologies, a summary of the human operator-critical characteristics of each technology, a technical summary of relevant human operator visual characteristics, and an evaluation of each technology by current visual display theoretical evaluation approaches. Section 2 of this report summarizes this task, the report for which will be published in early 1980.

The second task, Hue/Luminance Contrast Tradeoffs, involves laboratory research designed to develop a metric by which luminance contrast and chrominance contrast can be traded off in display design to provide a metric of total effective display contrast. A summary of work to date and activity planned on this task is contained in Section 3 of this interim report. Work described in Section 3 will be completed in late 1980, and a technical report of the results will be issued at that time.

The purpose of this Annual Summary Report is to indicate, to appropriate individuals, the nature of the research under this contract and the content of reports to be subsequently published. The authors would, of course, be pleased to receive comments or suggestions regarding these activities to make the ultimate products more useful to the scientific and engineering community.

## SECTION 2: HUMAN ENGINEERING SURVEY AND ANALYSIS

During the past two decades, there has been a greatly increased amount of activity in research and development of new types of visual displays, many of which have been intended to replace classic incandescent and cathode ray tube (CRT) display devices and systems.

Ten years ago it was predicted by many in the display system business that these new, solid-state (or flat-panel) displays would indeed totally displace the CRT for most if not all applications. The flat-panel displays showed promise of greater ruggedness, finer detail or resolution, less power consumption, better geometric image stability, less image distortion, and greater compatibility with their associated electronic circuitry.

During these ensuing 10 years, some (but not all) of those claims have been met. Simultaneously, the CRT has been improved greatly on the same dimensions. As a result, the flat panel display technologies have been used in many applications where CRTs were formerly used, but the replacement of CRTs with other forms has been anything but universal.

Today there exists the same challenge from the solid state display community. Further, the variety of available solid state display types continues to increase, due largely to continued emphasis on the research and development critical to the electronic interfacing and materials needed for these devices. As a result, the systems engineer or human factors engineer concerned only with selecting an appropriate display device for a given application is faced with many candidates and few criteria for valid selection. This report is an attempt to provide useful, conveniently packaged information for that systems or human factors engineer.

## Purpose

The purpose of this task final report is to provide the critical background information that the systems or human factors engineer needs to make an intelligent display device selection for a given application. It is not intended as a designer's manual, as a menu of required future research projects, nor as an authoritative sourcebook of display systems engineering.

To make an intelligent and valid display device selection, or to specify appropriate criteria for display device fabrication and selection, the human factors/systems engineer requires a working knowledge of (1) the fundamental physical concepts inherent in each display technology, (2) functional relationships between display types and display parameters pertinent to the human operator's use of the display, and (3) the quantitative relationships between human performance in generic or typical tasks and functional characteristics of the display, irrespective of the display technology.

It is the purpose of this report to provide that information needed by the systems/human factors engineer.

## Organization

Chapter 2 of the task final report presents an overview of current flat-panel display technologies. Each technology is described in terms of its basic physical concepts and materials; its electrical, photometric, and geometric characteristics; its inherent advantages and limitations; and a prognosis for its future development. For purposes of consistency, each technology is described by the same 13 parameters or categories. These parameters or categories are defined at the beginning of Chapter 2, which concludes with a comparative description of the technologies. Chapter 2 also includes, using the same 13 categories of description, the CRT display, for the CRT remains the traditional standard against which all other display devices are compared.

Chapter 3 describes the spatial, temporal, and chromatic capabilities of the normal human visual system. The approach taken is that of the application of (1) current multichannel processor concepts of the visual system, and (2) linear systems analysis of both the display and the visual system to result in an analytic ability to directly compare the visual system's "requirements" with the information displayed. This analytic approach is developed in Chapter 4, which also summarizes known human operator performance data pertinent to the design and evaluation of these flat panel display devices.

Because there are, unfortunately, substantial gaps in our knowledge of display design requirements for human operator optimal performance, these data gaps are described in Chapter 5. The data gaps, or research needs, will be noted in appropriate places throughout the report, as they become pertinent to various subjects of the report.

Chapter 6 attempts to apply the data and generalizations to three types of display environments, a shipboard command and control room, a Marine Corps information system, and airborne displays for data readout as well as for aircraft and weapons control.

Finally, Chapter 7 summarizes the report, examining briefly the current and future flat panel display technologies, their ability to meet the display needs of the human operator, and the display and/or human performance research and development necessary to maximize the selective use of these flat panel display technologies.

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# SECTION 3: HUE/LUMINANCE CONTRAST TRADEOFFS

## Introduction

In applications where a human operator is presented information on an achromatic or monochromatic display (e.g., a black and white CRT or a green phosphor CRT), contrast is provided by varying the luminance of the displayed information. Polychromatic displays achieve contrast by providing variation of the spectral content and the luminance of displayed information.

One of the conclusions of the Task I report is that little is known about specifying the amount of color contrast needed to perform various tasks. There has been little research on how chrominance contrast, the contrast between two stimuli of differing hue and/or saturation, and luminance contrast combine into perceived color contrast. One objective of the present research is to determine the relative contributions of luminance differences and chrominance differences to the perception of color contrast.

There have been very few attempts to determine the form of a metric of color contrast. Chapanis (1949) suggested that chrominance contrast and luminance contrast combine to produce a total contrast. A second objective of the present research is to determine the form of a metric which specifies the contributions of luminance and and chrominance contrast to total contrast.

A review of the human factors literature reveals that very little research has been performed on either determining the form of a metric of color contrast or determining the relationship between the amount of color contrast and performance. Rather, the human factors literature has concerned itself with two major issues: (1) the utility of using color-coded information (e.g., Carter and Cahill, 1979; Christ, 1975; Oda and Barker, 1979), and (2) which colors are most easily named or recognized (e.g., Chapanis, 1965; Haeusing, 1976; Halsey and Chapanis, 1951). The results obtained from these studies are of considerable use to display designers, but they do not provide the data required for specifying a metric of color contrast.

The psychologiocal and psychophysical literature contains many studies of color contrast; however, these studies define contrast in ways that are quite different from the way in which a display designer would define contrast. Many of these studies have defined contrast in terms of the effects obtained when a chromatic stimulus is presented with a differently colored surround or "inducing field" (Yund and Armington, 1975). The results of such studies typically show that, for example, a yellow-green stimulus presented with a yellow surround appears more green than when the central stimulus is presented alone.

The magnitude of the effect of the surround on the target increases with increasing surround size (Yund and Armington, 1975), decreases as the spatial separation between the stimulus and the surround increases (Oyama and Hsia, 1966), and the greatest effects occur with small test fields and large surrounds (Marsden, 1969). The results of these experiments are of some interest to display designers; they indicate that the perceived hue of a color character or symbol is affected by the color of the surround and the surround size. The problem is.that these results are not related to the perceived contrast between a target and its backround, nor have they been related to typical performance measures. A further problem with these results is that they cannot be used directly in the design of displays.

Very little research is available which contributes to the formation of hypotheses of how chrominance separation contributes to the perception of color contrast. Much research has followed the lead of MacAdam (1949) in determining just noticable differences among colors. This previous research addresses the complement of the visual display color contrast problem; it attempts to specify the amount of chrominance separation permitted before a subject detects a difference between a reference stimulus and a test stimulus.

In essence, this research determines the threshold for color contrast achieved by chrominance separation. The results of these studies are of considerable use to the paint and dye industry in specifying quality control criteria, but these results do not enable the display designer to specify particular levels of suprathreshold contrast.

The results obtained by MacAdam and other investigators indicates that the CIE and CIE-UCS color spaces are not uniform with respect to chromaticness or lightness (brightness) (Wysecki and Stiles, 1967). This means that equal changes in color coordinates do not result in equal changes in perception. Efforts to develop uniform color spaces or to transform existing color spaces into uniform color spaces have met with little success or require complicated transformations (Wsecki and Stiles, 1967, chap. 6) and are often of limited generality.

A further obstacle to the formation of a metric of total perceived color contrast is the lack of correlation between luminance and perceived lightness, subsumed under the label of "luminance additivity." A typical experiment demonstrating nonadditivity was performed by Guth (1967). The experiment involved measuring the luminance added to a monochromatic test field to make the test field detectable, or just over threshold. If luminance additivity holds, then for monochromatic fields of different wavelengths a constant amount of luminance has to be added to make the test field detectable. The results reported by Guth for monochromatic fields of 10 different wavelengths indicate that luminance additivity does not hold. The results indicate that the larger the wavelength difference between the subthreshold test field and the added light, the greater the luminance of the added light required to make the compound stimulus detectable.

Experiments investigating luminance nonadditivity have generally been conducted using stimuli at or near threshold. It is important to establish how these results may be generalized to suprathreshold stimuli and the perception of contrast, for suprathreshold contrast is much more pertinent to display design. The studies which would permit such generalization have not been reported, if they have indeed been conducted.

The nonuniformity of the CIE color space and color spaces derived from the CIE color space in both chromaticness and brightness (or lightness) limits the utility of these systems in predicting perceived color contrast. If these color spaces were uniform then it might be possible to scale, by a constant multiplier, the difference between the coordinates of two stimuli in order to predict the perceived contrast. The nonuniformity of the CIE and CIE transformed color spaces indicates that equal changes in coordinates do not yield equal changes in perception; thus, no simple function of the difference between coordinates can be expected to correlate highly with perceived contrast.

A rather severe limitation of the psychophysical research on the perception of chromatic stimuli stems from the limited range of stimuli which have been studied. One such limitation is a results of the use of narrowband (monochromatic) stimuli. Although the use of such stimuli simplifies, to some extent, the analysis of results and the formulation of theory, it limits the generality of the results obtained. This is especially true since the emitted spectra of most color displays are quite broad band.

Another limitation stems from the diversity of experimental paradigms in use and from the hesitancy of investigators to study two or more paradigms in parallel. As a result, there is a great deal of research in the literature, very little of which has been extended beyond a single experimental paradigm. This strategy simplifies the formation of theory and leads to well defined research questions, but it limits the generality of the results. Therefore, much of the existing literature cannot be used to determine the form of a metric of color contrast. Further, it is not clear how the various phenomena being studied might affect the perception of color contrast.

In summary, neither the human factors literature nor the psychological and psychophysical research have provided the data or theory necessary to form a metric of color contrast. Due to nonuniformities, neither the CIE nor the CIE derived color coordinate sytems can be simply and efficiently adapted to predict perceived color contrast.

## Statement of the Problem

At present, there are no data which allow the determination of how contrast achieved by luminance separation and chrominance separation combine to produce color contrast. These data need to be obtained over a wide range of suprathreshold conditions before a metric of color contrast can be formed.

A second question, of considerable practical importance, concerns the effect of a surround-induced hue shift on the perceived color contrast between a surround and a central target. If surround induced hue shifts affect color contrast, then the chromatic content of the surround, which influences the direction of the perceived hue shift, becomes an important display design factor. Although considerable research has been performed on surround-induced hue shifts, no research data have been reported which predict the effect of a surround induced hue shift on color contrast.

## Research Approach

In order to determine how the components of color contrast combine, we shall present subjects with: (1) stimuli of differing hue and saturation but constant brightness, and (2) stimuli with the same hue and saturation but differing brightness. The subjects will be asked to match the contrast between two chromatic test stimuli to the contrast between two achromatic fields. The subjects will be able to adjust the contrast of the achromatic fields by adjusting the luminance difference between the two achromatic fields. The adjusted luminance difference between the two achromatic fields can be thought of as the equivalent achromatic contrast of two chromatic stimuli. The measured luminance difference between the achromatic stimuli will be used to form an interval scale of color contrast.

The use of this experimental task has several advantages. Judgements made by matching tend to be fairly easy to obtain, are fairly reliable, and have low variances. These advantages account for the tremendous popularity of this method among color perception researchers. A further advantage of the experimental task is that it provides a dependent measure which can be used to scale the contributions of luminance contrast, chrominance contrast, and the combination of both.

The data obtained from the experiment described above will be used to evaluate the utility of a vector-difference model of color contrast. A vector-difference model would use the difference between the color coordinates of two chromatic stimuli to predict the amount of color contrast between the stimuli.

In the experiments to be performed, subjects will be matching the equivalent achromatic contrast of stimuli which are of equal brightness and of varying chrominance, and will be matching the equivalent achromatic contrast of stimuli which are of varying brightness and constant chrominance. The data from these two sets of matches will be used to scale the relative contributions of brightness separation and chrominance separation to the perception of color contrast. We will form a vector difference model which takes into account the contributions of chrominance separations and luminance separation which predicts matched equivalent achromatic contrast.

The CIE and CIE transformed color spaces are non-Euclidean affine spaces (Cohen and Frieden, 1976; Wysecki and Stiles, 1967), and distances between points in an affine space have no meaningful physical interpretation. In order to appropriately evaluate a vector difference model, a Euclidean color space is needed. Cohen and Frieden (1976) have developed a Euclidean color space, and we will be evaluating the utility of a vector-difference model of color contrast based on their coordinate system. A second experiment will be performed to assess the effects of surround induced perceived hue shift on the perception of color contrast. During the course of this experiment, subjects will be matching the achromatic contrast of two achromatic fields to the contrast of two chromatic stimuli presented concentrically, as a small central target within a larger target.

The question of primary concern is whether the derived metric of color contrast has to take into account the effect of surround-induced contrast hue shifts. One possibility is that by knowing the coordinates of the hue-shifted test field, one can use the metric of color contrast developed in the previous experiment to predict perceived contrast. Measurements of surround induced hue shift will be made in order to provide for the inclusion of these effects in the metric of color contrast.

## Development of Display Capability

The research program discussed above requires a display that: (1) has the ability to present a wide range of broad band colors, (2) has the ability to present stimuli in a wide range of spatial configurations, and (3) has the ability to display stimuli on command without frequent recalibration. The above requirements can be met by using a computer controlled digital image generator in conjunction with a high resolution color television monitor.

The display system used in the present research consists of a Conrac 5411 color television monitor equipped with a Mitsubishi high-resolution picture tube, which is driven by an International Imaging System digital image generator. The digital image generator is in turn controlled by a PDP 11/55 minicomputer.

The television monitor contains a red, a blue, and a green electron gun. The CIE x-y chromaticity coordinates of each gun are at a vertex of the triangle shown in Figure 1 Colors within the triangle are generated by adding different amounts of red, green, and blue. The amount of red, green, or blue added is determined by the number of intensity bits set for each gun.

The capability of displaying stimuli of particular chromaticity coordinates requires determination of the relationship between commanded intensity bits and the amount of luminance at the display. The relationship between luminance and intensity bits and laws of additive color mixing can be used to calculate the intensity bit settings needed to display specific colors.

## Development of Measurement Software and Technique

Figure 2 contains a simplified block diagram of the radiometric system used to make measurements of the output of the display system. The system consists of a probe, a

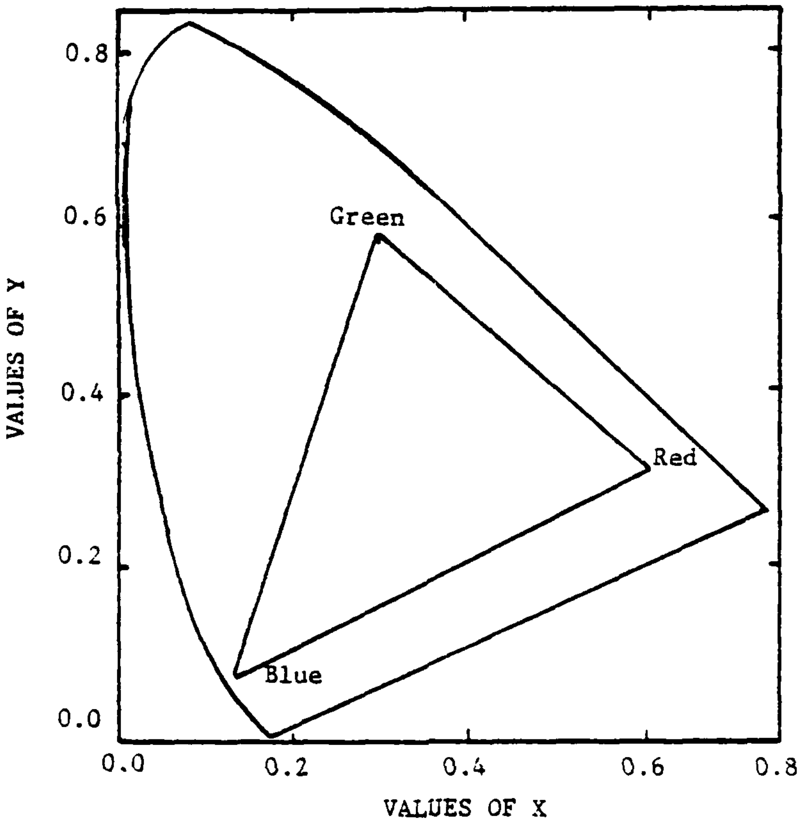

Figure 1: The CIE x,y Coordinates of the Red, Green, and Blue Phosphors

fiber optic cable, a monochromator, a photometric multiplier tube, a monochromator scanning control, and a digital radiometer. A standard spectral radiance source is also required for calibration of the measurement system. Functionally, the probe collects the light emitted by the display. The fiber optic cable transmits the emitted light to the monochromator. The monochromator takes the incoming light and displaces it according to wavelength. The scanning controller selects a narrow wavelength band to be sent to the photomultiplier tube. The photomultiplier tube is the sensing element of the system which transforms photons into electrons. The potential generated by this transformation is measured by the digital radiometer.

A program was written which placed the radiometric measurement system under computer control. The software senses the position of the monochromator head, sends a signal to advance the monochromator head to the next wavelength to be sampled, senses when the monochromator head has moved to the next wavelength to be sampled, and samples the output of the radiometer.

A calibration program was written which compares the known output of a standard source to the output measured by our system and calculates a correction factor at each wavelength between 300 and 800 nm. The results of the calibration program were analyzed by a program which calculates chromaticity coordinates, radiance, and luminance.

Four parameters of data collection had to be fixed before characterization of the display could proceed. The first parameter to be fixed was the allowable error in the placement of the monochromator sensing head. The error is the difference between the intended head position and the current head position. The error value, or hysteresis value, was chosen to be as small as possible before a continuous hunting for head placement took place.

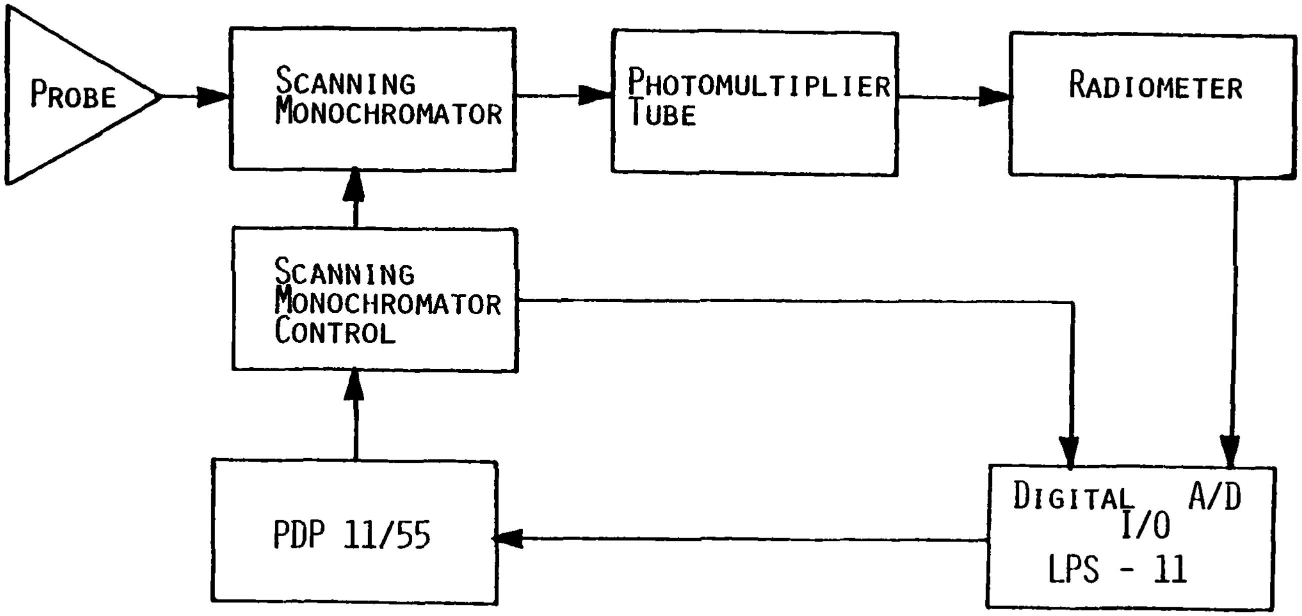

Figure 2: A Simplified Block Diagram of the Radiometric System

The second parameter to be fixed was the time interval spent at each wavelength during sampling of the radiometer output. Due to the noise present in the radiometric measurement system, measurements of the radiometer output were made once every millisecond and averaged over a sampling time interval. A sampling time interval of 100 ms was chosen. Smaller times yielded larger errors in the calculated color coordinates of the standard source. Sampling time intervals of longer than 100 ms did not yield appreciable decreases in the error of calculated standard source color coordinates.

A series of scans of a laser beam (Spectra Physics Model 155, helium-neon) imaged onto a diffuser were made to determine the transfer function of the radiometric measurement system. Figure 3 shows the results of a scan of the laser beam made in 1 nm increments. The response of the system is very sharp and the half-amplitude width is approximately 3 nm. The wavelength of the laser was specified by the manufacturer as 632.8 nm. The average measured peak amplitude was 632.6 nm with a standard deviation of .966 nm.

The final parameter to be fixed was the number of scans needed to estimate the mean luminance and radiance within 3 percent of the true mean at the 95% confidence level or better. A sample size of five scans was chosen using the sample size estimation technique described by Seeberger and Wierwille (1976).

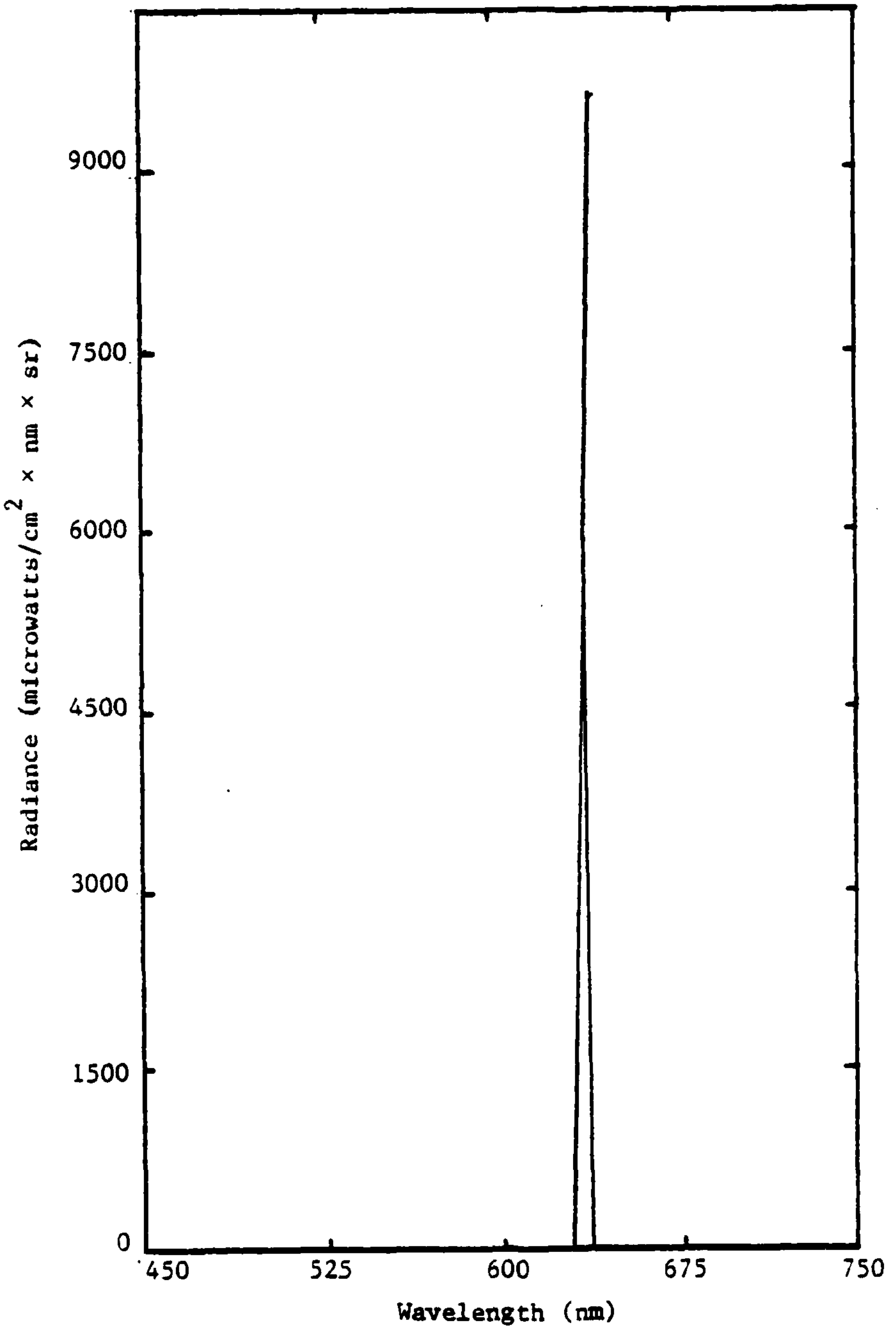

Figure 3: Radiometric Measurement System Results for Laser Scan

In summary, we have developed software and measurement techniques which allow us to measure spectral density functions and to calculate the luminance, the radiance, and the color coordinates of any displayed stimulus. In addition, these measurements are made to known tolerances.

## Characterization of the Display System

Figure 4 shows the nonlinear relationship between displayed luminance and the number of intensity bits set for each of the Red, Green, and Blue electron guns. The figure shows that the luminance range of the Red and Blue guns are quite a bit smaller than the luminance range of the Green gun. Quadratic models fit the luminance-intensity bit data quite well (for the Red gun, $r^2 = 0.996$, for the Green gun, $r^2 = 0.996$, for the Blue gun, $r^2 = 0.991$).

To facilitate the transformation of coordinates to intensity bit settings, the luminance output of the display was linearized. Examination of the quadratic models of the luminance-intensity bit data revealed that these models would not be accurate enough for use in luminance output linearization. The method chosen for linearization involved measuring the luminance output of each gun at sixteen equally spaced intervals over the range of intensity bit settings (0-1023). A linear function was fit between the luminances recorded for 0 bits and 1023 bits. Finally, a table was constructed which maps a 0 to 255 bit linear scale

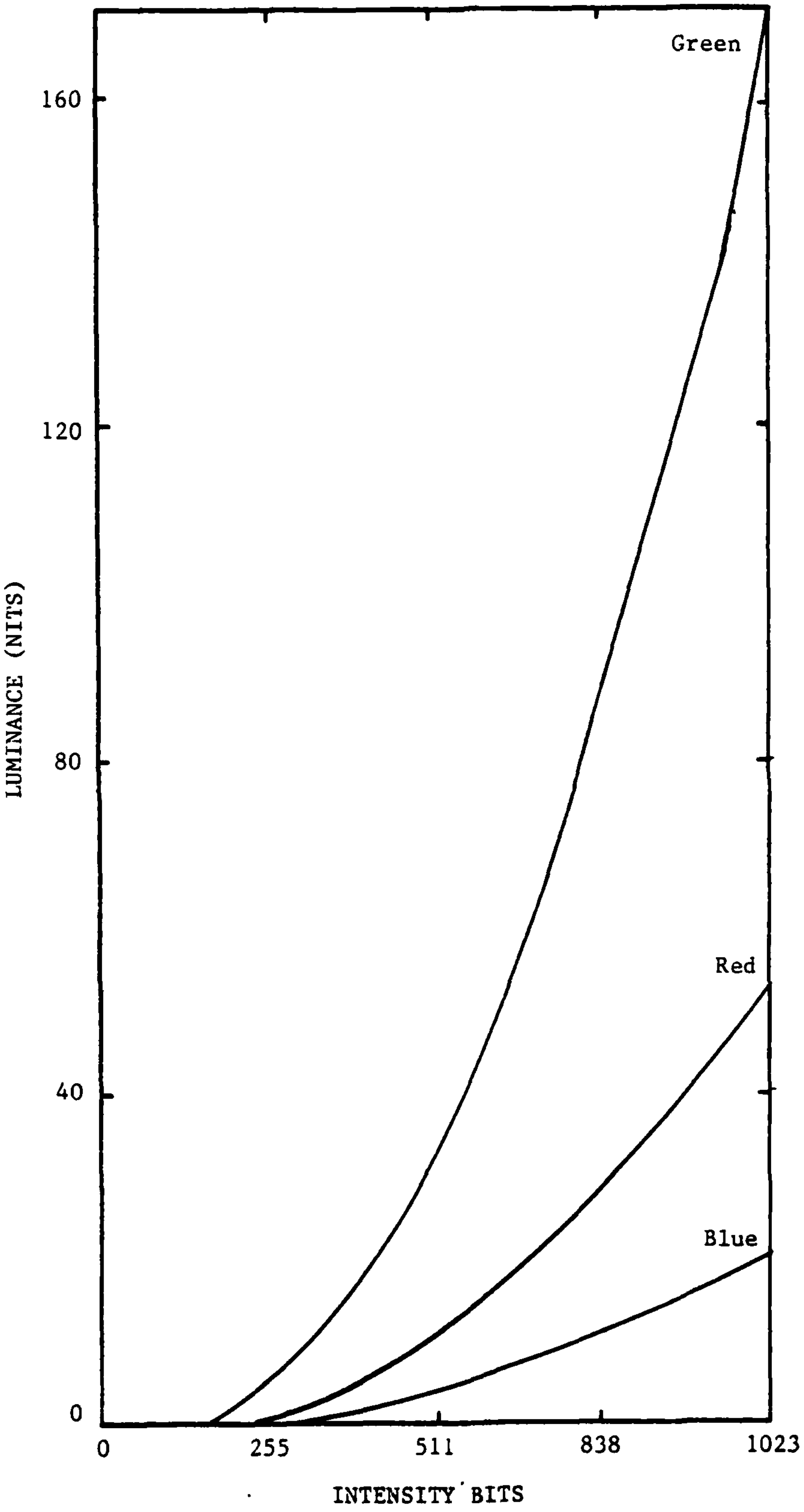

Figure 4: Luminance-Intensity Bit Relationships

into the 0 to 1023 output scale such that the relationship between input bits and luminance is linear. The 0 to 255 bit linear scale is the scale used in calculations described below. The results of the linearization are illustrated Figure 5

The program which calculates the intensity bit settings accepts as input the x,y chromaticity coordinates and the luminance of the desired color. The fact that tristimulus values are additive, the result that the tristimulus values associated with each gun are a linear function of the 0-255 bit linear scale, and the defining equations for chromaticity coordinates yield a system of simultaneous linear equations. This system of equations may be used to solve for the bit value settings given the x,y chromaticity coordinates and the luminance of a desired color.

The bit values returned from the above program then serve as the midpoint of a search interval for each of the Red, Green, and Blue channels. All possible combinations of bit values within the intervals are used to calculate chromaticity coordinates. The bit value combination which yields coordinates closest to the desired coordinates is returned.

Once the 0 to 255 bit linear output table has been built an experimenter need only run the program which calculates the intensity bit settings in order to be able to display a color. With the capability developed thus far, it is very

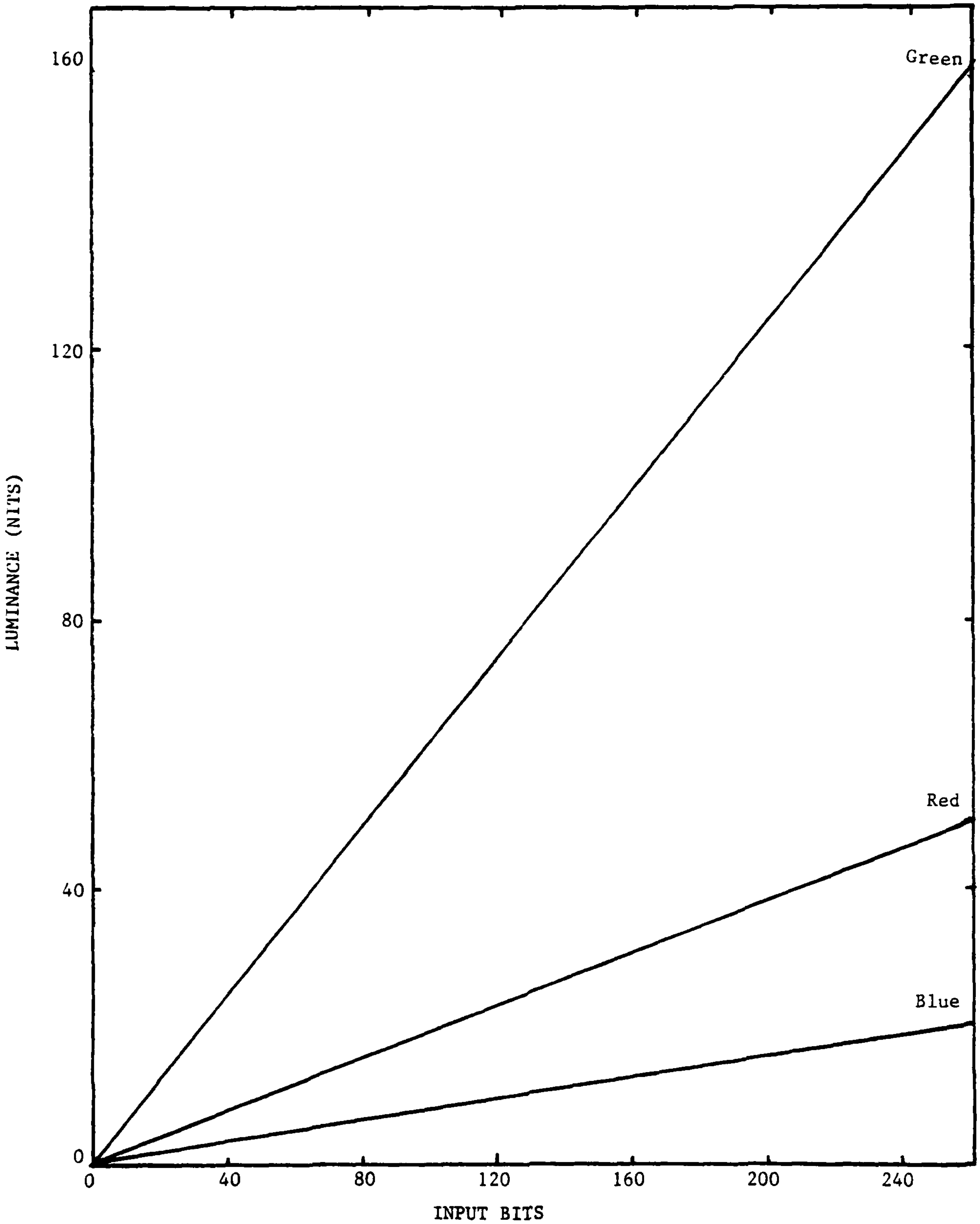

Figure 5: Linearized 0-255 Bit Scale

easy to change stimuli for a particular experiment or to specify the stimuli for a new experiment.

## Task Summary

A review of the human factors literature and the psychophysical literature reveals that there is little or no data which can be used by a display designer in specifying the amount of color contrast a human operator will perceive. In order to provide the data necessary to form a metric of color contrast, experiments will be performed which investigate the relative contributions of luminance separation and chrominance separation to the perception of color contrast. In addition, an experiment will be performed which seeks to investigate the effects of a chromatic surround on the perception of color contrast.

A flexible display capability is required to perform the experiments described in this report. The display system must permit the experimenter to present a broad range of chromatic stimuli in many spatial configurations. A digitally controlled color television system provides the required flexibility, provided that the system can be adequately characterized.

Software and measurement techniques were developed which enable the measurement of radiometric and photometric quantities as well as chromaticity coordinates within known tolerances. These measurements were used to develop software which permits an experimenter to specify and display stimuli of known chromaticity coordinates.

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