Accommodation With Displays Having Color Contrast

by

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INTRODUCTION

The presence of the video display terminal (VDT) in the work place has become ubiquitous as industry attempts to find more productivity gains through computerization and automation. New technology has not only brought a greater number of VDTs to the workplace, but has enabled the cost effective introduction of multicolor displays as well as the more traditional monochromatic terminal into the work environment. As VDTs of all types become more commonplace in the work environment, their effect on the human visual system becomes a larger determinant of the overall well-being of the working population. Therefore, it is imperative that we further investigate the effect of the use of the VDT on those workers who must regularly use the terminal.

Reports of visual complaints among those persons who use VDTs are common (see, for example, Brown, Dismukes, and Rindalducci, 1982; Dainoff, Happ, and Crane, 1981; National Research Council, 1983; and Ostberg, 1980), and are an indicator that this type of work may adversely affect the human visual system. The most often cited visual complaints are ocular discomfort, burning or pain in the eyes, blurring of vision, and double images. These symptoms have often been gathered under the ambiguous term visual fatigue. Also temporary changes in the observers' visual function have been reported. Among these are reduced visual acuity, changes in the near point of accommodation and convergence, changes in hue perception and some color contingent aftereffects (Brown et al., 1982). Performance decrements have also been associated with long term work at the VDT. While many of the visual symptoms cited above occur after the performance of any near-term visual task, the frequency of the reported complaints among VDT users when compared to their counterparts who do not use VDTs appears to be greater and certainly more severe.

Several aspects of the VDT have been mentioned as possible contributors to the visual discomfort experienced by those who are required to use the terminal regularly. The image generated on a VDT is relatively blurred when compared to the image achieved with hard copy, image contrast is also not as large as that normally obtained with hard copy, and the periodic nature of the refresh of the cathode ray tube (CRT) image have all been suggested as affecting the observers' visual system. As a consequence, the image quality of the electronically generated image is not as good as that obtained with good printed matter. Snyder (1980) reviewed the effects of image quality on the human visual system when generated by an electronic display.

Because the image produced on a VDT is typically not of the quality of printed material, it has been suggested that some of the visual complaints experienced by VDT users may be due to the observers' inability to obtain and maintain focus on the characters presented on the VDT. Mourant, Lakshmann, and Herman (1979) hypothesized that the visual system may be stimulated to attempt continually to achieve proper focus and that this action may contribute to some of the reported visual discomfort. They cited an increase in the time to bring a near or distant object into focus after long term use at the VDT as support for their hypothesis. Later, Ostberg (1980) suggested that temporary reductions in the observers' range and speed of accommodation after long term work with VDTs were measures of visual fatigue. Both researchers suggested that the poorer image quality produced by the VDT may result in a poorer stimulus for accommodation and that the action of the observers' visual accommodation system to bring characters into focus may contribute to the visual discomfort reported by VDT users. Later work (Rupp, McVey, and Taylor, 1984) has demonstrated no significant differences in an observer's ability to accommodate to characters presented on a CRT when compared to hard copy, but questions concerning how VDT use affects the visual system remain.

The use of the multicolor CRT as the display terminal creates new questions concerning the observers' visual function. In terms of visual resolution, it is more difficult to create an image on a color CRT than on a monochromatic display terminal and, as a consequence, the image may not be as sharp as that produced with a monochromatic CRT or printed matter. Additionally, the visual system is not a linear system with respect to color in that the optics of the eye exhibit chromatic aberration causing the visual system to respond differently to light of differing wavelengths. These two factors suggest that the visual system may have more difficulty accommodating to characters presented on a multicolor CRT and that this may lead to an increase in the visual problems experienced by users of multicolor CRTs.

The data reported here seek to characterize the observers' accommodation responses to chromatic characters presented on colored backgrounds, relate accommodation to color contrast, and determine if there is a relationship between the observers' focus and visual performance, all in an effort to understand better the observers' visual functions while using a multicolor CRT.

BACKGROUND

Accommodation

Visual accommodation is the ability of the eye to focus objects at different distances. In the normal human eye, contraction of the ciliary muscles that control the shape of the lens effect a change in the refraction of the lens and, as a consequence, a change in the optical power of the lens of the eye. Through this process, the eye can clearly focus objects from about 6 meters to 10 to 20 centimeters. Thus, approximately a 10 diopter change in the power of the lens of the human eye can be obtained in visual accommodation (Graham, 1965).

Under normal viewing conditions, factors that influence the accommodation response of the eye include distance, apparent size, and stereoscopic viewing. Binocular accommodation is also aided by the conjugate convergence of the eyes and by pupillary changes that can affect one's depth of field.

Unique monocular cues for accommodation have been much more difficult to identify. This difficulty results from the complexity and subtlety of the monocular stimulus for accommodation. One of the earliest interpretations proposed that chromatic aberration exhibited in the optics of the eye supplied the necessary cues to indicate the magnitude and direction of the change in the refraction necessary to bring an image into focus on the retina of the eye. It was suggested that the effects of chromatic aberration in controlling the accommodation response in white light are that the retinal point spread function, the blur circle, would tend to be surrounded by a red fringe in hyperopia and a blue fringe in myopia (Fincham, 1951). The result is that in the case of over-accommodation, the short wavelengths are most out of focus and in the case of under-accommodation, the longer wavelengths are the most out of focus (Millidot, 1982).

Campbell and Westheimer (1958), concerned about resolving the individual differences observed in accommodation response under monochromatic conditions, tested Fincham's hypothesis. In white light their findings very closely resembled those of Fincham, but when the chromatic fringes were removed by requiring the observer to view the stimulus in monochromatic light, three of four subjects could accommodate as accurately as they had in white light, whereas the fourth subject needed several dozen trials. These results indicated to Campbell and Westheimer that chromatic aberration was only used by some observers for accommodation control and that spherical aberration must also play an important role in monocular accommodation.

Manipulating stimulus distance and blur, Smithline (1974) concluded that blur alone was not a sufficient stimulus for accommodation. He suggested, as have others (Cornsweet and Crane, 1973; Toates, 1972), that an odd-error signal, perhaps arising from spherical lens aberration, must also be present for accommodation control. Millidot (1982) concurred in stating that in monochromatic light, spherical aberration along with changes in blur during microfluctuations of accommodation indicate the necessary direction and amplitude for accommodation. In summary, the data suggest that in monochromatic light, individuals can learn to use the stimuli available in the environment for accommodation when the cues normally used are eliminated (Campbell and Westheimer, 1958; Cornsweet and Crane, 1973).

More recently, Owens (1980) noted that a reduction in either luminance or contrast of the visual stimulus results in increasing errors of accommodation. Based on these observations, he suggested that the accommodation system acts to maximize the spatial contrast at the fovea and, further, that the contrast of the foveal image is an important stimulus for accommodation. Subsequent studies have not only supported the importance of contrast as a stimulus for accommodation, but have indicated that luminous contrast is both a sufficient and a necessary stimulus for accommodation (Wolfe and Owens, 1981).

Factors Affecting Accommodation

It is the latter perspective that is most interesting when investigating the ability of the observer to accommodate to images produced on a VDT. Snyder (1980) discussed the relationship of human visual performance while observing images generated on an electronic display. He suggests, as have others, that visual performance varies as the contrast sensitivity function of the visual system and that visual performance is quite predictable in terms of the quality of the observed image. The ability of the human observer to see the displayed image is a function of the image luminance, spatial frequency, contrast, color, and temporal characteristics. Prior research has investigated the effect of image luminance, spatial frequency, and contrast on accommodation. It should be noted that these three factors do not act independently to affect accommodation, but that luminance and spatial frequency of the observed image can be manipulated to affect the image contrast, and consequently, the accommodation response. The following sections will discuss the effect that each of these factors has on the observer's accommodation response.

Luminance. The relationship between luminance and accommodation has been a topic of considerable research. Most of this research has concentrated on the effect of low illumination on an observer's accommodation response, a condition known as night myopia or dark focus. At low luminance levels the observer tends to become myopic. Melerio (1966), in a review on accommodation at reduced levels of illumination, attributed the nearsightedness experienced by observers to one or more of the following factors: (1) the change in the spectral sensitivity from photopic to scotopic conditions (the Purkinje shift) coupled with the chromatic aberration of the eye; (2) spherical aberration of the eye, together with the large pupil diameter produced by low illumination levels; and (3) accommodation of the lens which tends towards a constant at and near darkness. The level of accommodation during low illumination levels is consistent with the value obtained for the resting position of accommodation, that is, the focus of the eye under conditions where there is no stimulus for accommodation. It has been found that rather than being focused at infinity, the accommodation system assumes an intermediate value of one to four diopters.

The concept of a dark focus or resting position of accommodation is important in determining the effect of luminance on accommodation because it has been found that accommodation is most accurate at the intermediate distance corresponding to one's dark focus. Errors will result in accommodation to targets at vergences that are greater than or less than this intermediate value. At all luminances, individuals will over-accommodate distant objects and will under-accommodate near objects with the direction of the accommodation error always towards the observers' dark focus or resting position of accommodation. The error in accommodation becomes progressively larger as luminance is reduced and as the stimulus distance moves away from the dark focus value (Johnson, 1976).

At high luminances, errors in accommodation are relatively small. Johnson (1976) also concluded that the observed decline in visual resolution with decreasing luminance and stimulus distance (DePalma and Lowry, 1962) disappears if one corrects for errors in accommodation; that is, the correction for accommodation errors effectively eliminates variations in visual resolution as stimulus distance is reduced.

Spatial Frequency. The spatial frequency of the object to be focused has been investigated to determine its role in the accommodation response (Bour, 1981; Charman and Heron, 1979; Charman and Tucker, 1978; Owens,1980). The study of the response of the visual accommodation system to targets of a single spatial frequency has been undertaken to understand better the response to targets made of broadband frequency components. At spatial frequencies of less than one cycle per degree, the accommodation response is substantially in error and generally corresponds to the level exhibited at an observer's resting position of accommodation. During this condition, often called empty field myopia, errors of focus have little effect on image modulation and, consequently, a large focusing error is acceptable (Charman and Tucker, 1977). As the spatial frequency of the target increases, the reported data conflict and the resultant role of the spatial frequency of the target to be focused is interpreted differently. Charman and Tucker (1977, 1978) found that as the spatial frequency of a sinusoidal target increases, the accommodation response necessary to bring the target into focus monotonically increases. Accommodation was also more accurate at higher spatial frequencies. The observer in the study could not bring a high frequency target into focus at the highest vergence, indicating some role for the low frequency components in guiding the accommodation response. Charman and Tucker (1977, 1978) concluded that low frequency components of an object containing a broadband frequency spectrum are used to guide the initial accommodation response and the high frequency components are utilized to maintain the steady state response. Later experiments (Charman and Heron, 1979) demonstrated these effects.

Owens (1980) and Bour (1981) obtained results differing from those of Charman and Tucker when investigating the relationship between the spatial frequency of a target and an individual's accommodation response. Their results indicate that the accommodation response to sinusoidal targets of single frequencies varies in a manner consistent with that of the contrast sensitivity function of the visual system. Accommodation accuracy and response reach an optimum at an intermediate frequency of about three to five cycles per degree and decline at both higher and lower spatial frequencies. From these results and a high correlation between one's accommodation response and the contrast sensitivity function,Owens (1980) suggested that the mechanisms underlying foveal contrast sensitivity are involved in steady state accommodation.

Bour (1981) additionally investigated fluctuations in the mean accommodation response and found that r.m.s. deviation increases with increasing spatial frequency and decreasing contrast for the same dioptric step. Bour concluded from these data that lower frequency components may guide the accommodation response, confirming Charman and Tucker's hypothesis, but his data do not support the theory that high frequency components were instrumental in maintaining steady state accommodation. Support of the latter hypothesis would have demanded smaller r.m.s. deviations in mean accommodation response as the spatial frequency of the target increased. This is not consistent with the data obtained. The data of Owens and Bour suggest the importance of the intermediate frequency components in an individual's accommodation response.

Differences in the studies of Charman and Tucker (1977, 1978), Owens (1980), and Bour (1981) have been attributed to the instructions given to the subjects. Charman and Tucker required their subjects to maintain the best focus that could be achieved, a voluntary accommodation. Owens and Bour asked their subjects to accommodate naturally, without straining their eyes, a reflex or involuntary accommodation. The voluntary effort to accommodate as accurately as possible could have resulted in the monotonically increasing function observed in the Charman and Tucker experiments (Bour, 1981; Owens, 1980).

In all studies, accommodation to targets of a broadband frequency spectrum, as represented, for example, by a Snellen target, has resulted in an accommodation response that is more accurate than to any target of a single frequency. Targets of wider spatial bandwidth can use lower spatial frequencies to guide the accommodation response and the intermediate to higher frequencies to obtain the image modulation required to maintain the accommodation response at the appropriate level. The richness of the complex target due to its wider spatial bandwidth thus results in a more stable accommodation response.

Contrast. Based on studies involving the effects of luminance and spatial frequency on the accommodation response, it has been proposed that the contrast of the foveal image serves as an important stimulus for steady state accommodation. In general, reduction of the contrast of a visual stimulus results in systematically increasing myopia for distant objects and increasing hyperopia for nearer objects (Owens, 1980). Experimental work has demonstrated that greater accommodation error occurs at low contrast for targets of single frequencies, but this relationship does not necessarily hold for complex stimuli. With complex stimuli, some higher frequency components may fall below threshold as contrast is reduced and, as a result, effect a more accurate accommodation response. Bour's data show that as the spatial frequency of the target increases, the contrast value for the minimum r.m.s. deviation of accommodation response increases. Thus, when high frequency components drop below threshold, the accommodation system requires lower contrast to reach an optimum response and a more accurate accommodation response results.

Owens (1980) reports a high correlation between an observer's accommodation response and the contrast sensitivity function and from this finding he suggests that similar mechanisms are responsible for accommodation control and contrast resolution. Accordingly, Owens proposes that the accommodative system acts as a servo mechanism which strives to maximize spatial contrast at the fovea. Under conditions where the visual system is insensitive to contrast or the spatial contrast is not affected by focus, the accommodation system lacks the necessary input for control and returns to its neutral state. The accommodation values obtained during night myopia and empty field myopia can be explained using this model.

Charman and Tucker (1978) also discussed the role of retinal image contrast in steady state accommodation. They offered three hypotheses to account for optimal steady state accommodation: (1) the eye first locates the optimal image plane and then relaxes until the perceived image contrast begins to deteriorate; (2) the eye accommodates to a level away from its resting position just above that necessary to produce an image modulation above threshold; (3) a dynamic evaluation of the temporal changes in image modulation is involved in steady-state accommodation. Charman and Heron (1979) later demonstrated that the initial response to an out-of-focus target must be based on low spatial frequency information and that as the retinal image focus becomes closer to optimal, higher spatial frequency information becomes available. They suggest that this permits refinement in the accommodation response.

In summary, luminance, spatial frequency, and image contrast affect accommodation accuracy in the same manner as they affect an observer's visual resolution. Consequently, these data indicate that the mechanisms responsible for accurate accommodative control may be related to image quality parameters in much the same way as image quality is related to visual performance where the observers' spatial vision is of concern.

<u>Accommodation and Color</u>

To investigate the accommodation response in relation to a multicolor display terminal, one must determine the effect that the chromatic aberration of the lens of the eye has on an individual's ability to properly focus a target. Due to the chromatic aberration in the eye, light of differing wavelengths will be differentially focused on the retina of the eye. Light of shorter wavelengths will tend to be focused at a point nasal to the optic axis and light of longer wavelengths will tend to be focused at a point temporal to the optic axis. This results in a condition that requires a different refraction from the eye to bring images of different colors into clear focus. Thus the eye may have to refocus to bring differently colored items on the multicolor display into sharp focus. Early studies indicated that as much as 3.35 diopters difference in the refractive power of the lens is necessary to bring a stimulus into focus that is 365 nm dominant wavelength when compared to a stimulus that is 750 nm dominant wavelength (Wald and Griffin, 1947). Bedford and Wyszecki (1957) found similar results, although over a less disparate range of wavelengths.

Accommodation in monochromatic light was investigated by Charman and Tucker (1978). Initially, they found that accommodation accuracy was less than ideal in monochromatic light when compared to accommodation in white light, but adequate training permits an equally accurate response in monochromatic light. They concluded that the only fundamental difference in accommodation in different colors of light was that due to the variation in the power of the eye with wavelength and perhaps a reduced acuity at the blue end of the spectrum. Errors in accommodation followed the same pattern that was observed in white light, over accommodation for distant objects and under accommodation for near objects, with the subject's resting point of accommodation acting as a point of reference. There were no differences in the precision of accommodation reported with differing wavelengths.

Chromatic contrast has been investigated as a stimulus for accommodation in an experiment where individuals were asked to accommodate to a bipartite field in which each half varied only in chromaticity (Wolfe and Owens, 1981). The results indicated that a strong chromatic edge does not improve accommodative responsiveness and that with fields of the same brightness, a disruption in the accommodation process occurred. It was concluded that chromatic contrast is not a sufficient stimulus for accommodation and that luminance contrast is not only sufficient for accurate steady-state accommodation, but is a necessary condition. A subjective assessment suggested that the accommodation system continued to try to find focus on the isobrightness edge, but that fluctuations of accommodation were relatively slow.

Rupp, McVey, and Taylor (1984) tested four observers' accommodation response while reading hard copy material and while reading a CRT display under focused and defocused conditions. They found a significant difference in mean level of accommodation, mostly attributed to chromatic aberration, but no differences in the variability of accommodation among the tested conditions.

In experiments using multicolor cathode ray tubes, it has been determined that accommodation shifts with respect to one's accommodation using achromatic stimuli. The shift in accommodation has been attributed to the chromatic aberration experienced in the human visual system, but is not of the amplitude that would have been predicted from studies using monochromatic light. Murch (1982), in an experiment with six fully saturated colors and white presented on a color graphics terminal, found those colors produced by multiple phosphor combinations tended to cluster around the ideal value for the display distance when white characters are observed. Further, the refraction required to focus a pure red target when compared to a pure blue target was outside the observers' depth of field. Based on these results, Murch (1982) suggested using only colors created by multiple phosphors. His data indicate this strategy will keep the range of dioptric power needed to correct for the chromatic aberration due to differentially colored characters within the observers' depth of focus and will consequently remove the necessity for refocusing.

Accommodation and VDT Viewing.

The literature concerning CRT viewing and the observers' accommodation response has primarily emphasized the role the accommodation system plays in contributing to the visual discomfort reported by VDT users. Mourant, Lakshmann, and Herman (1979) suggested that because the image quality is typically poorer on a CRT when compared to printed text, that the accommodation system may continually hunt for the appropriate focus and that this action may lead to the reported visual problems. They found that the accommodation latency for both near and far objects increased with the time on task. They provided these data as support for their hypothesis and further suggested that the increase in time to focus was an indicator of visual fatigue. Ostberg (1980) utilized laser optometry to investigate the effects of long term VDT viewing on the observers' accommodation response. He too reported increases in the time to bring a target into focus with time on the VDT task. Additionally, Ostberg reported some temporary myopia and shifts inward of the observers' dark focus. He concluded that each change in accommodation could be used as a measure of visual fatigue.

Rupp, et al. (1984) performed a study to examine how accommodation changed as the image was defocused to determine if there was a link between the observers' accommodation performance and the relatively blurred CRT image when compared to printed text. In this study, the observers were required to observe printed text, a normal CRT image, and a defocused CRT image. A shift in the mean accommodation was reported, attributed to the chromatic aberration of the eye when viewing the green phosphor, when compared to the mean level obtained while viewing the hardcopy, but no significant differences in the stability of the accommodation response were found when the standard deviation of the accommodation response was used as the measure of the variability in the accommodation response. This study provided no support for the hypothesis that the accommodation system responds differently when CRT images are observed than it does when focusing on printed material.

Murch (1982) performed the only studies dealing specifically with multicolor CRTs. His study, described in the previous section, indicates that the effect of viewing chromatic characters on a black background is much less than would have been predicted by the earlier studies with monochromatic light. The change in mean accommodation response over the tested range was approximately 0.4 diopter. He further suggests that by avoiding characters generated with pure phosphors that refocusing should not be required to maintain proper focus over the rest of the spectrum.

While each of these studies provides data concerning one's accommodation response to images presented on the VDT, accommodation data have been taken only at sampled intervals throughout the task, rather than during task performance. As a result, the data collected tell little about accommodation during task performance. No data have been reported describing the accommodation response to chromatic characters displayed on chromatic backgrounds. Lastly, this review of the literature found no research which attempted to relate the accommodation response to the effective contrast between chromatic foregrounds and backgrounds or the relationship between an observer's ability to focus the displayed image and visual performance. Data of this type are necessary if we are to understand better the role accommodation plays in VDT viewing and its relationship to visual performance and the visual discomfort reported in the VDT environment.

RESEARCH OBJECTIVES

The purpose to this research was to investigate an observer's continuous accommodation response to targets presented on a multicolor cathode ray tube and to relate the accommodation response to task performance in an environment where a multicolor VDT is used as a medium for information transfer.

The specific objectives of this research were:

1) To measure an observer's accommodation response to targets of one chromaticity and purity against backgrounds that differ from the target in chromaticity, purity or in both chromaticity and purity.

2) To determine the relationship between an observer's accommodation response and the color difference between the target and background under conditions of color contrast.

3) to determine the relationship between visual task performance and an individual's accommodation response in a color contrast situation.

METHOD

Two experiments were performed investigating the effect that wavelength and purity have on an observer's accommodation to characters displayed on a multicolor CRT. In each experiment the wavelength and purity of the foreground (the target) and the background (a uniform field) were parametrically manipulated while the observer's accommodation response was being continuously measured and recorded. The experiments also investigated the effect of the different target/background combinations on visual task performance.

Experiment One

Five subjects participated in this experiment which was designed to assess an observer's accommodation response under conditions of color contrast. To investigate the effect of viewing targets that differed in chromaticity, purity, or chromaticity and purity from their backgrounds, it was required to hold either the foreground or the background chromaticity and the foreground and background luminance constant while varying the remaining independent variables to ascertain their effects on an observer's accommodation response. This analysis strategy was necessitated because a full factorial experimental design combining all possible target/background combinations results in 12 cells that constitute uniform fields (the foreground is the same as the background). These stimuli were not considered meaningful in the context of the present study. The resultant experimental design consisted of six 5 X 2 X 2 full factorial within-subjects designs investigating the effects of background wavelength, background purity, and foreground purity on an observer's accommodation response with a target that does not vary in chromaticity.

Four replications of each design were run. Block diagrams illustrating the structure of the experimental designs employed are contained in Figures 1-6. Each of the six designs has a different foreground/background color deleted. The univariate designs were repeated for both measures of accommodation response. The independent variables manipulated in the designs were background wavelength, foreground wavelength, background purity, and foreground purity. The levels of background wavelength and foreground wavelength were generated on a multicolor CRT and used backgrounds or targets of dominant wavelengths of approximately 460 nm (blue), 490 nm (cyan), 559 nm (green), 577 nm (yellow), 610 nm (red), and -520 nm (magenta). The generic name given in the parenthesis following the stimulus dominant wavelength will be used to denote a level of foreground wavelength or background wavelength in all of the discussion that follows. A more detailed radiometric characterization of the experimental stimuli appears in Appendix A.

The two levels of background purity and the two levels of foreground purity are designated high and low. The high purity stimuli lay on a line connecting the single gun response for the red, green, and blue phosphors at approximately 1.5 cd/m^2 luminance when plotted on the 1931 CIE chromaticity diagram (Appendix A). This triangle encloses the set of colors that can be generated by the

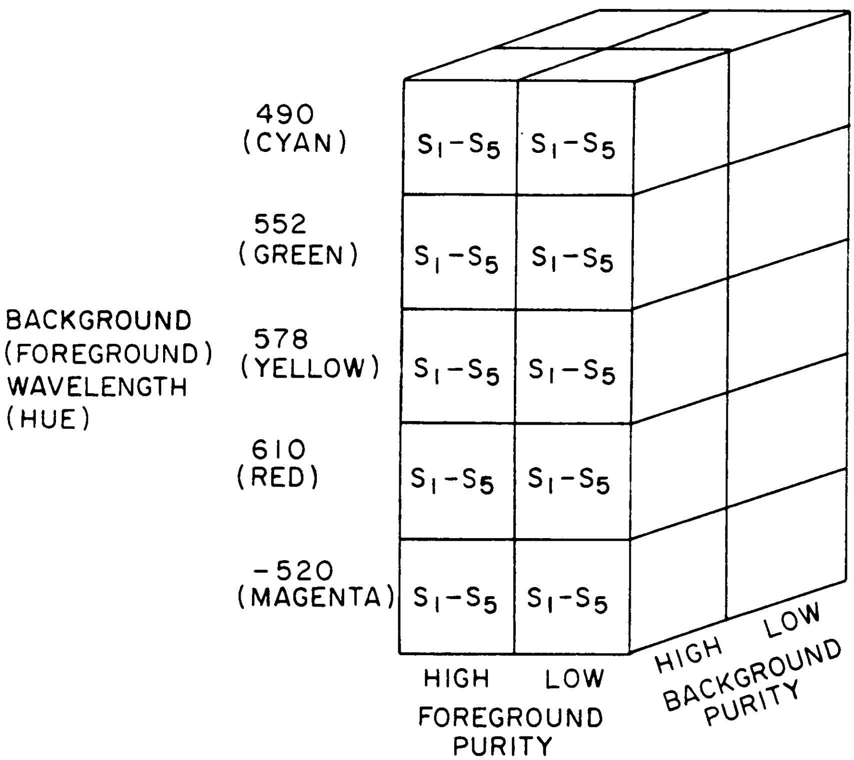

Figure 1. Experiment 1 block diagram, blue foreground or background.

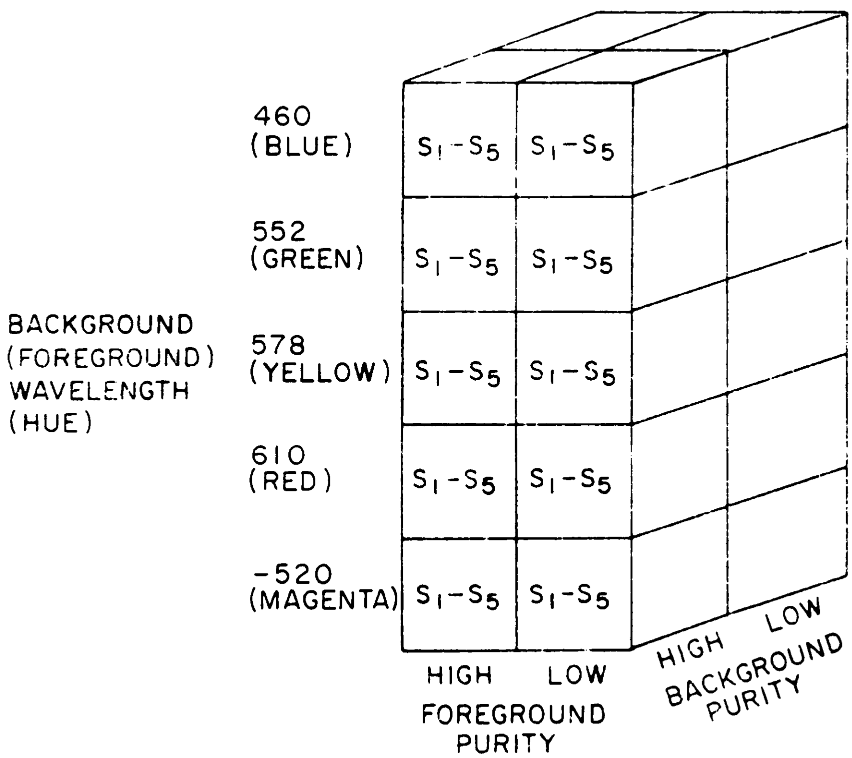

Figure 2. Experiment 2 block diagram, cyan foreground or background.

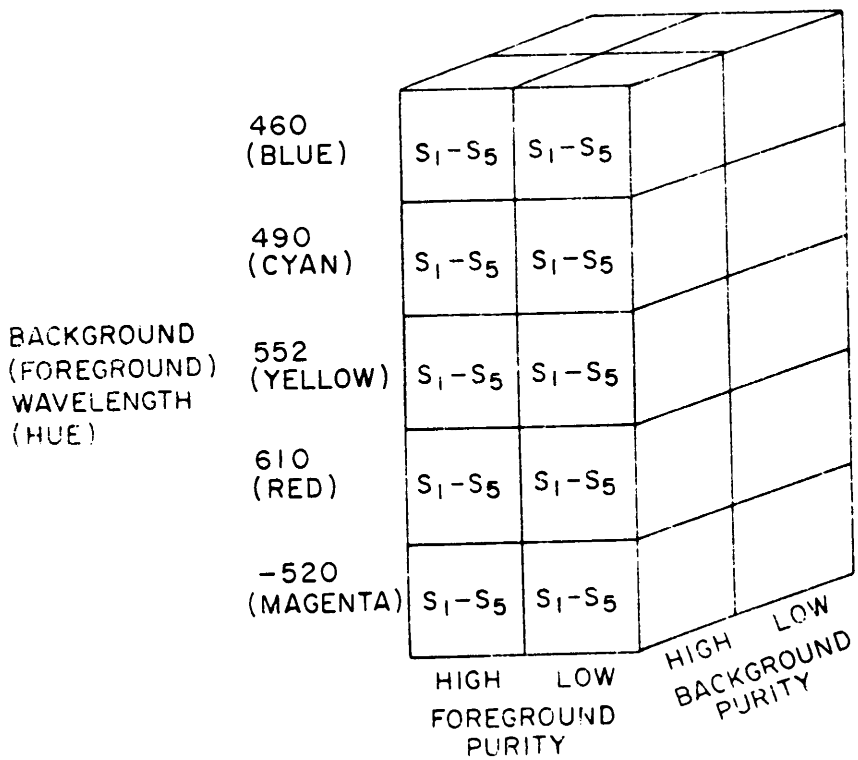

Figure 3. Experiment 1 block diagram, green foreground or background.

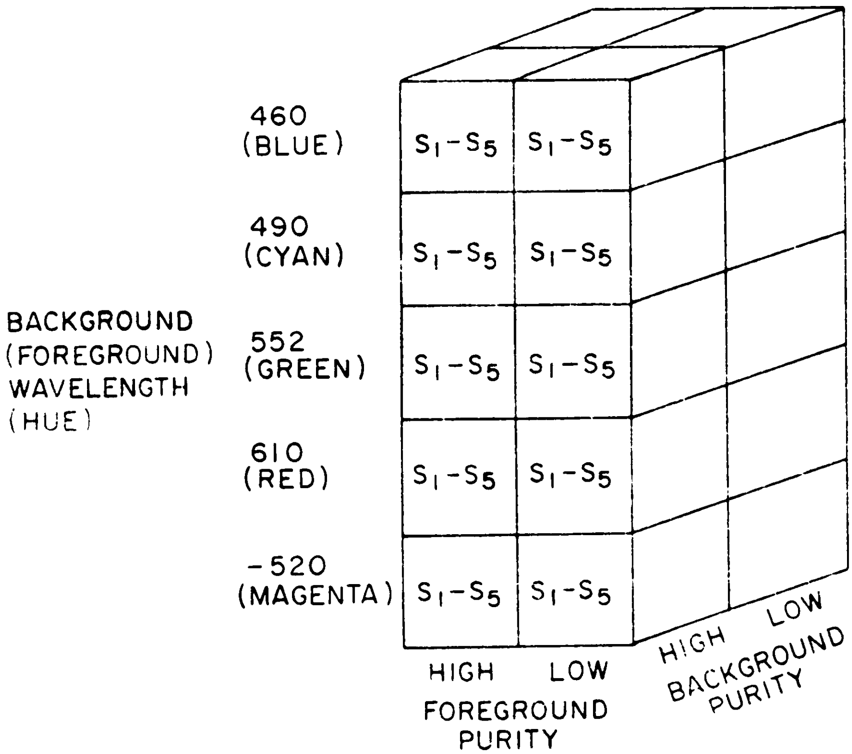

Figure 4. Experiment 1 block diagram, yellow foreground or background.

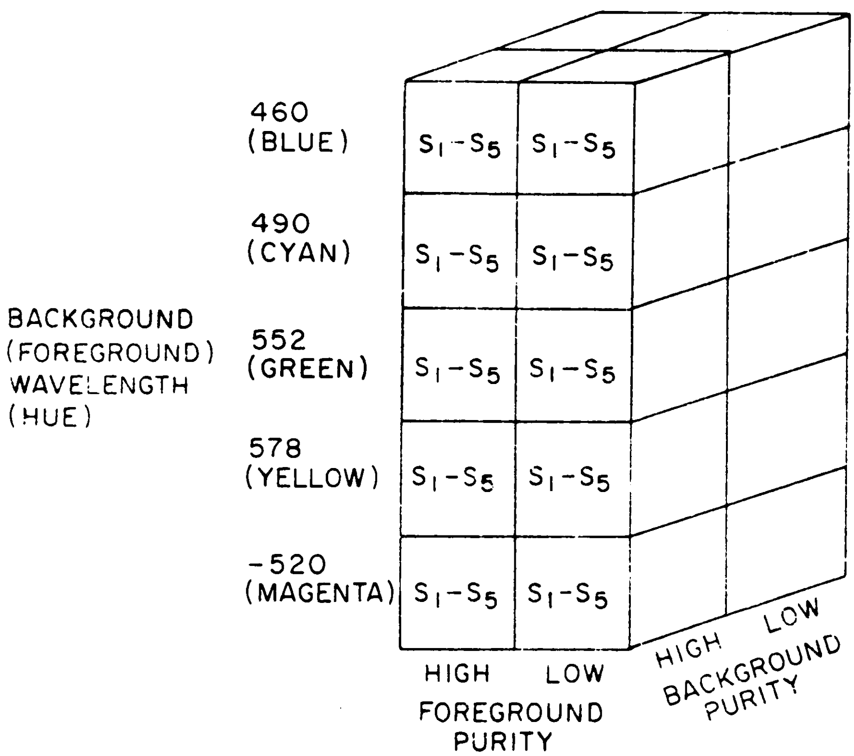

Figure 5. Experiment 1 block diagram, red foreground or background.

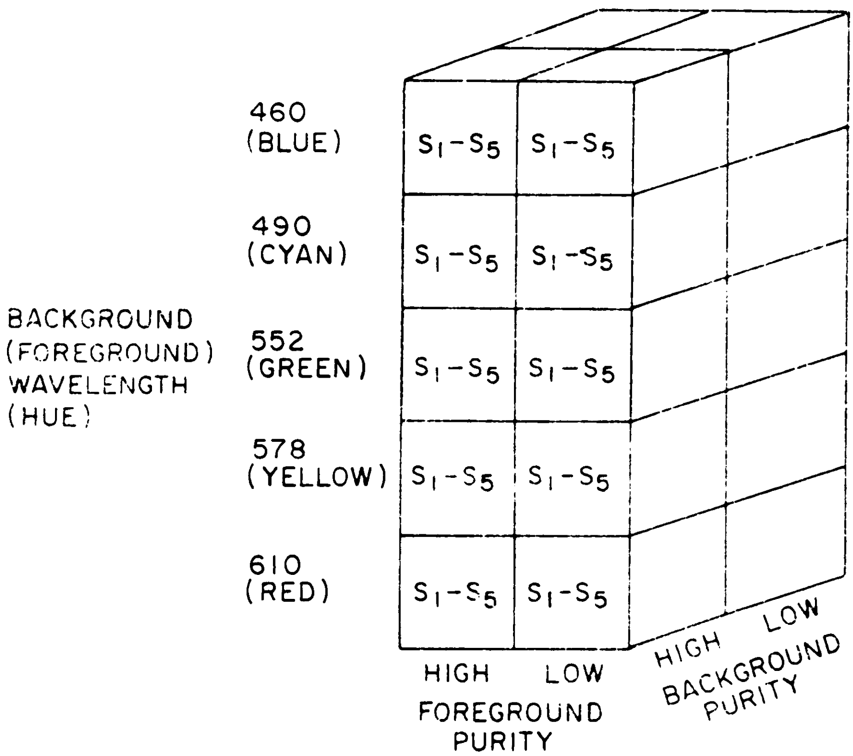

Figure 6. Experiment 1 block diagram, magenta foreground or background.

multicolor CRT used in this study. The low purity stimuli reside at points 1/2 the distance between the high purity stimuli and the center of the triangle previously discussed. The luminance of the stimuli was carefully controlled to assure, to the extent possible, isoluminance between the foreground and the background. Purity and luminance values for all stimuli are contained in Appendix A.

The observers' accommodation responses, as indicated by the mean level of accommodation obtained during a trial, and the standard deviation of the observers' accommodation responses for the trial,were collected continuously throughout the target/background presentation. Task time for a visual performance task was also recorded. No data were collected between the experimental trials.

The data collected in experiment one also required the observers to view achromatic targets on chromatic backgrounds and chromatic targets on achromatic backgrounds. These conditions were analyzed separately because the creation of a black stimulus effected a luminance difference between the target and background. The experimental design used to investigate accommodation response under these conditions resulted in two 6 X 2 X 2 within-subjects experiments. In the first of these experiments, the background was achromatic and foreground wavelength, background luminance, and foreground purity were each varied to determine the effect of observing a colored stimulus on an achromatic background. The chromatic stimuli used in this portion of the study were the same stimuli that were use in the first part of this study. There were six levels of foreground wavelength corresponding to blue, cyan, green, yellow, red, and magenta; two levels of foreground purity, high and low; and two levels of background luminance , high and low. The high luminance (white) background had a luminance equal to that of the chromatic stimuli, whereas, the low luminance (black) background had zero luminance.

The second of these experiments permitted the investigation of the observers' accommodation responses to achromatic foregrounds. The foreground in this experiment remained achromatic while the background wavelength (six levels), background purity (two levels), and foreground luminance (two levels) were manipulated. The chromatic stimuli were the same that were used in the previous part of this first experiment. High luminance denotes white targets, and low luminance denotes a black or zero luminance target. Block diagrams of this experiment can be found in Figures 7 and 8.

All trials for each replicate of the study were run in the same experimental session.

Experiment Two

Because it was necessary to hold the foreground wavelength or background wavelength constant and then manipulate the remaining variables, the interaction between foreground wavelength and the background wavelength could not be investigated in the first experiment. As a result, a full factorial second experiment was designed to investigate further this relationship. Secondly, an error in software prevented the full counterbalancing of the task data in

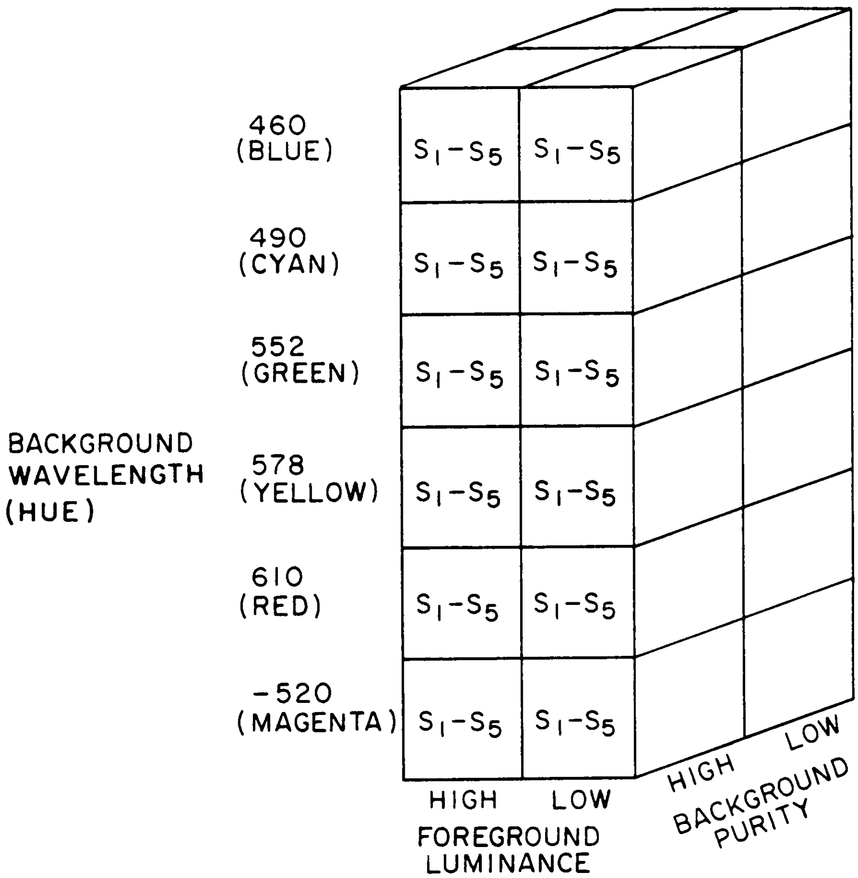

Figure 7. Experiment 1 block diagram, achromatic foreground.

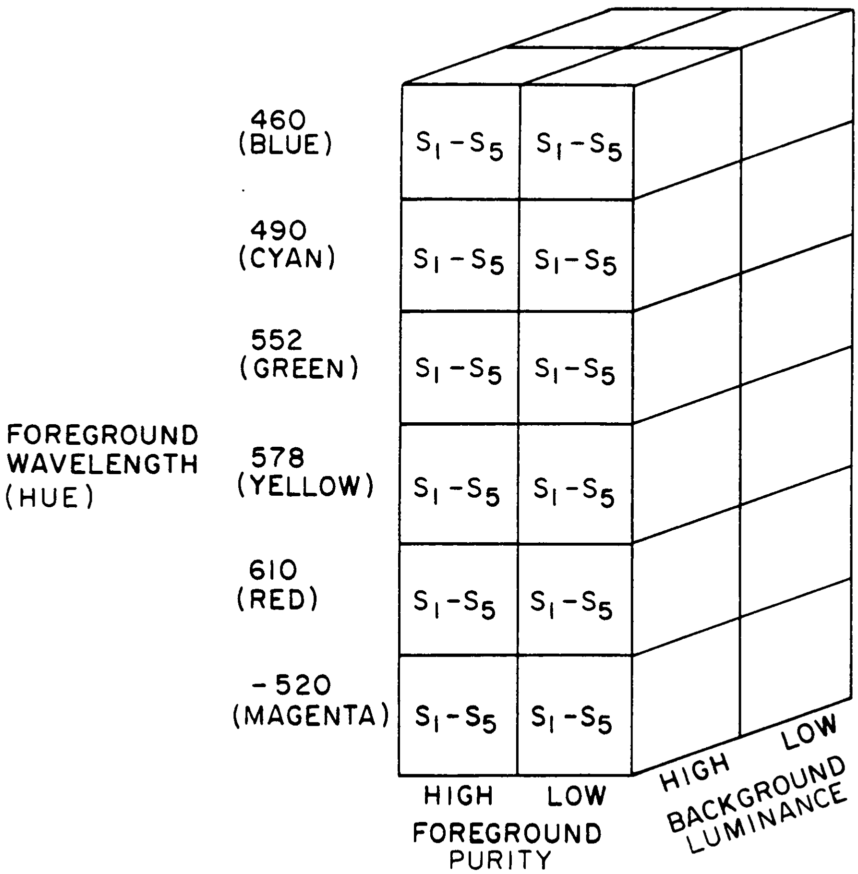

Figure 8. Experiment 1 block diagram, achromatic background.

the first study and resulted in the performance data being confounded with the target/background conditions under which the task was presented. The second experiment was run using a restricted set of the stimuli in the first experiment to compensate for the limitations encountered in the first study.

A full factorial 3 X 4 X 2 X 2 within-subjects design was run to investigated the effects of background wavelength (three levels), foreground wavelength (four levels), background purity (two levels) and foreground purity (two levels) on an observer's accommodation response. A block diagram of the experimental design is contained in Figure 9. Four replications of the experiment were run.

The stimuli were generated on a multicolor CRT and perceptually matched the stimuli used in the first study. The three levels of the background wavelength consisted of stimuli of dominant wavelength 610 nm (red) and 490 nm (cyan) and an achromatic stimulus. Four levels of foreground wavelength consisted of stimuli with dominant wavelengths 460 nm (blue), 552 nm (green), 578 nm (yellow), and - 520 nm (magenta). Appendix A contains the radiometric characterization of all stimuli used in experiment two. As in experiment one, the high purity stimuli lay on a triangle formed by connecting the responses of the individual color guns of the multicolor CRT as plotted on the 1931 CIE chromaticity diagram (Figure A-2). Low purity stimuli lay approximately 1/2 the distance between the high purity stimuli and the center of the triangle, the achromatic point. The two levels of the achromatic background were white and

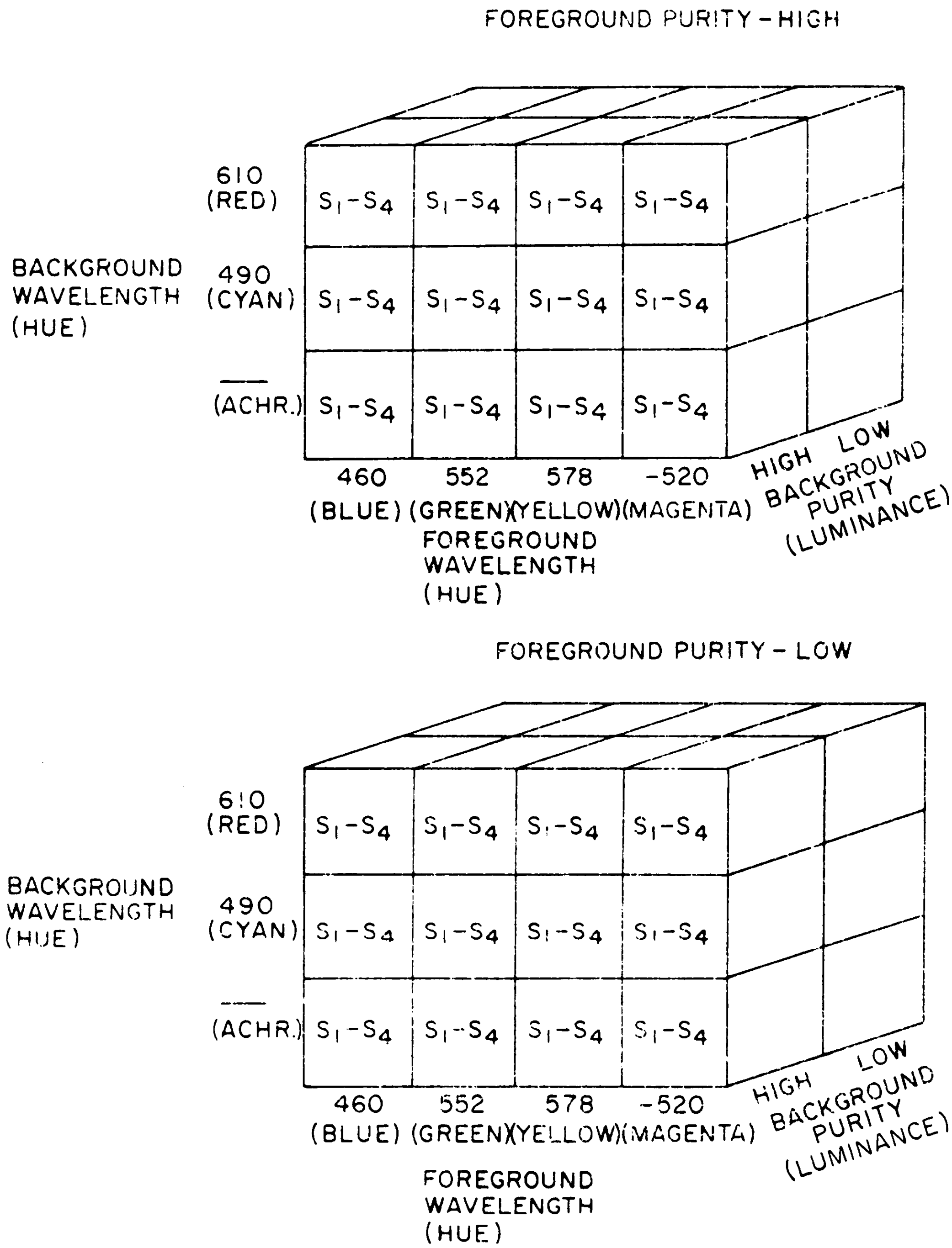

Figure 9. Experiment 2 block diagram.

black. The black background effected a luminance difference between the target and the background.

During the experiment the observers' accommodation responses to the target/background combinations were continuously sampled. Task time to the visual performance task was also calculated and recorded. The four replications of the design constituted one full replicate with respect to the task variable.

Four of the five subjects that participated in experiment one served as subjects for this experiment.

Task

During the course of each trial, the subject was required to perform two tasks. First, the subject was asked to observe a cross hair of one color on a background of another color (Figure 10), bring the target into focus, and maintain focus on the target. When proper focus had been obtained, the subject was required to depress the left most button on a keypad located on the right arm of the chair in which she was sitting. The cross hair was observed for a minimum of five seconds. Depression of this push-button presented a target of six numeral pairs (Figure 11) after a random interval of time (0 to 4 seconds). The subject was required to read the numeral pairs as quickly as possible and count the number of pairs in which the numeral in the first column matched the numeral in the second column. Upon determination of the number of matched pairs, the subject released the push-button ending the task presentation. Release of the push-button also caused the interstimulus display to be presented. The subject

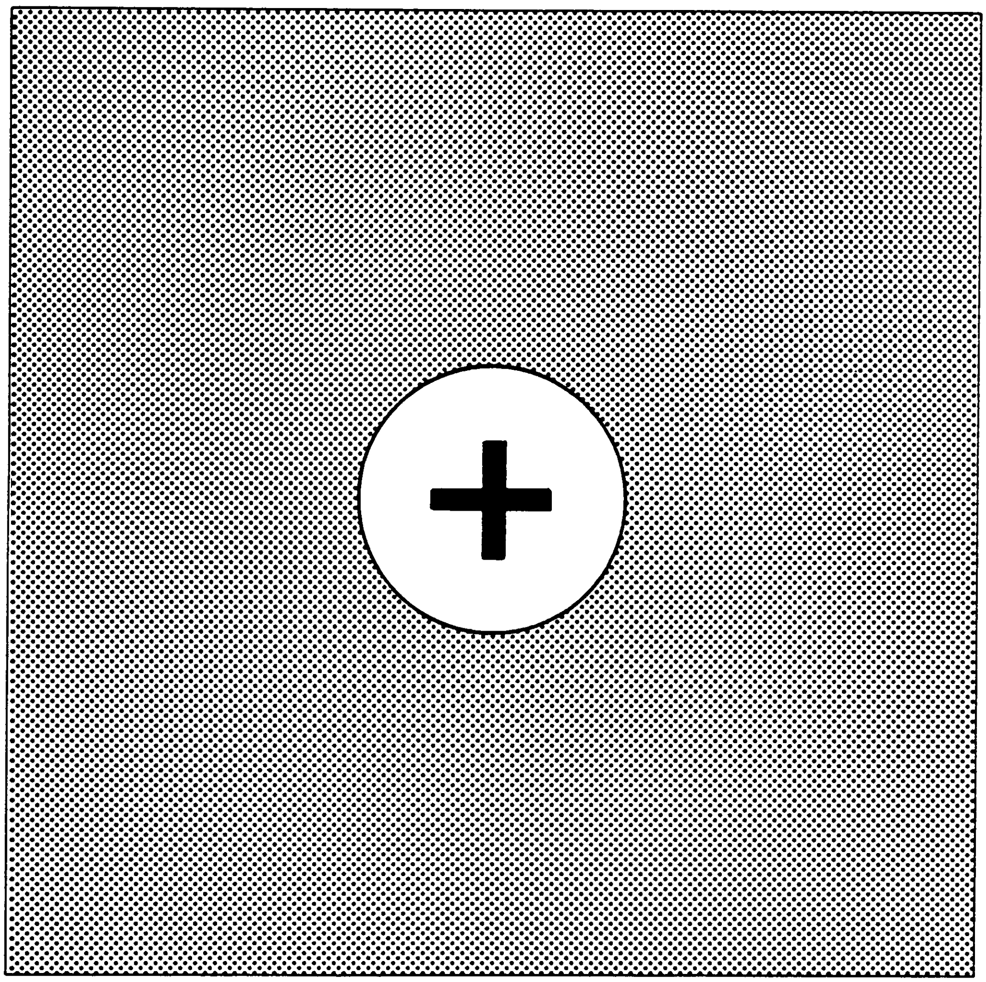

Figure 10. Fixation crosshair.

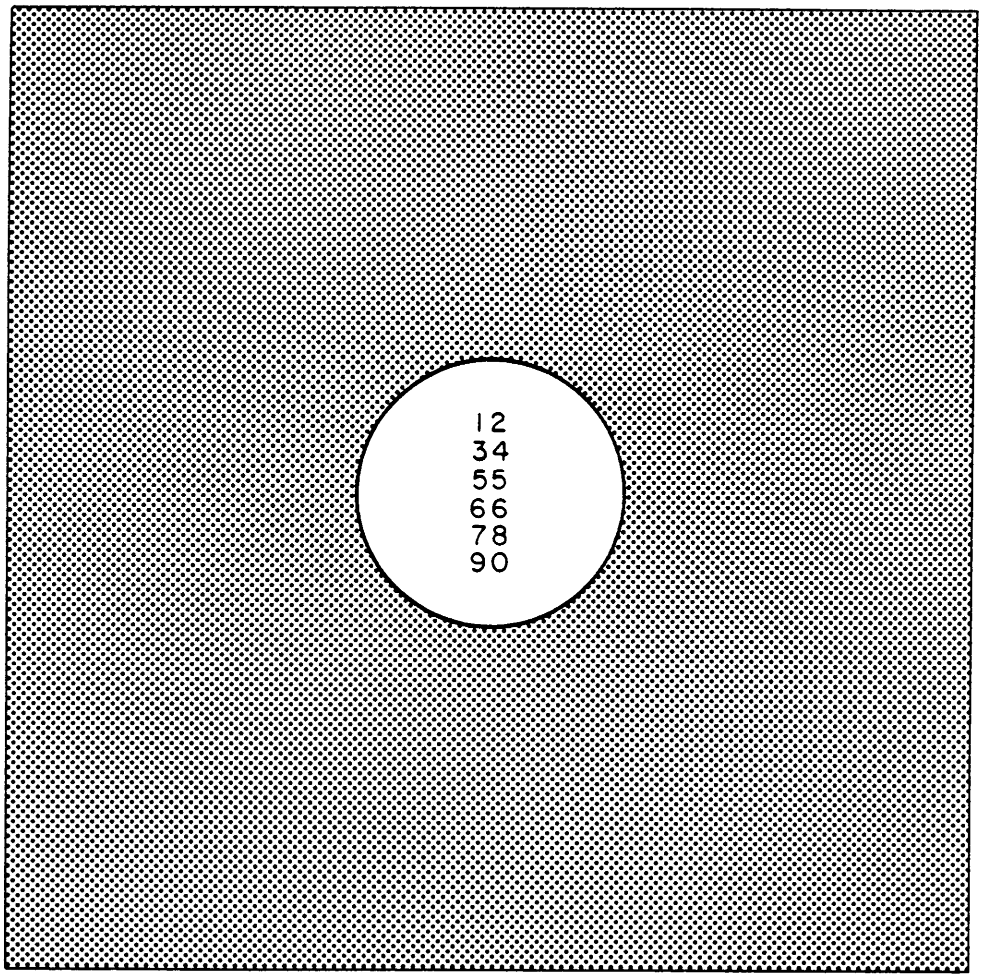

Figure 11. Task presentation.

was then required to indicate the number of matches that were observed by depressing the push-button located on the keypad that corresponded to the correct number of matches. The next trial could begin after the selection indicating the number of matched pairs in the column.

Subjects

Five female volunteers, age 21-29, were paid $30.00 each for participating in the experiments. All subjects were tested for 20/20 uncorrected monocular visual acuity in both eyes using a Bausch and Lomb Orthorater. The subjects were also screened for color normal vision using the Dvorine Psuedo-Isochromatic Color Plates. A rejection criterion of two misses was set for this test, but no misses were recorded for the subjects in the experiment. A subject biographical data sheet is contained in Appendix B.

Apparatus

Display system. The monitor used in the study was an Aydin Model 8025 with a 19-inch diagonal high resolution cathode ray tube (CRT). It employes a three-gun (red, green and blue) Mitsubishi shadow mask CRT incorporating P22 phosphors and a 0.29 mm triad pitch. The raster is positively interlaced and paints a complete image every 1/30 second. The display was masked to limit the active viewing area to a circle of 10 degrees visually subtended in diameter.

The monitor was driven by an International Imaging Systems (IIS) Model 70 digital image processor. Operation of the IIS is under the control of a Digital Equipment Corporation PDP 11/55 minicomputer. The IIS provided a 512 X 512 picture element image at the CRT screen.

At the viewing distance of 58 cm, the limiting resolution of the display was approximately 10.1 cycles/degree. The IIS command voltage for each gun is adjustable through 1024 discrete steps, permitting 1024^3 unique sets of tristimulus values, and is specified separately for each picture element.

The tristimulus values associated with each color selected were determined by first obtaining the spectral radiance distribution and then calculating the tristimulus values. The radiometric measurement system used at the Human Factors Laboratory of Virginia Polytechnic Institute and State University consists of a fiber optics collector, a monochromator, a photomultiplier tube, and a low noise amplifier. To measure the radiant energy from the CRT, light emitted from the color monitor is collected by the fiber optics cable and fed into the monochromator. The monochromator samples the radiance distribution from 380 to 760 nm in 50-nm increments under control of the laboratory computer. These samples are then converted into analog voltages and amplified by the photomultiplier tube. The signal then is directed through a low pass filter and amplified again so that the full range of the analog-to-digital converters can be utilized. The computer records the samples and calculates the tristimulus values.

The radiometric measurement system is calibrated by scanning a light source whose spectral radiance distribution is known and creating a file that can be used to compensate for changes in the system. Additionally, a dark scan is made at 10 nm increments to assess the dark current, electronic noise, in the system. The dark current is then subtracted from the scans of the unknown source, the color monitor, to obtain a purer measure of the color CRT's response.

Data acquisition system. An SRI International Dual Purkinje Image Eyetracker equipped with an infrared optometer was used to track the subject's eye position and accommodation response continuously throughout each trial. The PDP 11/55 computer sampled the X and Y coordinates, the dioptric power of the eye, valid position, and a response channel every 40 ms. The sampled information was continuously written to magnetic disk using a multiple buffered asynchronous data transfer technique during each trial. Data were not collected between the trials.

A response keypad was provided to the subject to initiate the task presentation and to enable the subject to indicate her response to the performance task. The response time and the response selection were written to disk upon completion of the task.

Stimulus Generation

The stimuli for accommodation, a cross hair on a uniform field or numerals presented on a uniform background (Figures 10 and 11), were both generated in a refresh memory plane of the IIS. The cross hair was 28 pixels long and 28 pixels high and subtended approximately 1.3 degrees visual angle at the subject's eye. Because a stable image was desired to obtain steady state accommodation, each member of the cross hair was two pixels wide. This assured that the horizontal member of the cross hair would be written during every refresh cycle. The numerals used as stimuli in the visual performance task were 7 X 9

Huddleston font dot matrix characters substending approximately 0.5 degrees vertically at the observer's eye. The cross hair and the numerals were written to different memory planes in the IIS, thereby permitting the transition from one display to the next in 1/30 second, the refresh period of the display. All manipulations required to prepare the cross hair or task presentation for display were accomplished during the interstimulus period.

The uniform background upon which the targets were presented consisted of all the picture elements not used in generating the stimulus display. Each picture element in the background was assigned the same tristimulus values. All backgrounds used in the study consisted of uniform fields differing only in chromaticity, purity, or chromaticity and purity.

The numeral pairs required for the performance task were generated randomly. The first column of numerals was selected from a computer software routine that produced a random sequence of numbers from 0 to 9 with replacement. The routine used the Digital Equipment Corporation's RT-11 system library routine RANDU to generate the random number sequences. The numeral trials were then divided into four groups, with each group being assigned one match, two matches, three matches, or four matches. Next, a routine generated 170 random number sequences from 1 to 6 without replacement. The numeral pairs were then paired by placing a number equal to the first column at the position where the "1" resided, if one match was needed for the column; at the positions where the "1" and the "2" were located for a column requiring two matches; and so on to a maximum of four matches. The number of matches for a particular stimulus condition was then balanced for target/background combinations across replications. To assure no order effect, the experimental trials were uniquely randomized for each subject and each session.

Interstimulus Display

An interstimulus display was created to maintain the subjects' photopic adaptation and to provide interference with possible after images. Its generation was performed in a third refresh memory plane of the IIS which permitted its presentation within 1/30 second. The interstimulus display consisted of a checkerboard grating created by making two pixels white and then two pixels black both horizontally and vertically. Every four rows were offset by two pixels to create a checkerboard effect. The luminance of the interstimulus display was set to approximately the level of all character/background combinations, or about 1.50 cd/m^2. This strategy was employed to minimize any adverse effects due to changes in the subjects' luminance adaptation throughout the experiment.

Procedure

Pre-experimental session. A pre-experimental session was scheduled for each subject. This session was divided into two parts. In the first portion of the pre-experimental session, the purpose of the experiment was explained to the subject and she was given the opportunity to ask questions concerning the nature of the experiment. The subject was then tested for visual acuity and for normal color vision. If the criteria for vision were met by the subject, she then was asked to read and sign an informed consent form indicating her willingness to participate in the experiment (Appendix C).

The purpose of the second part of the pre-experimental session was to insure that track lock could be obtained for the subject over the 10-degree active area of the display. First, the operation of the SRI Dual Purkinje Image Eyetracker was explained to the subject. Next, the subject was fitted with a bite bar, a wax dental impression on a U-shaped piece of aluminum. After the wax impression had dried, the bite bar was secured to a machinist stage that permitted movement of the bar in three axes. The subject was then seated in a dentist's chair equipped with a hydraulic lift and moved to the position of the bite bar. At this time the subject was instructed to bite down on the bite bar and center it in her mouth. The bar was then tightened so that it would not move during the session. The chair was adjusted to assure the subject's comfort and the subject was asked to fixate on a black cross hair displayed on a white field in the center of the color CRT. Track lock was obtained for the X-Y tracker using the procedure described by Guttman, Snyder, Farley, and Evans (1979). After track lock was obtained, each subject was asked to look at several points in the 10-degree to ensure that X-Y track lock could be maintained over the active area of the display. The infrared optometer was turned on and track lock was obtained using the procedure contained in the SRI International Operating Instructions (SRI, 1982). The optometer's infrared sources were then balanced to minimize any artifacts due to the rotation of the eye. All eyetracker and optometer settings were recorded. The subject was then scheduled for the four experimental sessions to be conducted over the next five days. Care was taken to schedule the subject about the same time each day.

Experiment one sessions. Upon arrival for the first session the subject was given the instructions for experiment one (Appendix D). The subject read the instructions and was permitted to ask questions concerning the experimental procedures. The subject was then taken to the experiment room where she was given ten minutes to adapt to the illuminance in the darkened experiment room. During this period the subject was seated at the eyetracker, her bite bar was centered and secured, initial alignment was achieved, and questions were answered concerning the experimental protocol. After the adaptation period, track lock was obtained utilizing the procedure described in the pre-experimental session and the subject was asked if she was ready to proceed. The experimental trials were presented when the subject indicated she was ready. The first experimental session contained 34 practice trials plus 170 trial presentations. All other sessions contained only the trial presentations. The subject was given a break of at least one minute every 17 trials to reduce the discomfort associated with being required to use a bite bar over a long period of time. Track lock was regained after each break and the experimental session continued. Additionally, all subjects were instructed that they could take a break for any reason throughout the course of the experiment. Each session lasted approximately 1 hour and 15 minutes.

Experiment two sessions. Experiment two was run about one month after experiment one and used four of the five subjects in the first experiment. The protocol for experiment two was identical to that used in experiment one. Upon arriving for the experiment, the subject was orally given a brief refresher concerning the procedures to be used in the experiment, she was given time to adapt to the luminance in the room and track lock was obtained. As in the first experiment, breaks were given every 17 trials after which track lock was regained before proceeding. Four replications of 50 trials were given to the subject during the experimental session. About two minutes were required to set up the software and randomize the trials between the sessions during which the subject was given additional time away from the bite bar. The total time for the four replications was about 1.5 hours for each subject.

Analysis Procedure

Data reduction. The infrared optometer produced an analog voltage corresponding to the refraction required to bring a target into focus. During the trial, this signal was sampled at the rate of 25 times per second, converted into a digital value using the capabilities of the Laboratory Peripheral System's D/A Converter, and then stored on magnetic disk. To transform these data into the dioptric power required to bring the target into focus, software was written that converted the digital value back into an analog voltage value from which the subject's refraction was calculated. This was accomplished for each point during the trial. Certain corrections were necessitated to assure that the accommodation data used in the analysis represented the observer's steady state accommodation to the stimuli presented. First, the samples taken during the first one-half second of the trial representing the refractory period of accommodation were not included in the sample; secondly, points taken during the time the observer was blinking were eliminated from the sample.

The refraction of an observer to a target/background condition was normalized to her average refraction to a white target on a black background such that minus dioptric values denoted that the observer was focusing at an optical distance more removed that the achromatic standard and the positive dioptric values indicated than the observer was accommodating to a point that was closer than the achromatic target. The CRT was placed at a distance of 1.7 diopters (0.58 meter) from the subject's right eye. The average dioptric power was calculated by determining the difference between the observer's accommodation value for the trial and the standard achromatic target for the observer in the current session, summing the differences, and then dividing by the number of data points.

The standard deviation of accommodation was calculated as follows:

$$SD = \sum_{i=1}^{n} (Y_i - Y)^2/(n - 1)^{0.5} \qquad (1)$$

Task time was also collected during each trial. This measure was defined as the period beginning with the presentation of the visual task and ending when the subject released the push-button indicating that she had determined the number of matches. The resolution of this measure was to 0.04 second. Prior research at the Human Factors Laboratory had indicated a positive skewness to task time data collected in tasks similar to the one required in the experiments. As a consequence, the task time data were reciprocally transformed into task speed data prior to being placed into the analysis routines.

After the data were reduced using the laboratory computing facilities, the data were copied to tape in a format that was compatible with the University's IBM computer system. SAS (Statistical Analysis System, SAS Institute, 1982) was then used to perform the necessary statistical analyses.

Analyses. Univariate statistical analyses were conducted on the mean accommodation response (AD), the standard deviation of accommodation response (SD), and task speed (TS) for all target/background combinations across all subjects. Analyses of variance were performed to determine the effects on accommodation response and task speed due to the independent variables and their interactions. Simple-effects F-tests were performed to further explain the significant interactions among the independent variables. The purpose of the analyses of variance was to isolate those factors which significantly contribute to the variance in the accommodation or task speed measures as a function of the color contrast between the foreground (the target) and the background.

Regression analyses were also performed to determine if relationships existed among an observer's accommodation response, task speed, and the color difference between target and background under conditions of color contrast. Additionally, the relationship between the chromatic content of the target or background and an observer's accommodation response was explored. All data used in the regression analyses were averaged across subjects.

RESULTS

The data collected in the experiments were analyzed in two stages. In the first stage, analyses of variance were performed to determine which among the independent measures combined to affect the observers' accommodation response or performance. Secondly, regression analyses were performed to determine the strength of the relationships among accommodation, color contrast and performance. The results are organized by type of analysis.

Analyses of Variance

Univariate analyses of variance were performed on the three dependent measures. These analyses were performed to determine the effects of background wavelength (BW), foreground wavelength (FW), background purity (BP), and foreground purity (FP) on an observer's accommodation response to characters presented on a multicolor CRT or her performance in a visual task as a result of the color contrast resulting from the stimulus conditions. Simple-effects F-tests were performed to isolate further any significant interaction effects. Newman-Keuls post hoc analyses were then performed at each level of the relevant independent variables to determine the locus of the interaction effect. A criterion level of $p \leq 0.05$ was set for all analyses of variance.

Summary analyses of variance tables are contained in Appendix E.

Experiment One-Average Dioptric Power. Results of the mean dioptric change to bring the character into focus will be discussed in terms of the observers' depth of focus. The depth of focus is not an absolute measure and varies as a function of the pupil size. A nominal value for depth of focus associated with a minimum pupil size of 5 mm will be used throughout the discussion of the results. This is consistent with the minimum pupil size necessary for the proper function of the SRI infrared optometer. Campbell (1957) investigated the relationship between pupil size and an observer's depth of focus. He found a depth of focus of approximately +/- 0.18 diopter for a 5 mm pupil. This corresponds to maintaining focus over the range of 53 cm to 65 cm at the display distance of 58 cm. The value of +/- 0.18 diopter will be used as the referent for discussion when considering the effects of varying the chromaticity and purity of the foreground relative to background on the observers' mean accommodation response.

In the discussion that follows the results are summarized by wavelength, as designated by the commonly associated hue, first by holding the background wavelength constant and investigating the effects of foreground wavelength, background purity, and foreground purity. Next, the foreground wavelength is held constant and the effects of background wavelength, background purity, and foreground purity are summarized.

All data collected in experiment one were collapsed over sessions since no significant differences due to sessions ($p = 0.3812$) were found across all analyses.

Blue. The observers' mean accommodation response was not significantly affected by changes in the chromaticity or purity of targets when they were displayed on blue backgrounds or when blue targets of either purity were displayed on backgrounds that varied in wavelength and purity.

Cyan. Foreground purity affects the observers' average accommodation value (p = 0.0232) when viewing characters on a cyan background. High purity targets required an average accommodation response of 0.07 D where as low purity targets required an average accommodation response of 0.05 D. The data are plotted in Figure 12 and show the difference in the mean response at the two levels of purity. While greater accommodative effort is required to bring the higher purity targets into focus, it is unlikely that refocusing would be necessary to keep all targets on cyan backgrounds in proper focus.

No significant differences were found in the observers' mean accommodation level when cyan targets were viewed on chromatic backgrounds.

Green. No significant differences in average dioptric power were found with green background or foreground.

Yellow. An observer's average accommodation response to targets on a yellow background is affected by an interaction among the background purity, foreground wavelength, and foreground purity (p = 0.0182). The effect of background purity and foreground purity across all foreground wavelengths was investigated to determine

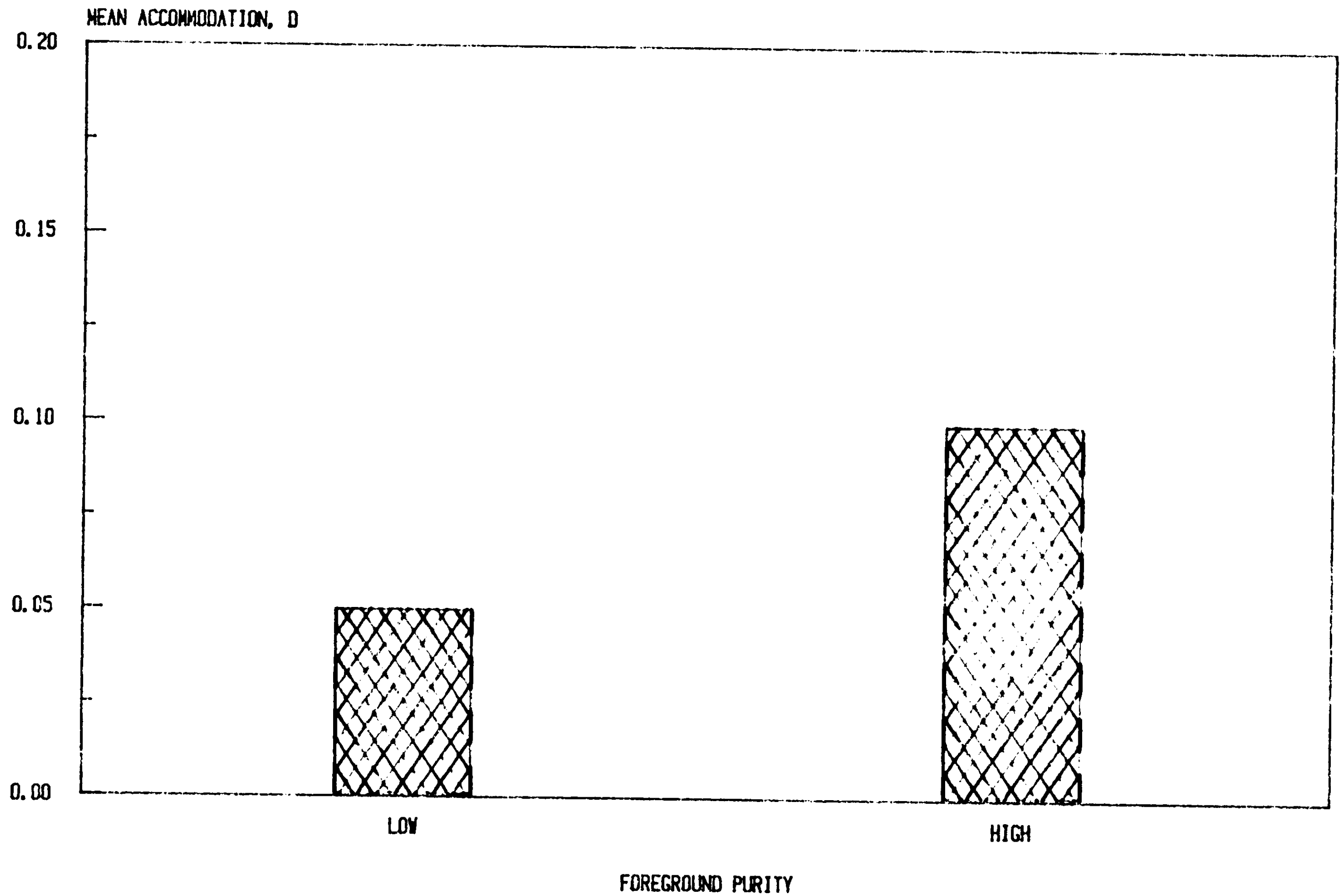

Figure 12. Cyan background-foreground purity effect on average accommodation.

how foreground purity and background purity combine to produce the effect. The results of these analyses show that when the targets are displayed on high purity yellow backgrounds, accommodation is differentially affected when targets of low purity are observed on those backgrounds. Cyan targets viewed on high purity yellow backgrounds produce an average accommodation response of 0.14 D (Figure 13), which is significantly larger than that obtained for any other foreground displayed on the high purity background. The mean accommodation responses for all other foreground wavelengths range from 0.00 D to 0.07 D, but they do not significantly differ. The change in the dioptric power required to bring the low purity cyan target into focus on a high purity yellow background is again within the observers' depth of field. No other combination of these variables significantly affects the observers' mean accommodation response.

When the foreground is yellow and the background wavelength is varied, a similar three-way interaction obtains. The BW X BP X FP interaction is significant ($p = 0.0308$). While there are no significant effects when the background purity is low, the mean accommodation response across background wavelength is affected at both levels of foreground purity when characters are viewed on a high purity background. The BW X BP X FP interaction is illustrated in Figure 14 and shows the very different accommodation response obtained when viewing high and low purity yellow targets on high purity backgrounds. The average

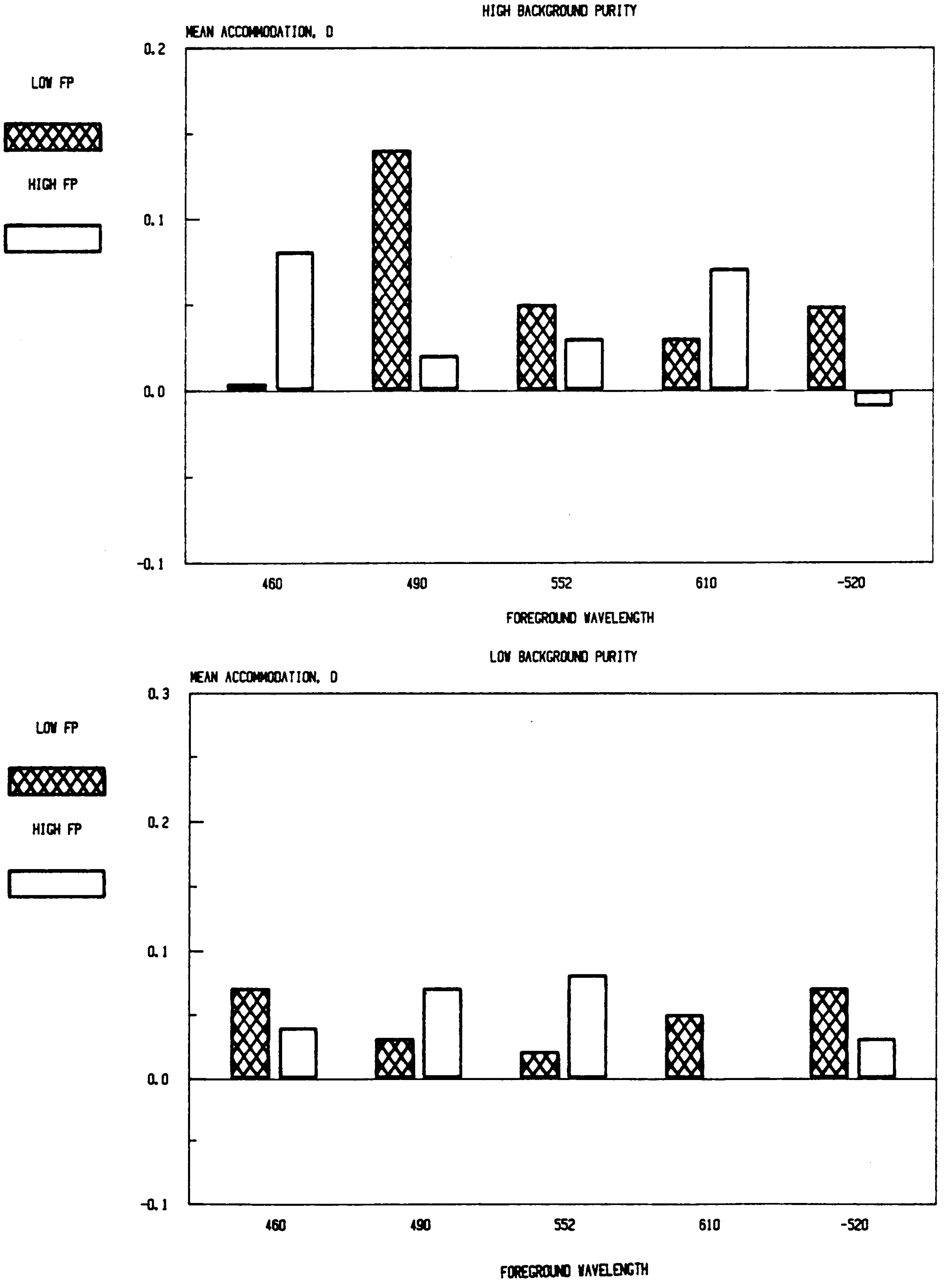

Figure 13. Yellow background-BP X FW X FP effect on average accommodation.

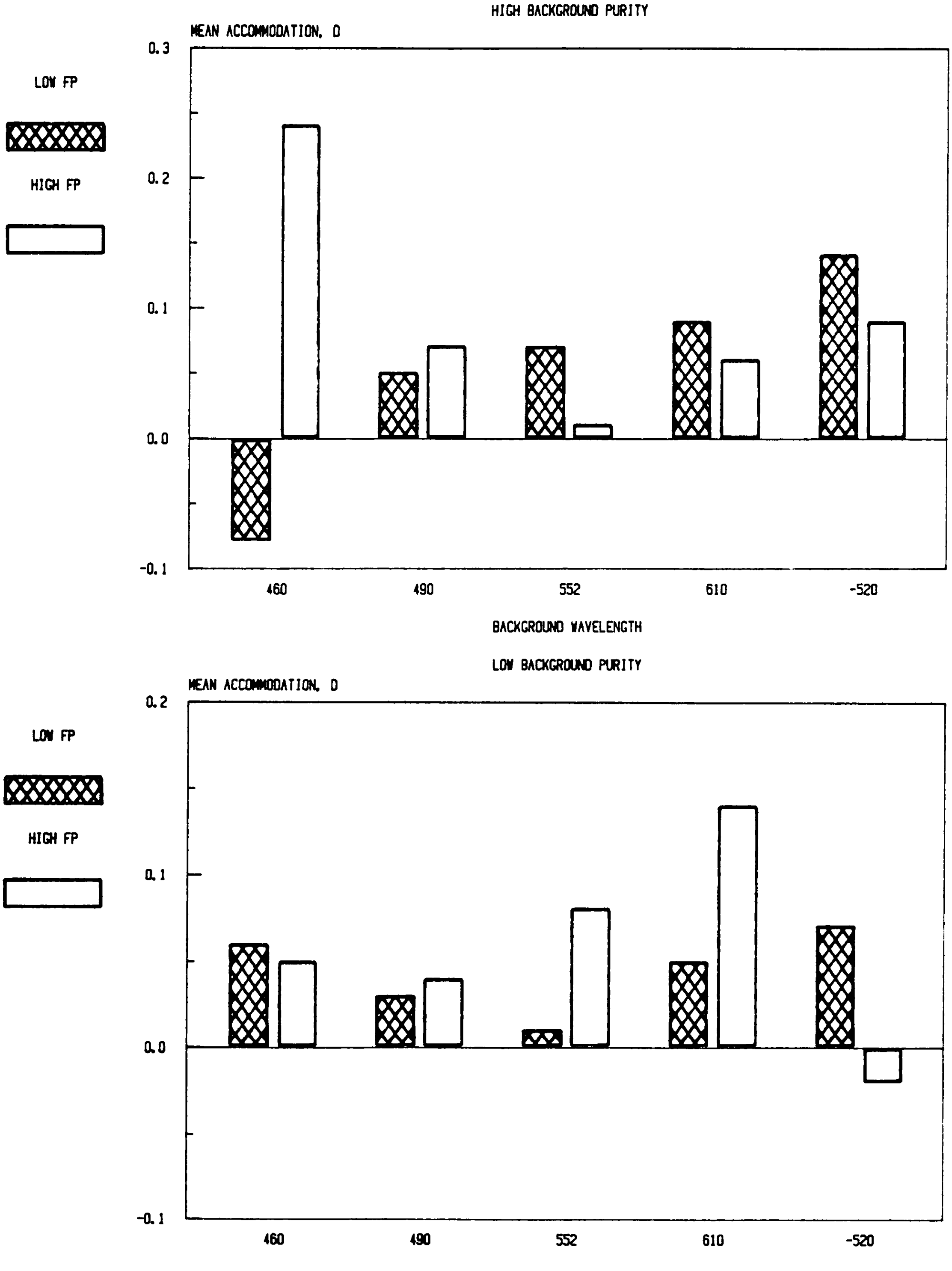

Figure 14. Yellow foreground-BW X BP X FP effect on average accommodation.

accommodation response to a high purity yellow target displayed on a high purity blue background is 0.24 D, which is significantly larger than the accommodation response obtained with backgrounds of any other wavelengths, for which there are no significant differences. When the foreground purity is low the average accommodation response of -0.08 D for the high purity blue background is significantly less than the accommodation response to the high purity magenta background for which a mean accommodation level of 0.14 D was obtained. There are no other significant differences with respect to the low purity yellow foreground.

The magnitude of the change in the refraction of the eye necessary to obtain proper focus on yellow targets is large enough to suggest that refocusing may be required if all target/background combinations are to be used. The range of accommodation response for the high purity yellow target is about 0.23 D, which is outside the observers' depth of focus, and refocusing may be required to maintain sharp focus. The data indicate that a change in refraction of about 0.22 D is required to maintain focus on the low purity yellow targets; however, the amplitude of the change about the optimal value for the display distance is within the nominal depth of focus used in this study. No refocusing is suggested for the low purity yellow targets. Also of interest is the very large difference (0.32 D) in mean accommodation response to the low purity target when compared to the response to the high purity target when observed on the high purity blue background. While both target/background combinations may provide high contrast between the target and background, the data indicate refocusing would be required to obtain sharp focus when sequentially viewing low purity and high purity yellow characters on a high purity blue background.

Red. There were no significant changes in the mean accommodation response across all conditions when the background is red. However, average accommodation to red characters is affected by background wavelength ($p = 0.0023$), background purity ($p = 0.0364$), the interaction between background wavelength and background purity ($p = 0.0364$), and the interaction between background purity and foreground purity. The mean accommodation response to red targets on blue backgrounds was 0.18 D which was significantly different from the accommodation response to backgrounds of all other wavelengths. There were no significant differences among the mean accommodation responses to backgrounds of other wavelengths, whose average values range from 0.04 D to 0.12 D. The BW main effect is illustrated in Figure 15. The observers' accommodation response to red characters on high purity backgrounds is significantly higher (0.12 D) than their response to red targets on low purity backgrounds (0.10 D). The effect of BP on their average accommodation response to red targets is shown in Figure 16.

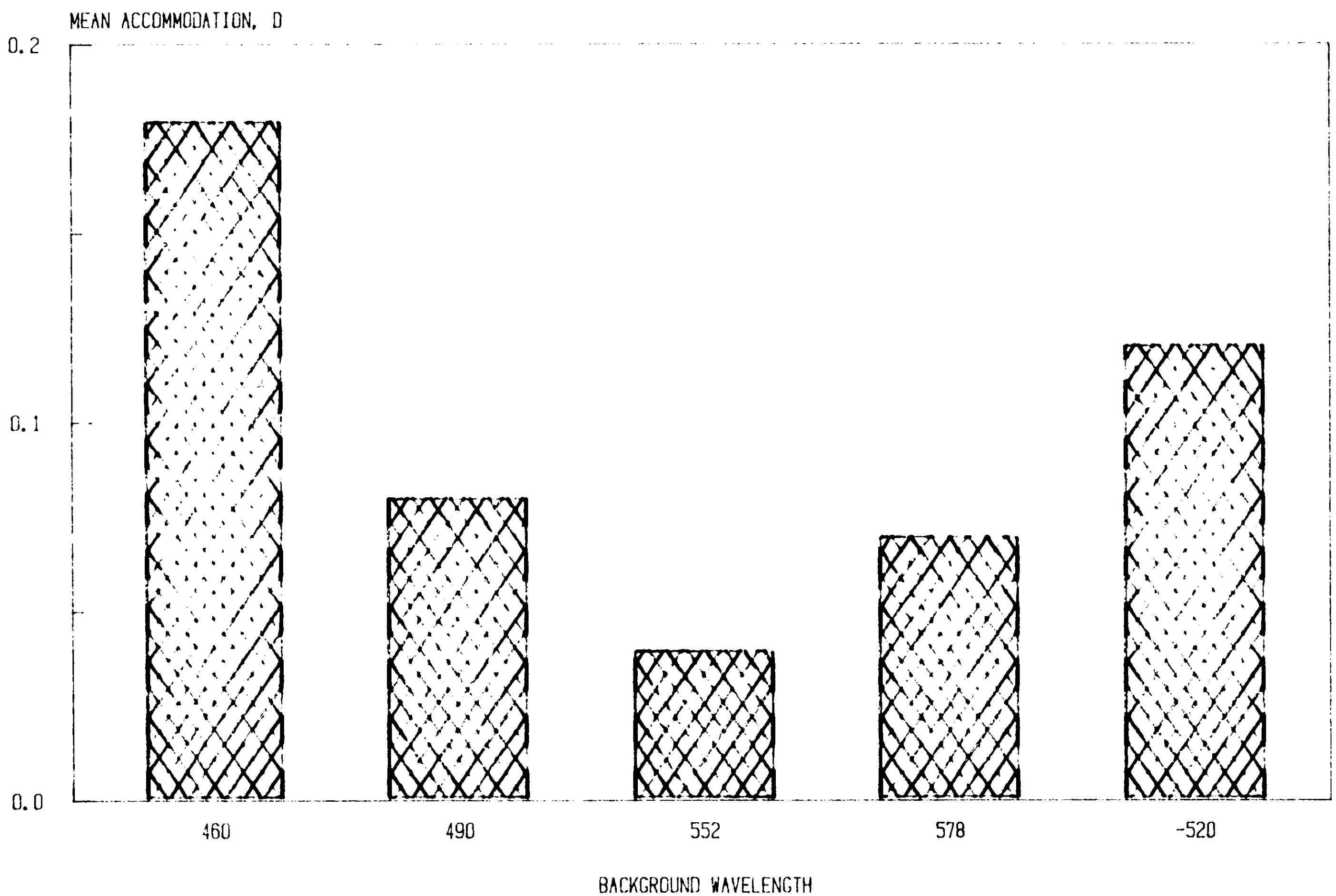

Figure 15. Red foreground-background wavelength effect on average accommodation.

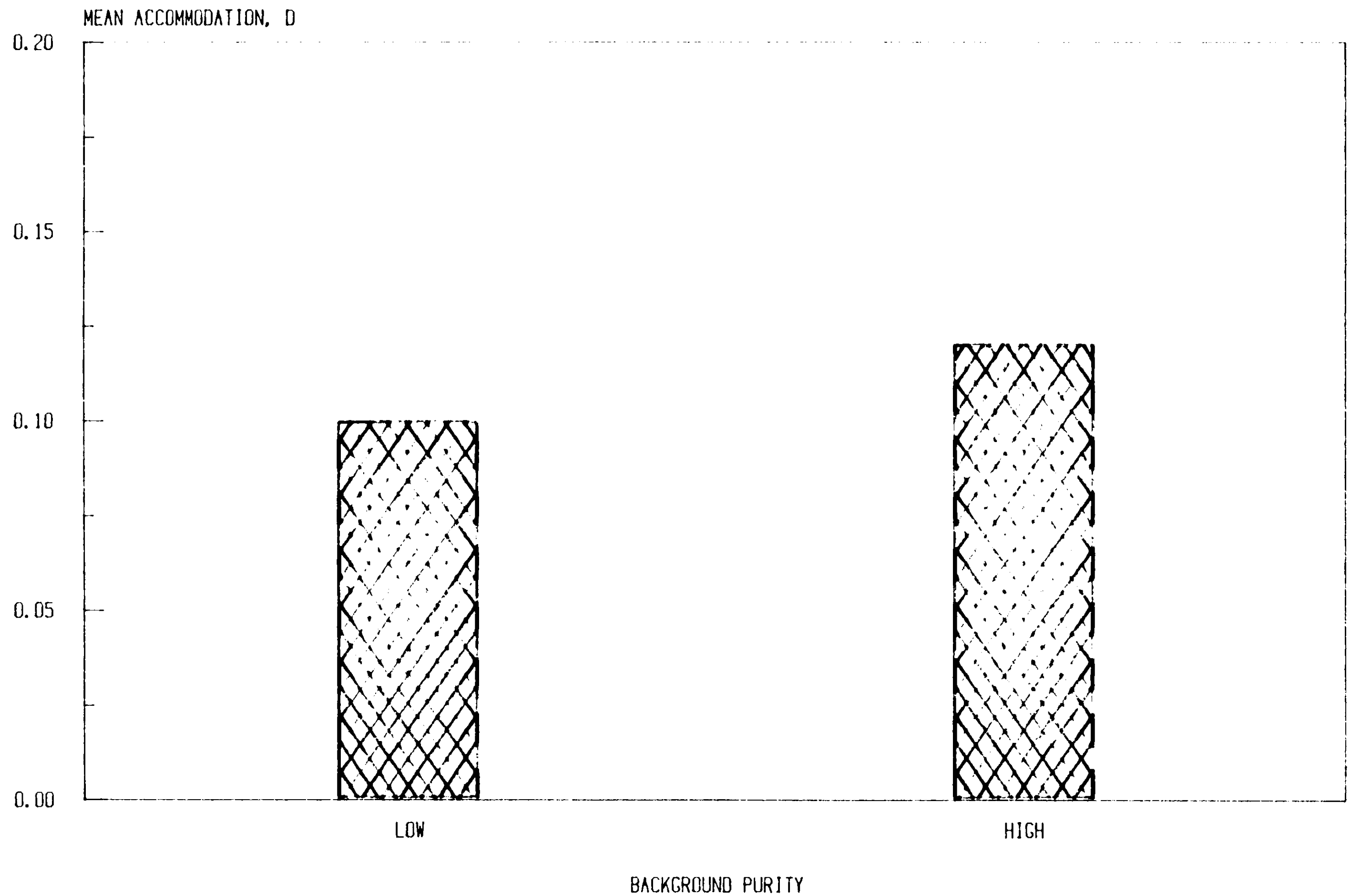

Figure 16. Red foreground-background purity effect on average accommodation.

BW and BP combine ($p = 0.0364$) to affect the mean accommodation response to red targets. At low background purities, there are no significant changes indicated in the observers' mean accommodation response; however, at high background purities the mean accommodation response is differentially affected. The average accommodation response to red characters on blue backgrounds is 0.26 D which is significantly higher than the mean response of 0.17 D to red targets on high purity magenta backgrounds. The mean accommodation response to red targets on high purity magenta backgrounds is significantly higher than the response obtained to backgrounds of all other wavelengths. Figure 17 depicts the BW X BP interaction.

Background purity and foreground purity combine to affect the accommodation response to red targets. As illustrated in Figure 18, the mean accommodation to red targets of high purity is differentially affected across the two levels of background purity. The average accommodation response to the high purity red target on a high purity background is 0.14 D which is significantly higher than the response of 0.06 D to low purity backgrounds. There is no significant difference at low background purities.

The results of the analysis of the effect of viewing red characters on backgrounds are important because they describe the most disparate range of wavelengths with which the observer must contend. The main effects analysis show that to obtain proper focus on the blue background the refraction required is at the edge of the

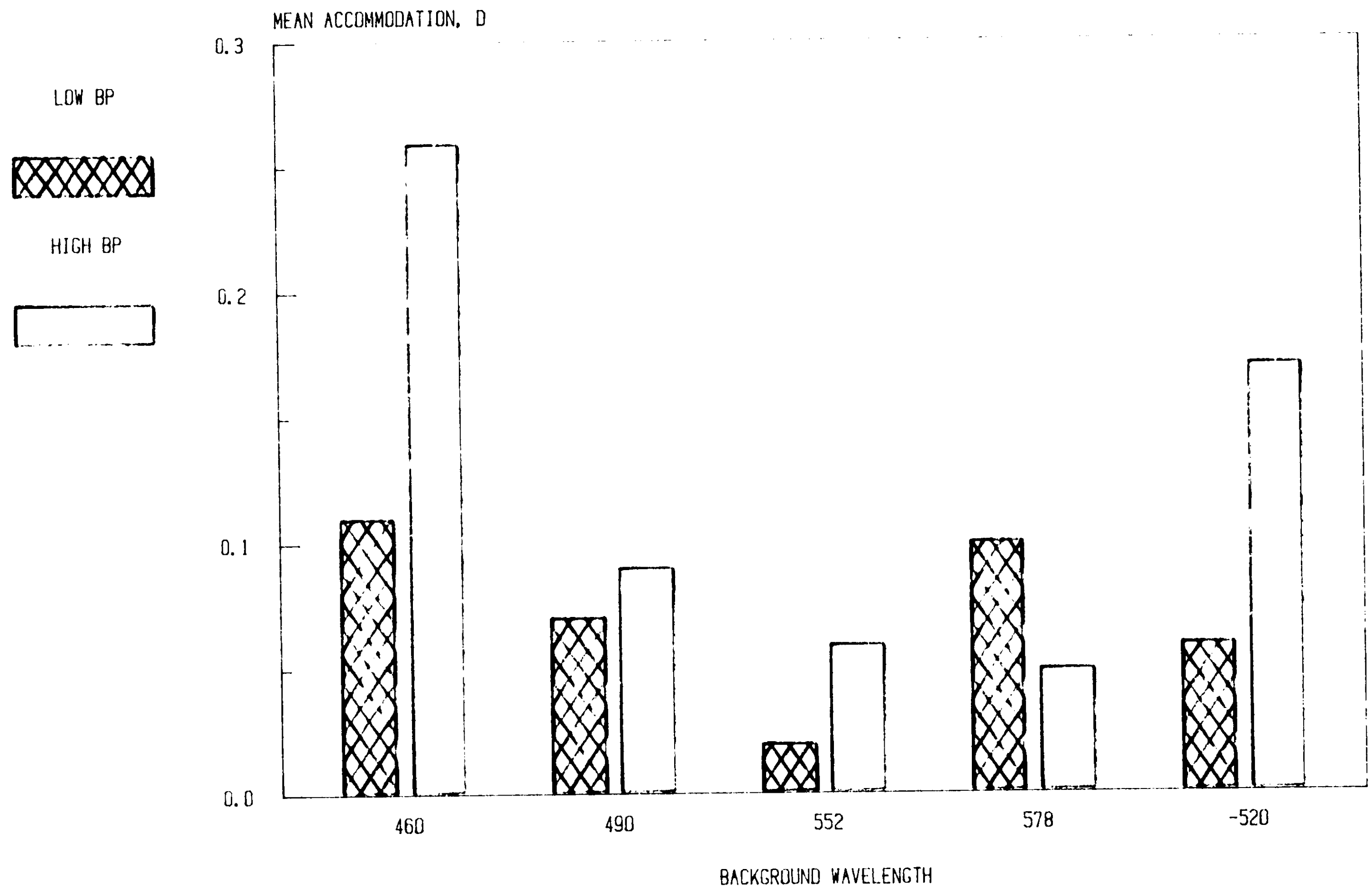

Figure 17. Red foreground-BW X BP effect on average accommodation.

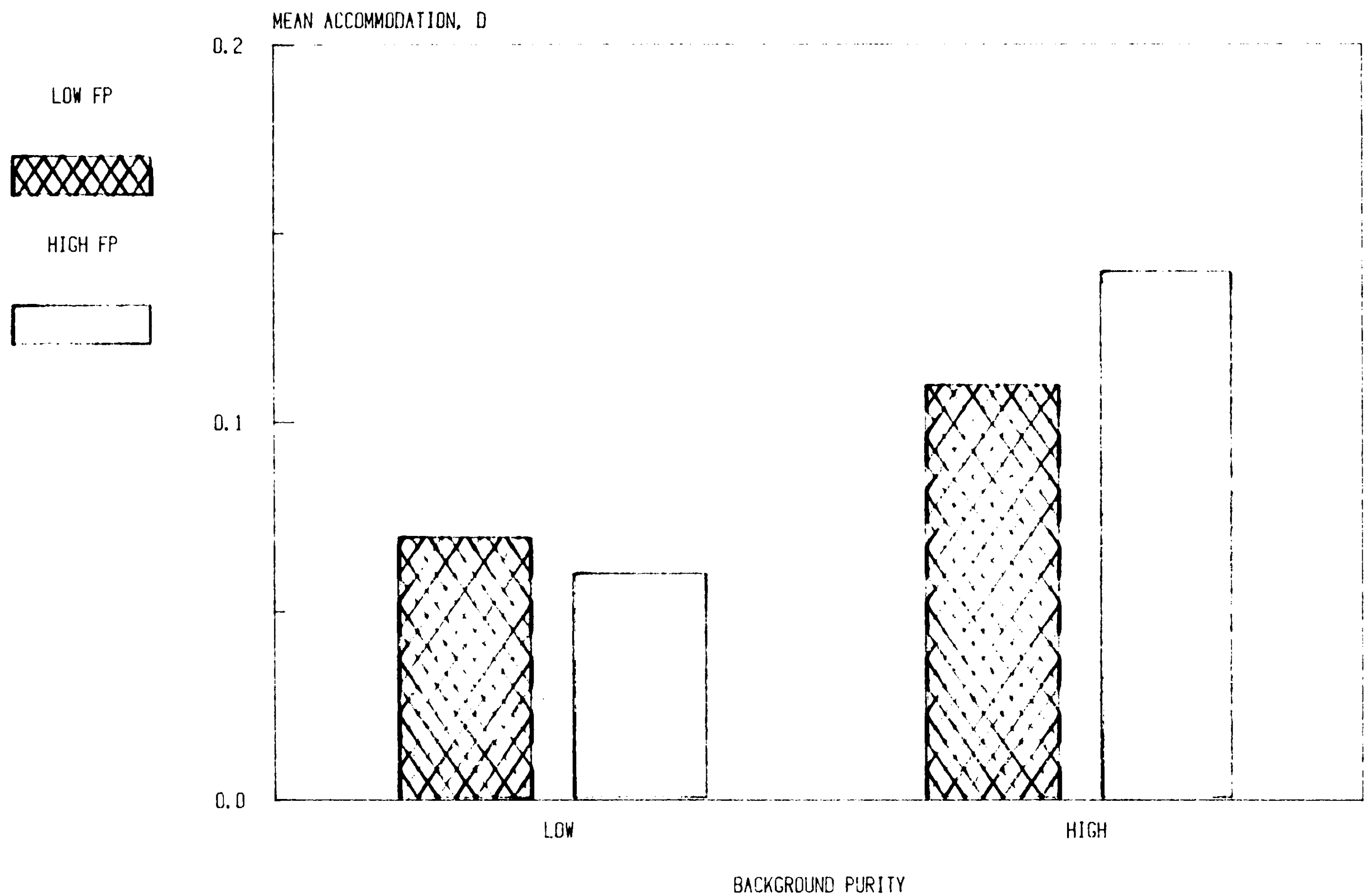

Figure 18. Red foreground-BP X FP effect on average accommodation.

observers' depth of focus. A further look at the response is obtained in the analysis of the BW X BP interaction. These results indicate that refocusing would be required to bring the red character into focus on the high purity blue background when compared to the optimal refraction for the display distance. However, refocusing is not suggested for any other combination of background and foreground when viewing red targets. If the observer assumes some intermediate position between the greatest and least refraction required, then no refocusing is indicated to obtain sharp focus across the background wavelengths. More importantly, the small magnitude of change in the necessary refraction of the eye to focus red targets on chromatic backgrounds is that of the most disparate foreground/background combinations in terms of color difference, the high purity red target on the high purity blue background.

Magenta. The purity of the magenta background significantly affects an observer's average accommodation response ($p = 0.0001$). As indicated in Figure 19, the mean accommodation response of 0.11 D to targets observed on high purity backgrounds is significantly higher than the 0.06 D obtained with low purity magenta backgrounds.

When the target is magenta, background wavelength ($p = 0.0001$), foreground purity ($p = 0.0294$), and the interaction among background wavelength, background purity, and foreground purity ($p = 0.0464$) affect the observers' average accommodation response. Figure 20 illustrates the effect of background wavelength on mean accommodation

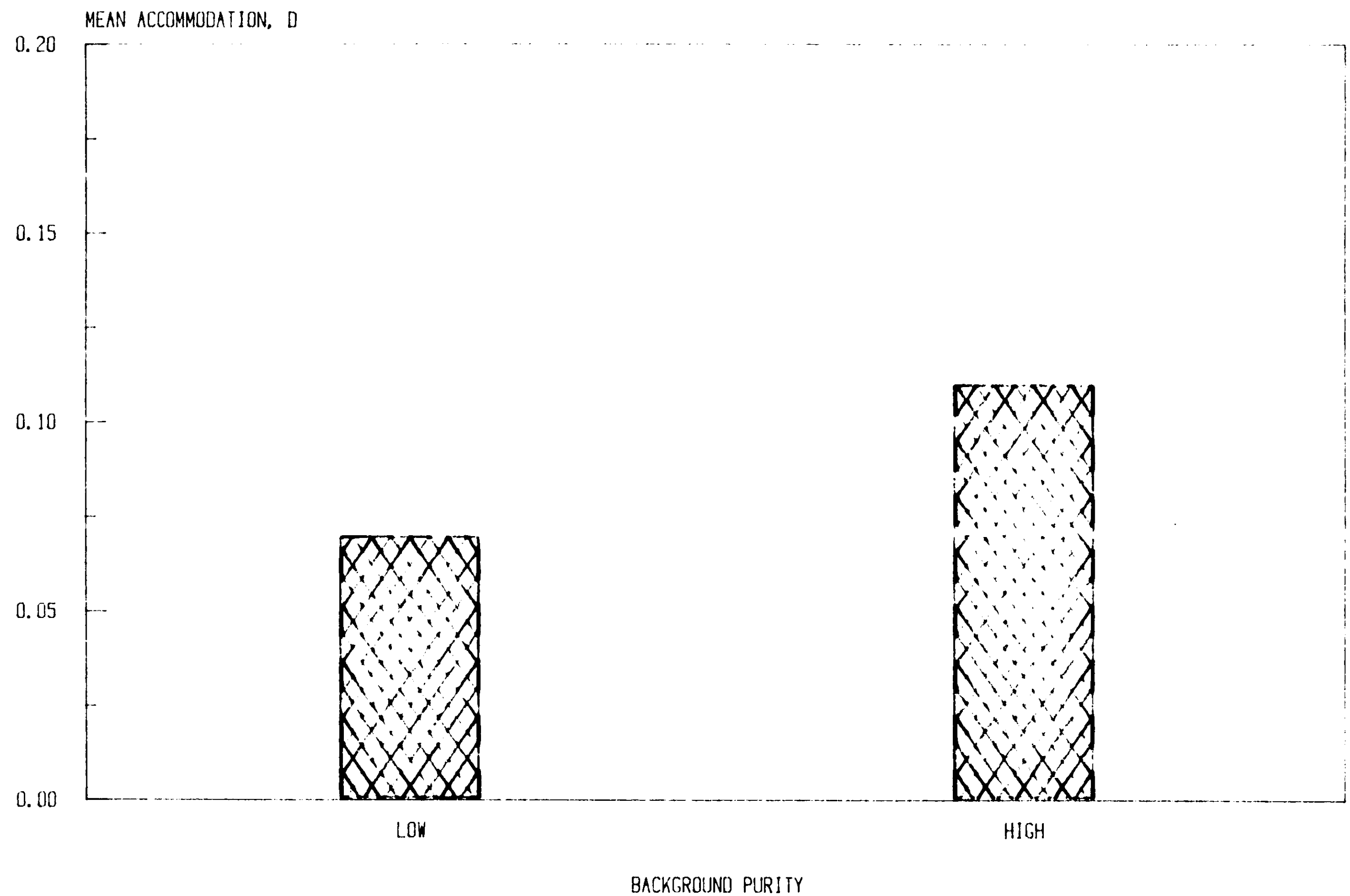

Figure 19. Magenta background-background purity effect on average accommodation.

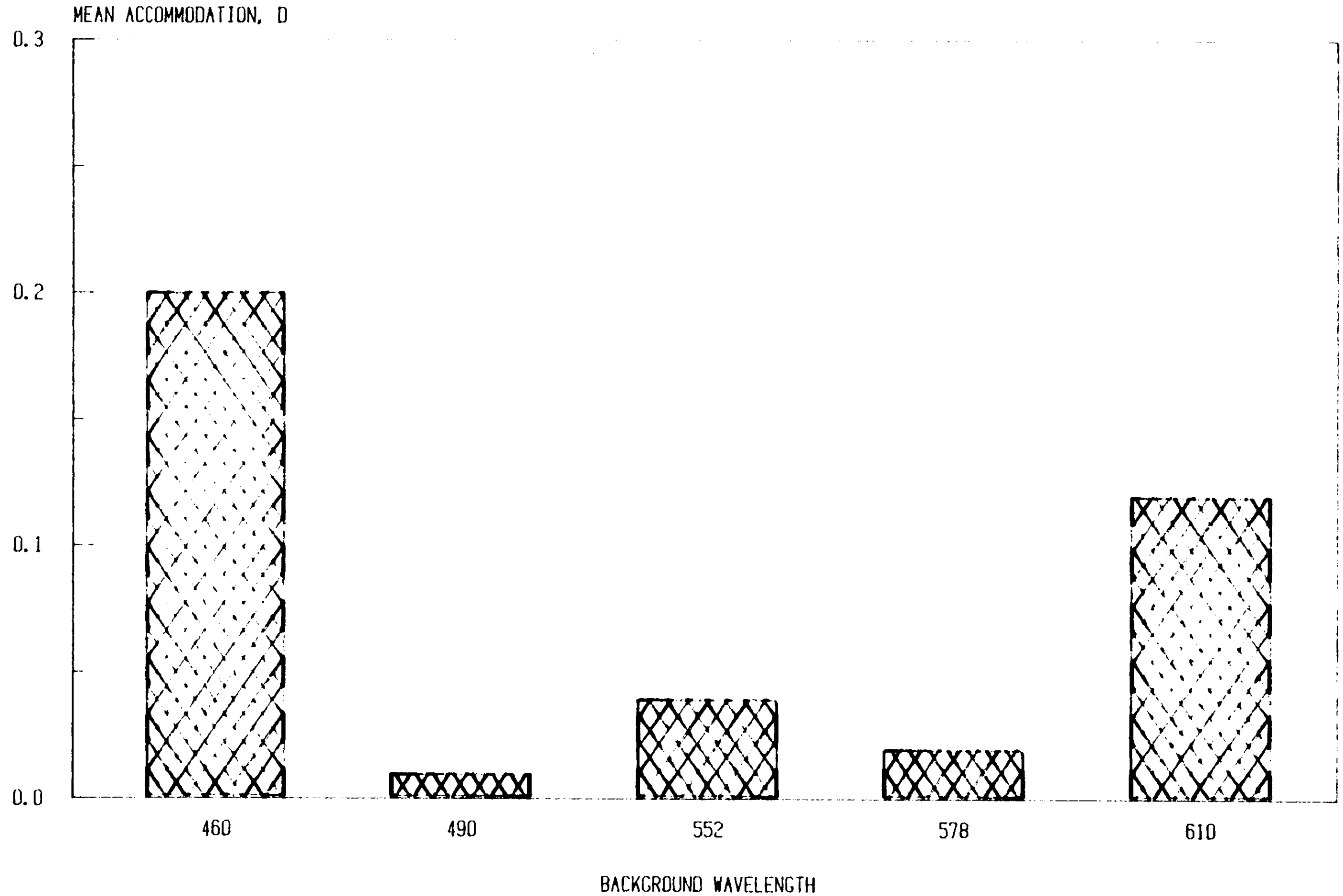

Figure 20. Magenta foreground-background wavelength effect on average accommodation.

response. An average accommodation to magenta targets on blue backgrounds of 0.20 D is significantly greater than the 0.12 D response obtained with red backgrounds, which is significantly greater than the mean response obtained with green, yellow or cyan backgrounds, all of which are not significantly different from one another.

Low purity magenta targets result in a mean accommodation response of 0.10 D which is significantly greater than the 0.05 D response obtained with high purity targets. Figure 21 depicts the effect of FP on the mean accommodation response.

The BW X BP X FP interaction suggests that the manner in which the observers' mean accommodation response is affected across background wavelength is dependent on the purity of the target relative to the purity of the background. Mean accommodation response is differentially affected across background wavelength for all combinations of background and foreground purity. Figure 22 shows the effect across background wavelength for the BW X BP X FP interaction. When both BP and FP are high, a mean accommodation response of 0.15 D is obtained for magenta targets on blue backgrounds, which is significantly greater than the response to backgrounds of all other wavelengths and which in turn do not significantly differ. The average accommodation response to high purity magenta targets on low purity blue backgrounds does not significantly differ from the 0.10 D obtained on low purity red

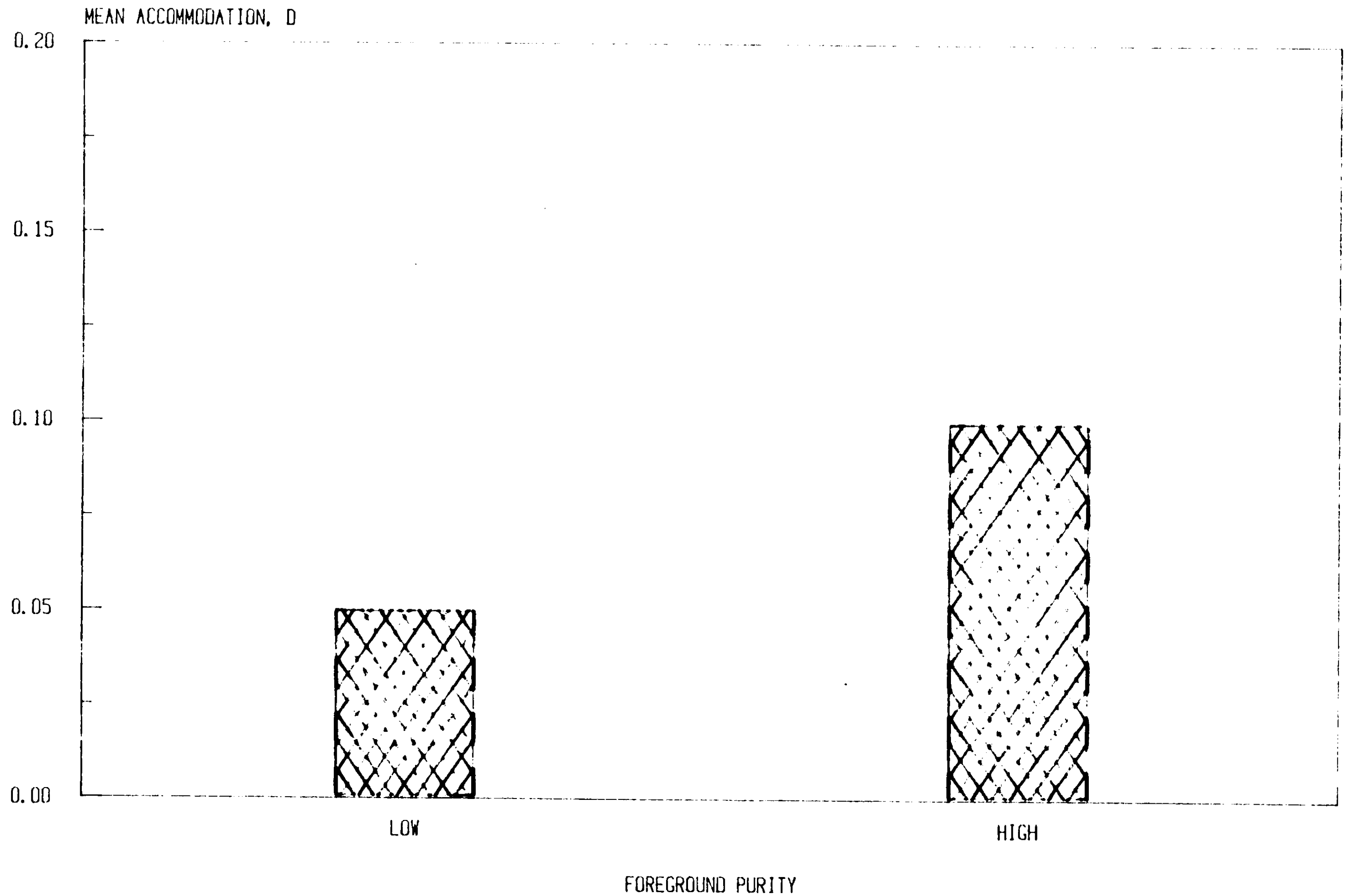

Figure 21. Magenta foreground-foreground purity effect on average accommodation.

backgrounds. The response to high purity magenta targets on low purity cyan, yellow, and green is significantly different from that obtained to red and blue backgrounds, as illustrated in Figure 22.

When the magenta target is of low purity, the mean accommodation to the target on a high purity blue background of 0.37 D is significantly different from all other responses, which do not significantly differ. A similar but not so pronounced effect occurs with backgrounds of low purity. Average accommodations to low purity magenta targets on blue (0.15 D) and red (0.17 D) backgrounds do not significantly differ, but they are significantly higher than the response obtained with background of all other wavelengths.

The results of the analysis of magenta foregrounds indicate that the display of magenta targets on blue or red backgrounds requires more accommodative effort than the other target/background combinations formed with the magenta target. Using +/- 0.18 D as the depth of field, the 0.37 D refraction required to bring the low purity magenta target will require refocusing when compared to the refraction required for other targets displayed on the high purity blue background. Also, the high mean accommodation levels across the three-way interaction were a result of combinations involving the magenta targets and the red and blue background, whose chromaticities combine to create the magenta target.

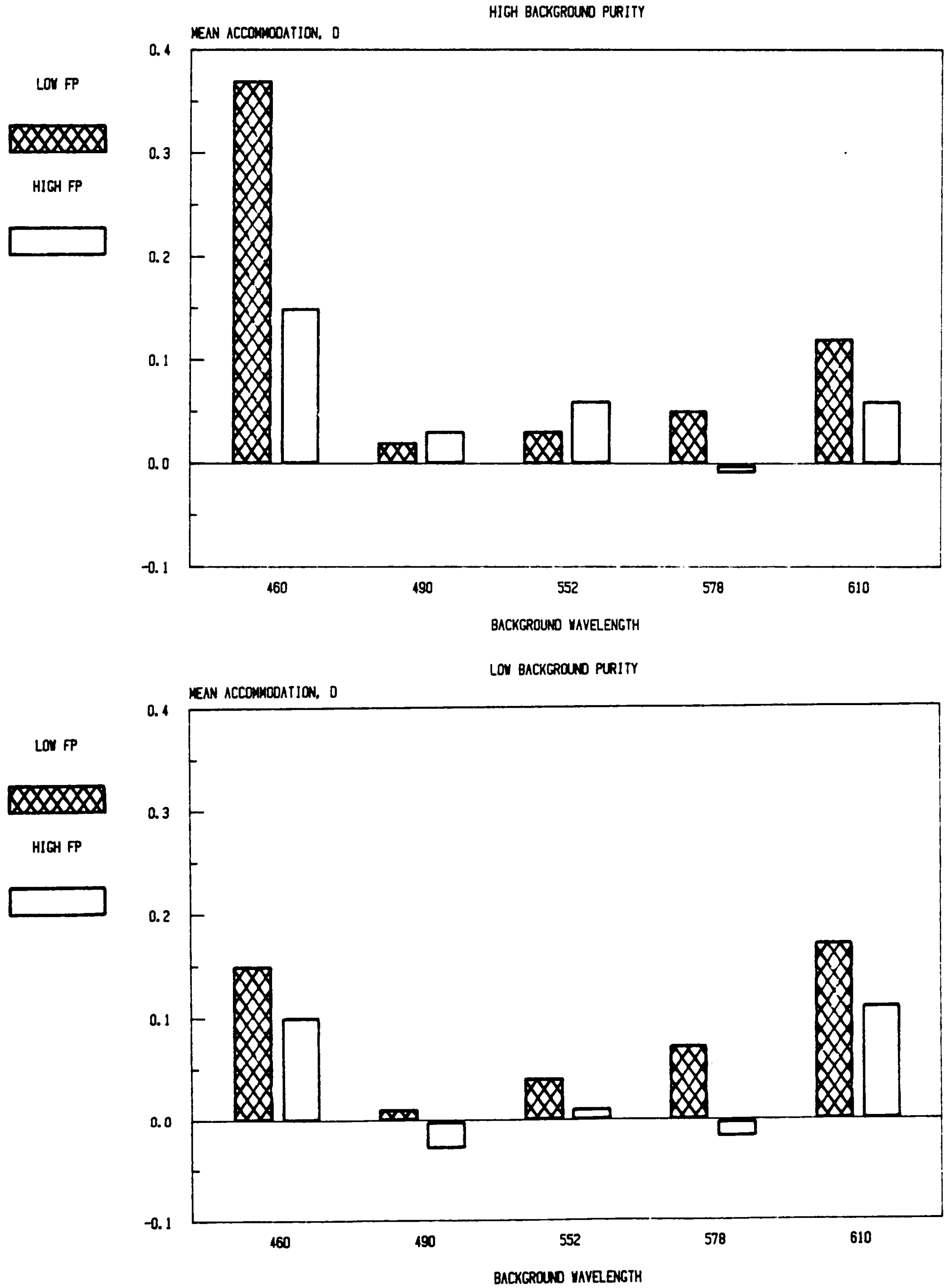

Figure 22. Magenta foreground-BW X BP X FP effect on average accommodation.

Achromatic. When the chromatic targets are observed on achromatic backgrounds, foreground wavelength (p = 0.0016) and the interaction between background purity and foreground wavelength (p = 0.0327) significantly affect an observer's average accommodation response. The average accommodation response to magenta (0.03 D), red (0.03 D) and yellow (0.02 D) targets is significantly higher than green (-0.02 D), cyan (-0.03 D) and blue (-0.05 D) targets. The effect of foreground wavelength on the mean accommodation response is shown in Figure 23.

The BP X FW interaction, as displayed in Figure 24, primarily demonstrates the effect of luminance differences between the target and achromatic background. At high target luminances, no significant differences result across foreground wavelength, but at low luminance, a result similar to the main effect of foreground wavelength is obtained. The refraction to blue (-0.15 D), cyan (-0.07 D) and yellow (-0.1 D) targets on a black background are not significantly different from each other, but are different from yellow (-0.01 D), red (0.0 D) and magenta (-0.01 D) which in turn, are not significantly different. It should also be noted that the observers' positively accommodated to chromatic targets on the high luminance achromatic background, but negatively accommodated to chromatic targets on the zero luminance achromatic background.

The mean accommodation response to achromatic targets on chromatic backgrounds is affected by the wavelength of the

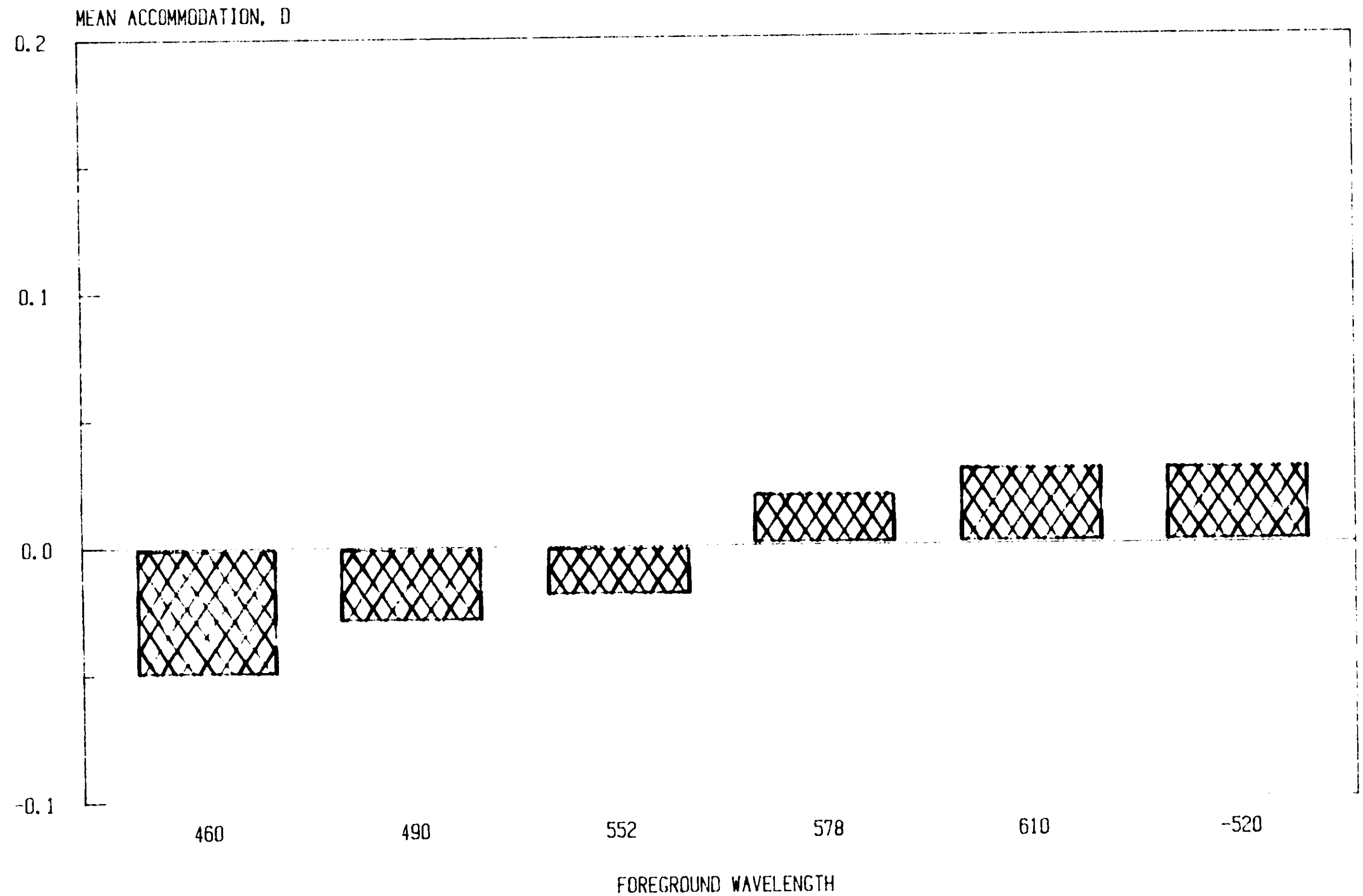

Figure 23. Achromatic background-foreground wavelength effect on average accommodation.

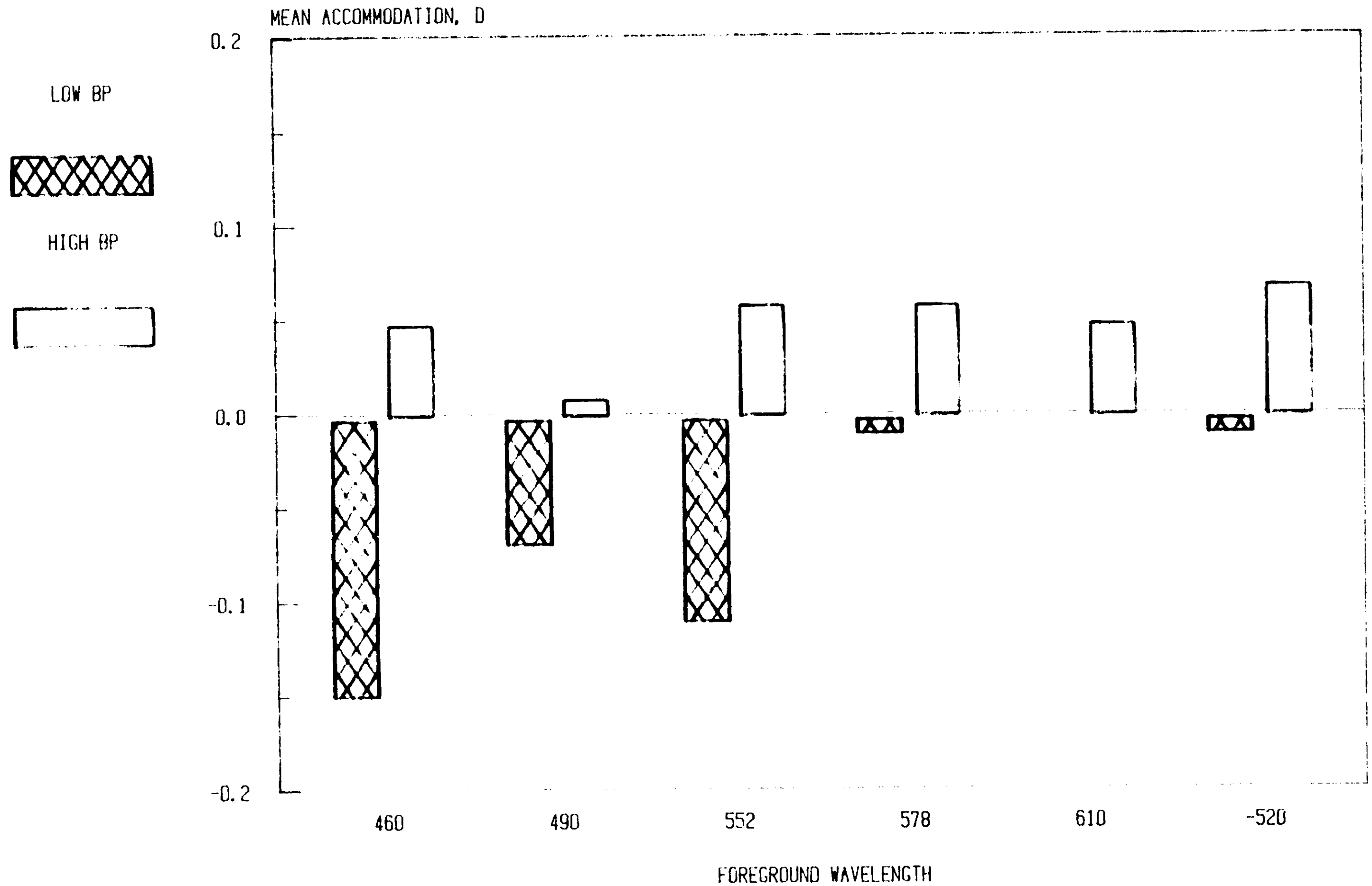

Figure 24. Achromatic background-BP X FW effect on average accommodation.

background (p = 0.0001). The average accommodation response to an achromatic target on a blue background is 0.18 D, which is significantly higher than the response to backgrounds of all other wavelengths. The main effect of background wavelength is plotted in Figure 25.

Because of the small range of accommodation across the achromatic targets and background, the data do not suggest a requirement for refocusing.

Summary. The analyses of experiment one suggest very few target/background combinations that would alter the observers' accommodation response to the extent that refocusing would be required to maintain focus on the presented characters. In each of these few cases, the characters were presented on a high purity blue background and consisted of colors that were at different ends of the color spectrum; yellows, reds, and magentas. In addition, it should be noted that the magnitude of the movement of visual accommodation due to the wavelength of the characters presented on the multicolor CRT relative to the accommodative range of the normal young observer is very small.

Experiment One-Standard Deviation of Dioptric Power. The standard deviation of the refraction of the eye relative to the mean accommodation response was calculated and used as a dependent measure to assess the stability of the observers' accommodation. It was reasoned that if the foreground/background combination provided a good stimulus for accommodation, the variance around

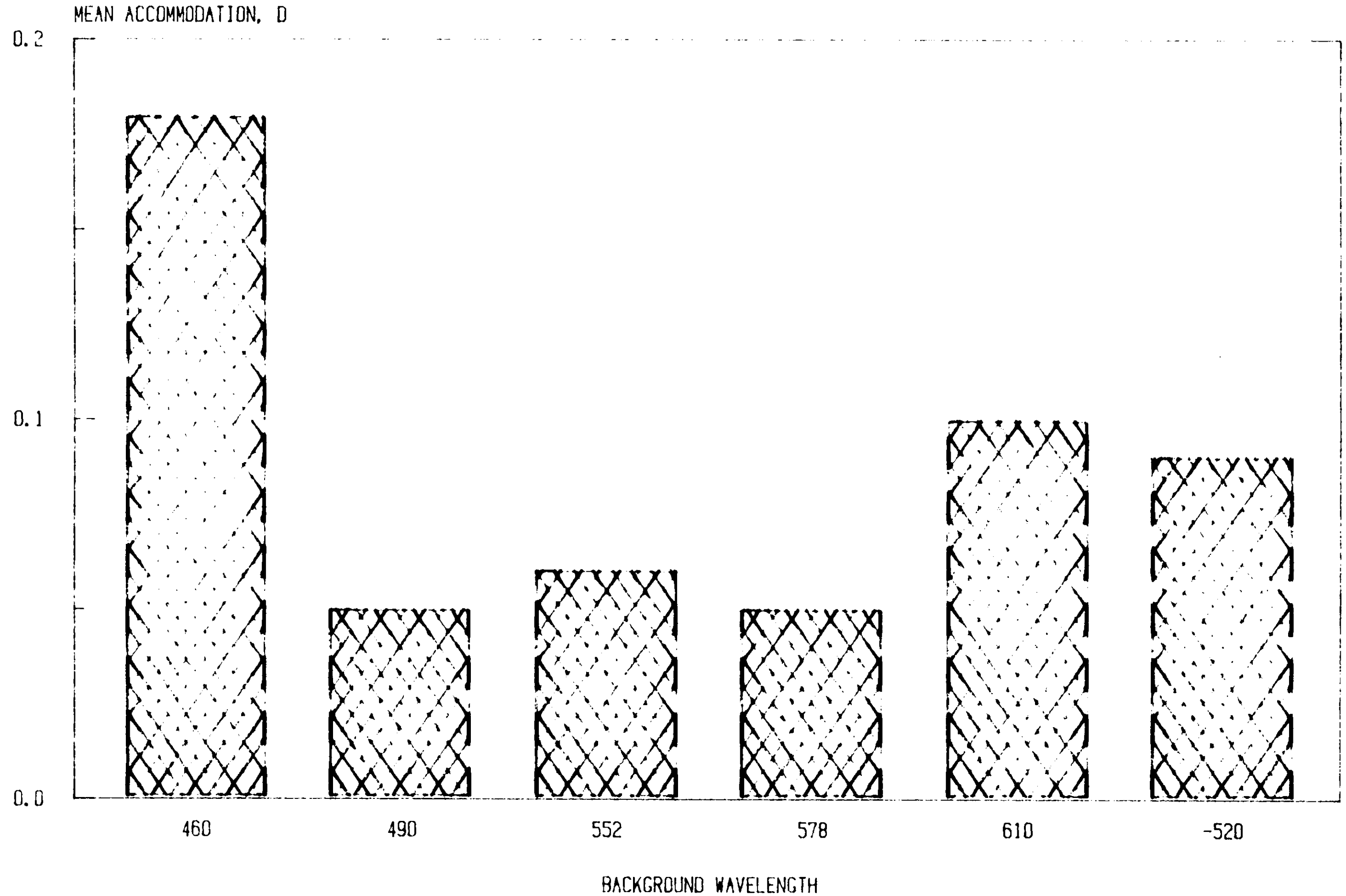

Figure 25. Achromatic foreground-background wavelength effect on average accommodation.

the mean would be small; conversely, those combinations providing poorer stimuli for accommodation would result in larger variance about the mean refraction of the eye. Thus, the characterization of the variability in the accommodation response should result in a measure of the stability of the observer's accommodation.

The stability of the focus of the eye may not only relate to the quality of the image as a stimulus for accommodation, but may as well be related to refocusing requirements imposed on the visual system while viewing a multicolor CRT. If the refraction associated with the target/background combination is at the edge of the observers' depth of focus and the variability is high, then the target may be in and out of focus, stimulating the accommodation system to actively seek the proper focus. As a result, the stability of accommodation may be valuable in assessing the contribution of viewing a multicolor CRT to the visual fatigue experienced by some users. As in the analyses of the average dioptric power, either the background or foreground was held constant while the effect on the dependent measure was assessed.

Blue. The stability of the accommodation response to chromatic targets on blue backgrounds is significantly affected by the wavelength of the foreground ($p = 0.0024$) and the interaction between background purity and foreground wavelength ($p = 0.0103$). The data for FW is displayed in Figure 26. The standard deviation of the accommodation response to targets displayed on blue backgrounds does not significantly differ for cyan (0.23 D), red (0.21 D), and

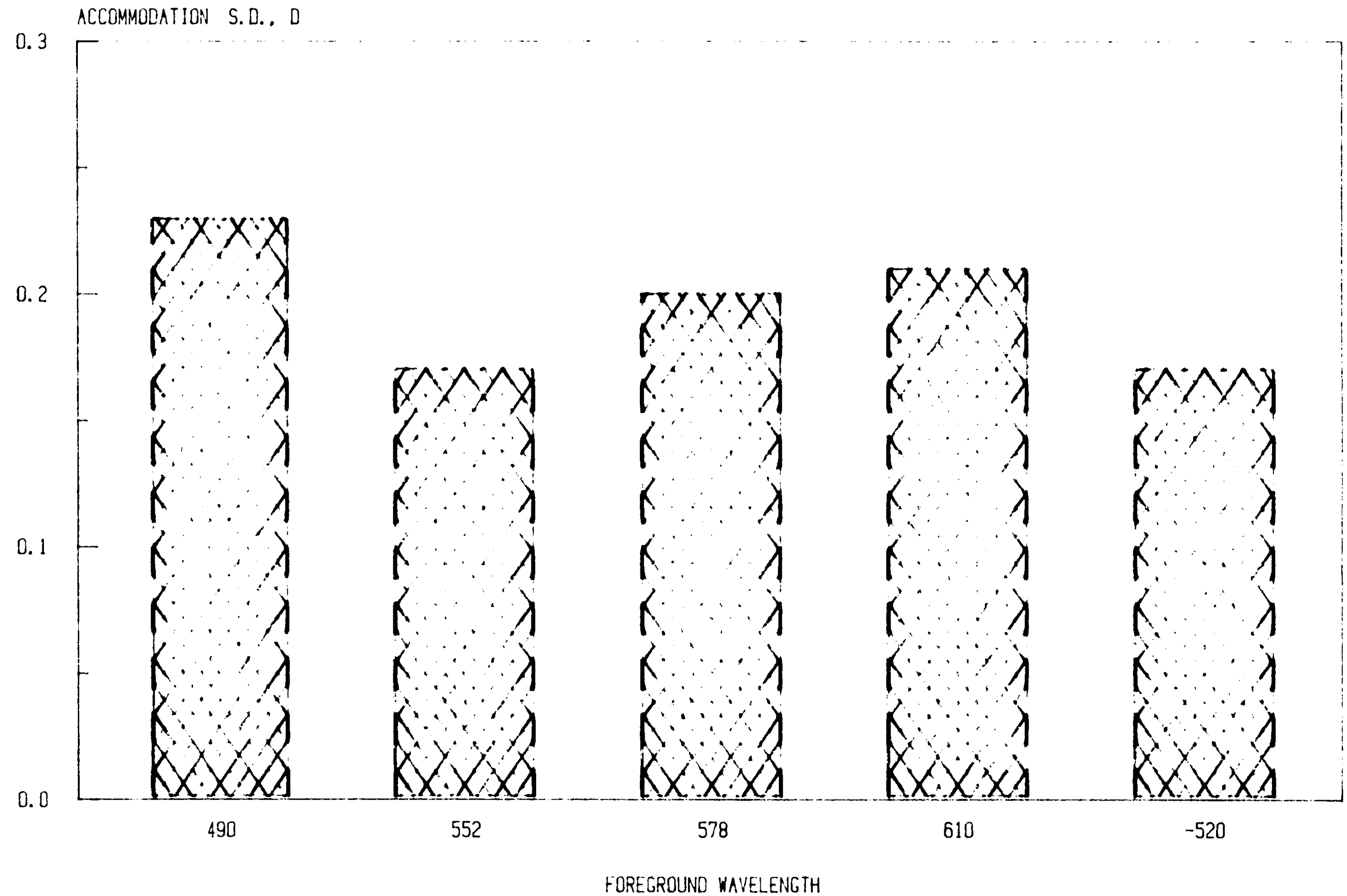

Figure 26. Blue background-foreground wavelength effect on standard deviation of accommodation.

yellow targets (0.20 D). The variability for cyan and red targets is larger than for green and magenta targets both of which have a standard deviation of 0.17 D. The stability of accommodation for yellow, green, and magenta targets does not statistically differ.

A plot of the BP X FW interaction (Figure 27) indicates that the accommodation response is more stable when targets of all wavelengths are viewed against low purity backgrounds than against compared to high purity backgrounds. When the background purity is high, the locus of the interaction effect is the same as that found in the analysis of foreground wavelength. There are no significant differences across foreground wavelength when targets are displayed on a low purity background.

There is an interaction between background wavelength and foreground purity ($p = 0.0211$) when blue targets are displayed on chromatic backgrounds. When the target purity is high, the stability of the accommodation response is significantly affected by the wavelength of the background. As indicated in Figure 28, the standard deviation obtained for high purity blue targets is 0.29 D for cyan and 0.24 D for red backgrounds, which do not significantly differ. However, these are significantly larger than the 0.16 D for green and magenta, which does not differ from the 0.21 D value obtained for yellow backgrounds. Thus, the stability to high purity blue targets on green, magenta, and yellow backgrounds is better than that obtained for red or cyan backgrounds. There were no

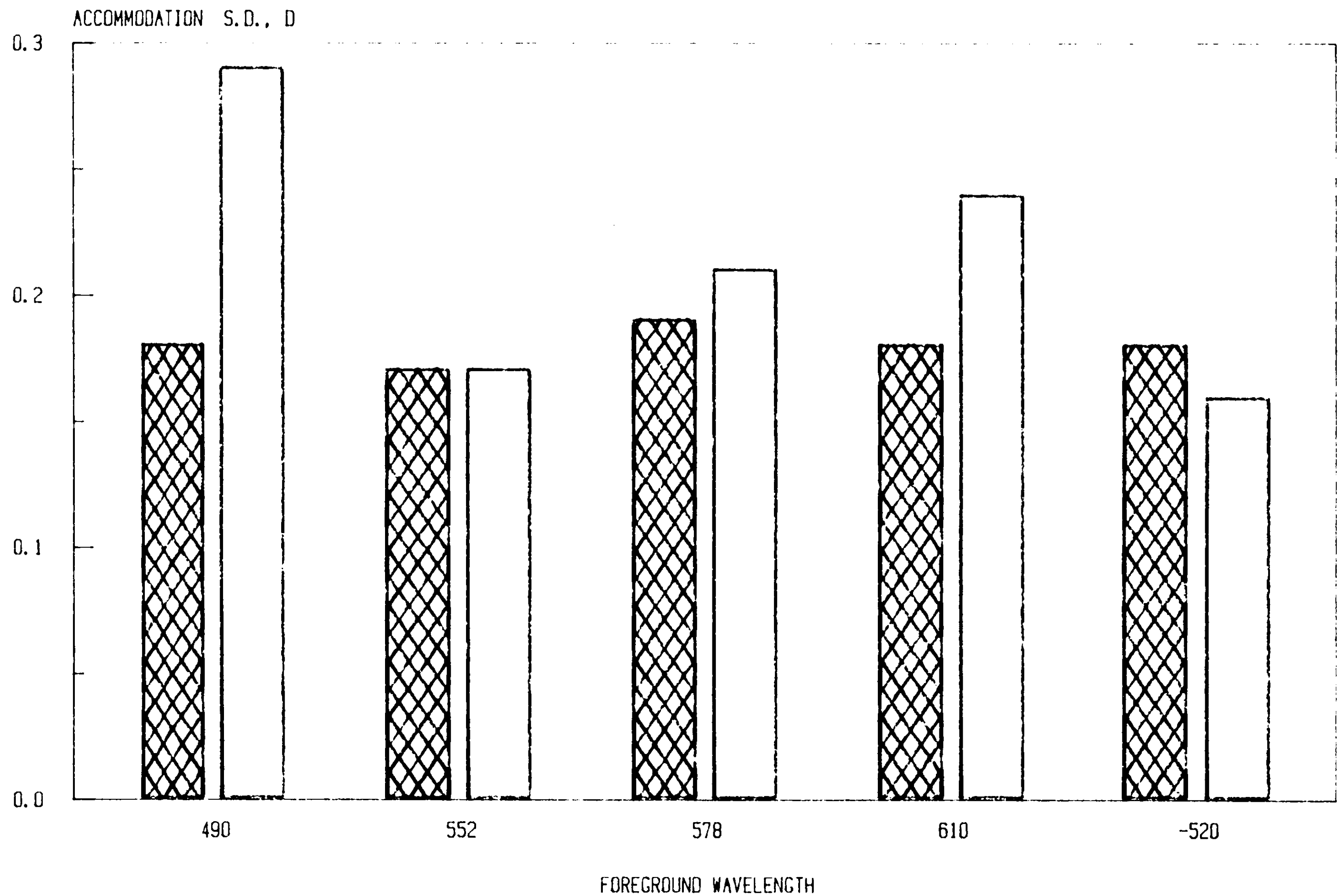

Figure 27. Blue foreground-BP X FW effect on standard deviation of accommodation.

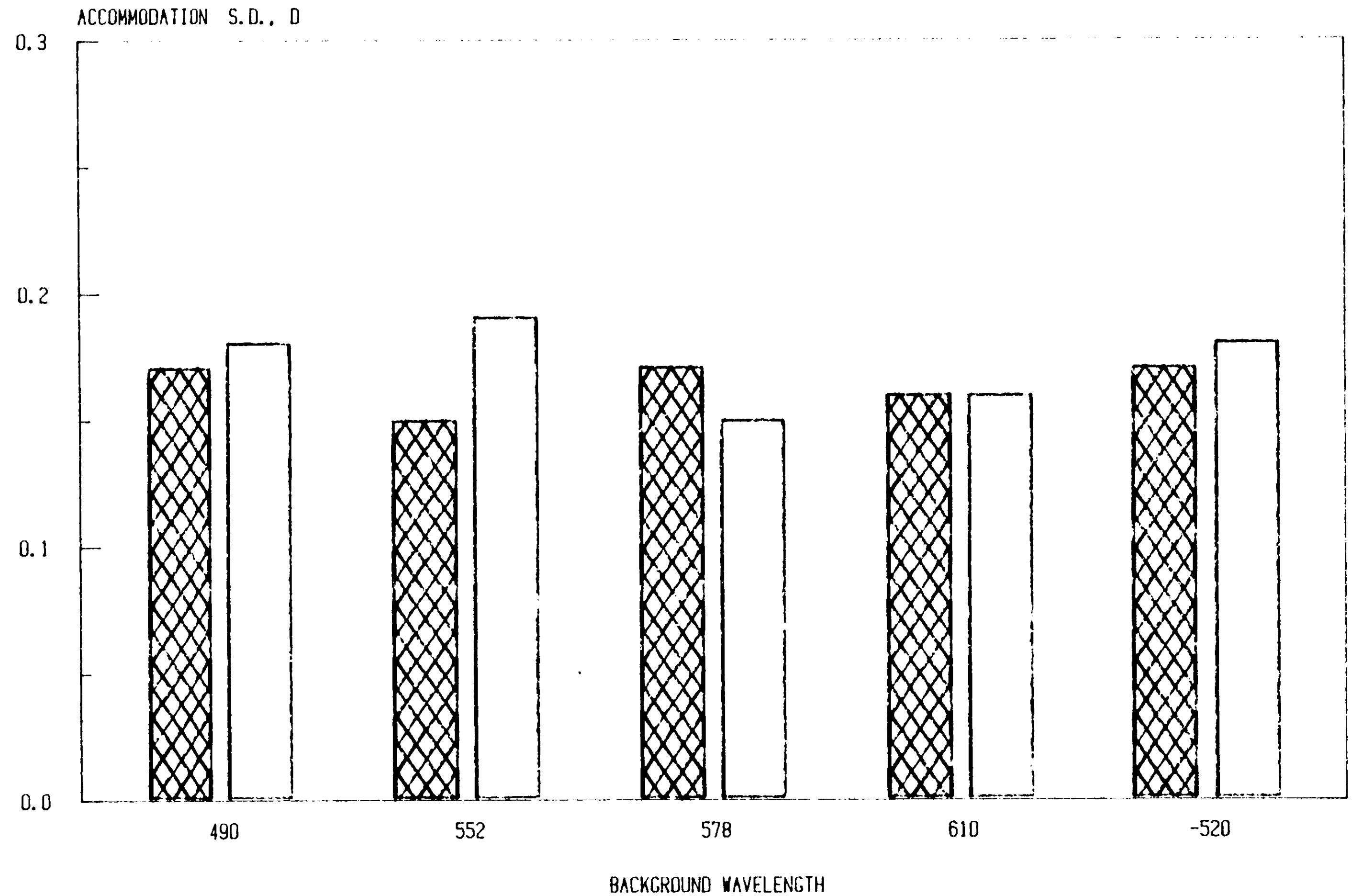

Figure 28. Blue foreground-BW X BP effect on standard deviation of accommodation.

significant differences found in the variability of the accommodation response displayed on low purity backgrounds. Across background wavelength, the magnitude of the stability of accommodation response was generally less for low purity backgrounds than for high purity backgrounds.

Cyan. When targets are observed on cyan backgrounds there are no significant differences in the observers' standard deviation of accommodation. However, when cyan foregrounds were observed, the stability of the observer's accommodation was affected by background wavelength ($p = 0.0036$), background purity ($p = 0.0413$), and the interaction between background wavelength and background purity ($p = 0.0048$). An observer's accommodation response to cyan targets is less stable to cyan targets on blue backgrounds (0.23 D) than to cyan presented on all other backgrounds. Figure 29 illustrates this effect. Further, the variability of accommodation when viewing cyan targets on low purity backgrounds (0.16 D) is significantly less than that obtained with high purity backgrounds (0.19 D) (Figure 30).

Analyses of the BW X BP interaction indicate that the observers' stability of accommodation is only affected by background wavelength when the background is of high purity. The standard deviation of accommodation to cyan targets on high purity blue background is 0.29 D which is significantly larger than the values obtained with other backgrounds (Figure 31).

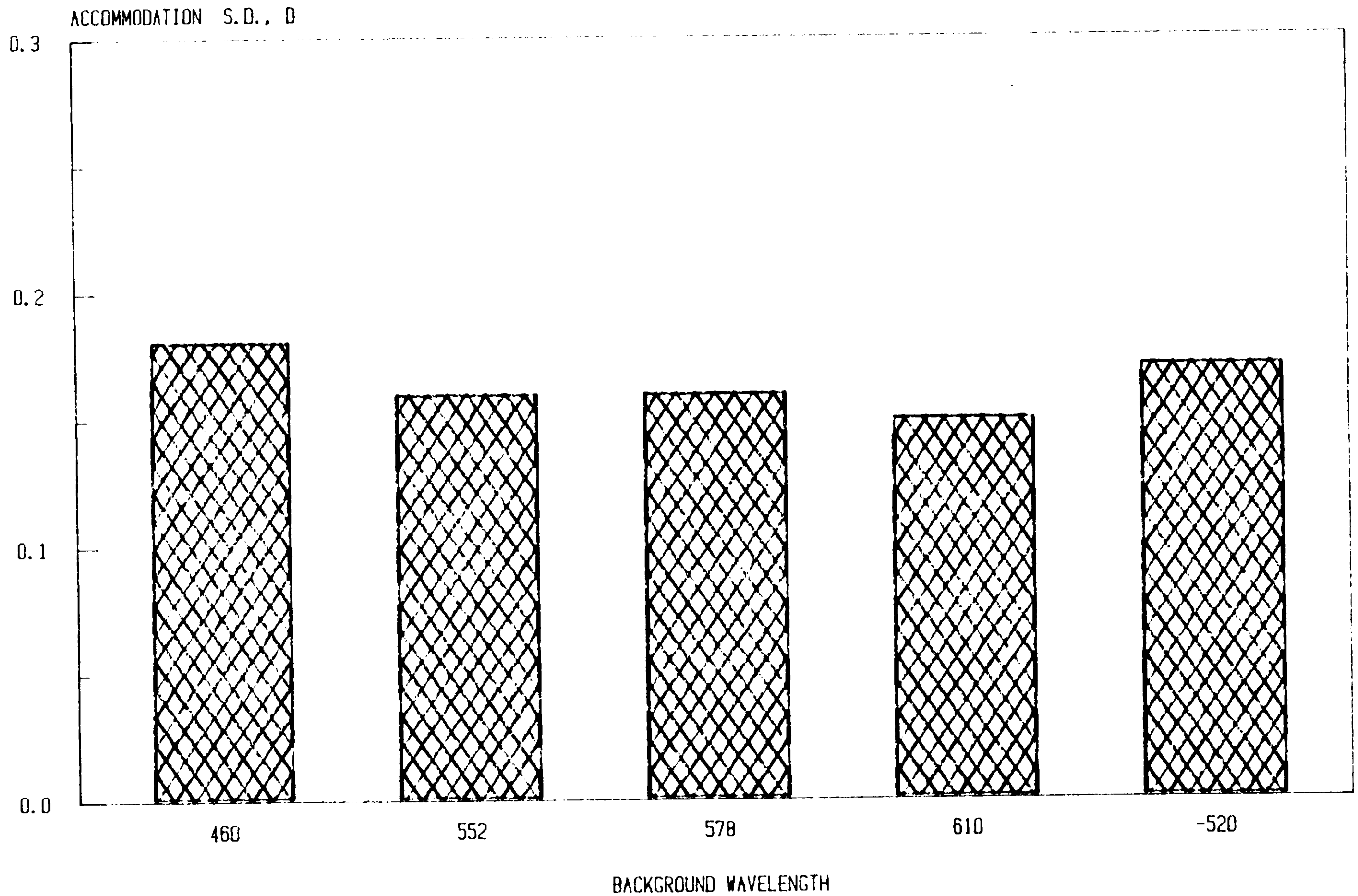

Figure 29. Cyan foreground-background wavelength effect on standard deviation of accommodation.

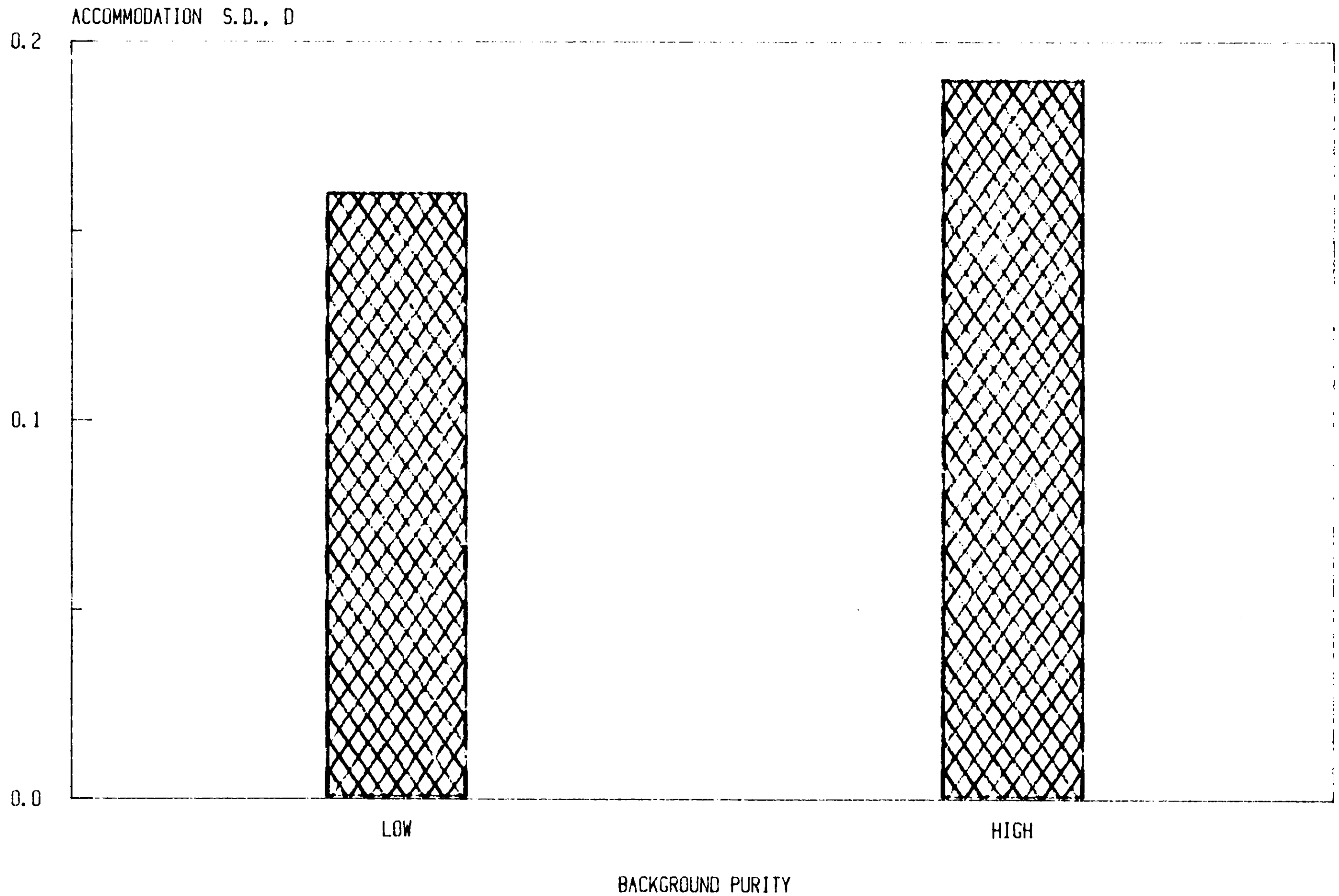

Figure 30. Cyan foreground-background purity effect on standard deviation of accommodation.

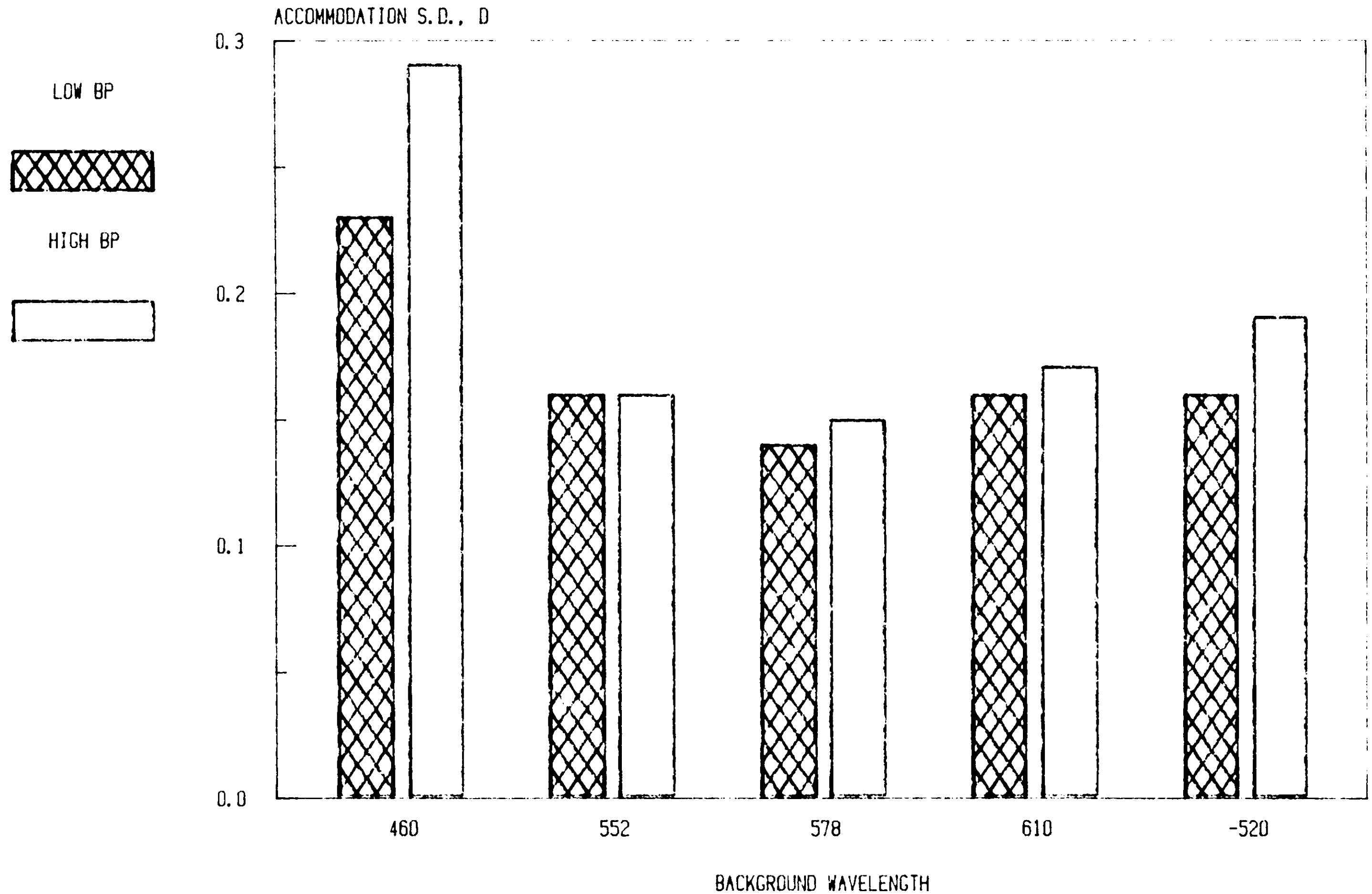

Figure 31. Cyan foreground-BW X BP effect on standard deviation of accommodation.

Green. The stability of the observer's accommodation response to chromatic targets on green backgrounds is affected by foreground purity ($p = 0.0453$). Figure 32 illustrates that a standard deviation of 0.16 D to high purity targets is significantly larger than the 0.15 D value obtained for low purity targets when they are observed on green backgrounds. Accommodation stability to green targets on chromatic backgrounds is affected by the purity of the background. Similar to the results obtained above, the variability of accommodation to green targets on low purity background (0.15 D) is significantly less than the value obtain with high purity backgrounds (0.17 D). These data are plotted in Figure 33.

Yellow. When targets are observed on a yellow background, the interaction between background purity and foreground purity affects one's stability of accommodation ($p =$ 0.0.0086). Analyses suggest that there are significant effects of foreground purity at both levels of background purity; however, the Newman-Keuls post hoc analyses for the background purity at each of the levels of foreground purity found no significant difference between the high and low background purity when a low purity target was displayed. When the targets were of high purity presented on a low purity background a more stable accommodation results. This is clearly illustrated in Figure 34. Accommodation to yellow targets was significantly affected by background purity ($p = 0.0182$). As is presented in Figure 35,

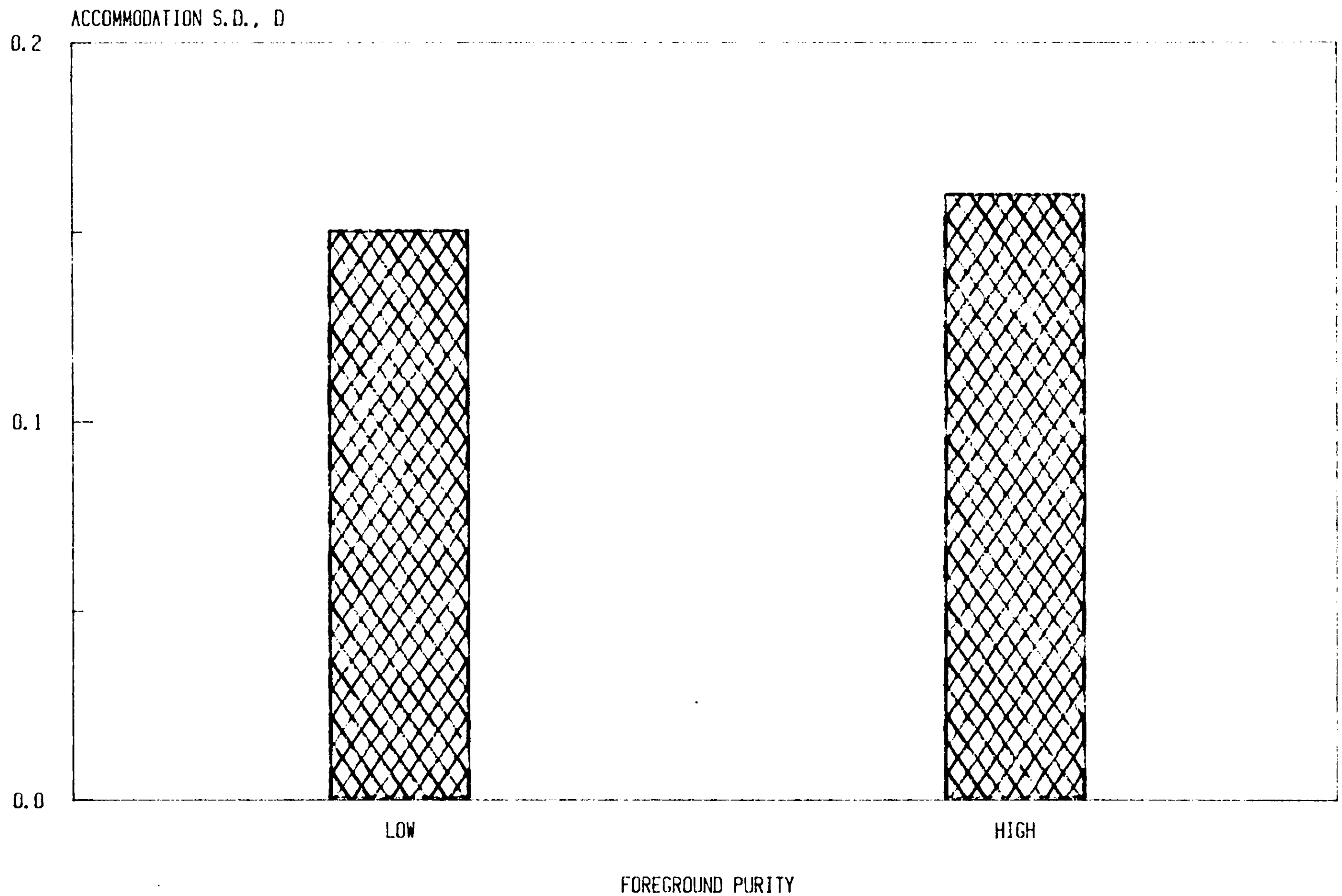

Figure 32. Green background-foreground purity effect on standard deviation of accommodation.

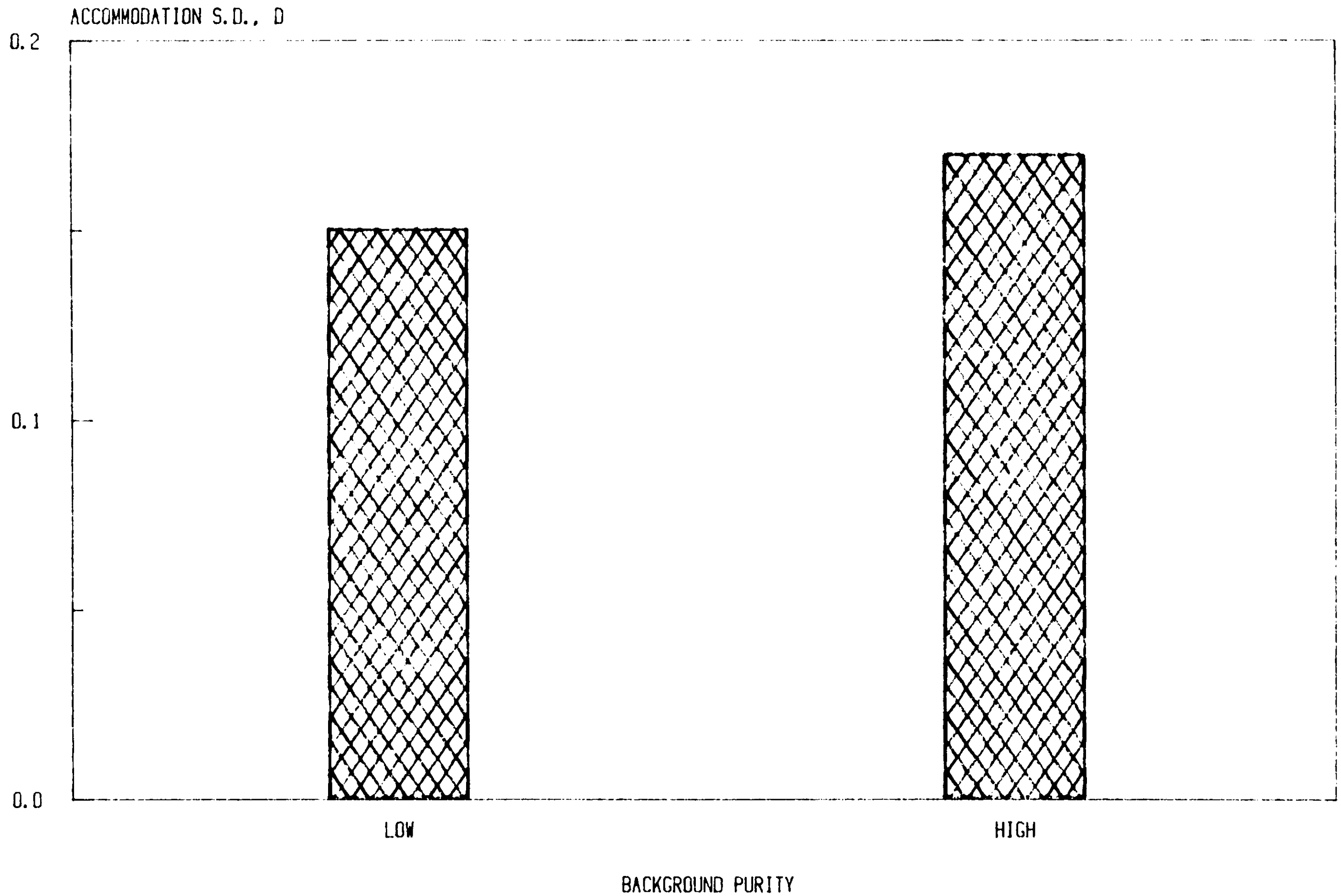

Figure 33. Green foreground-background purity effect on standard deviation of accommodation.

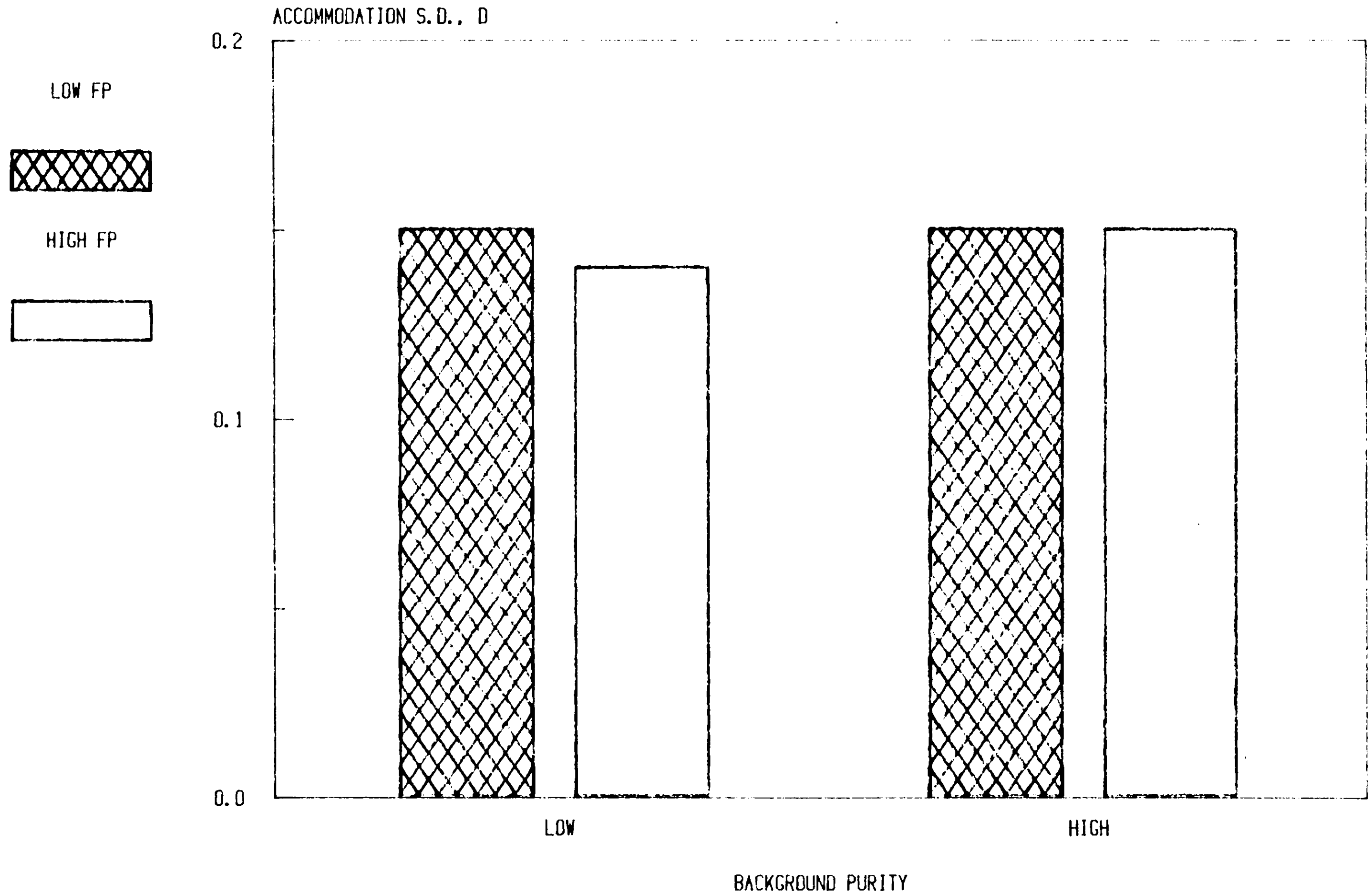

Figure 34. Yellow background-BP X FP effect on standard deviation of accommodation.

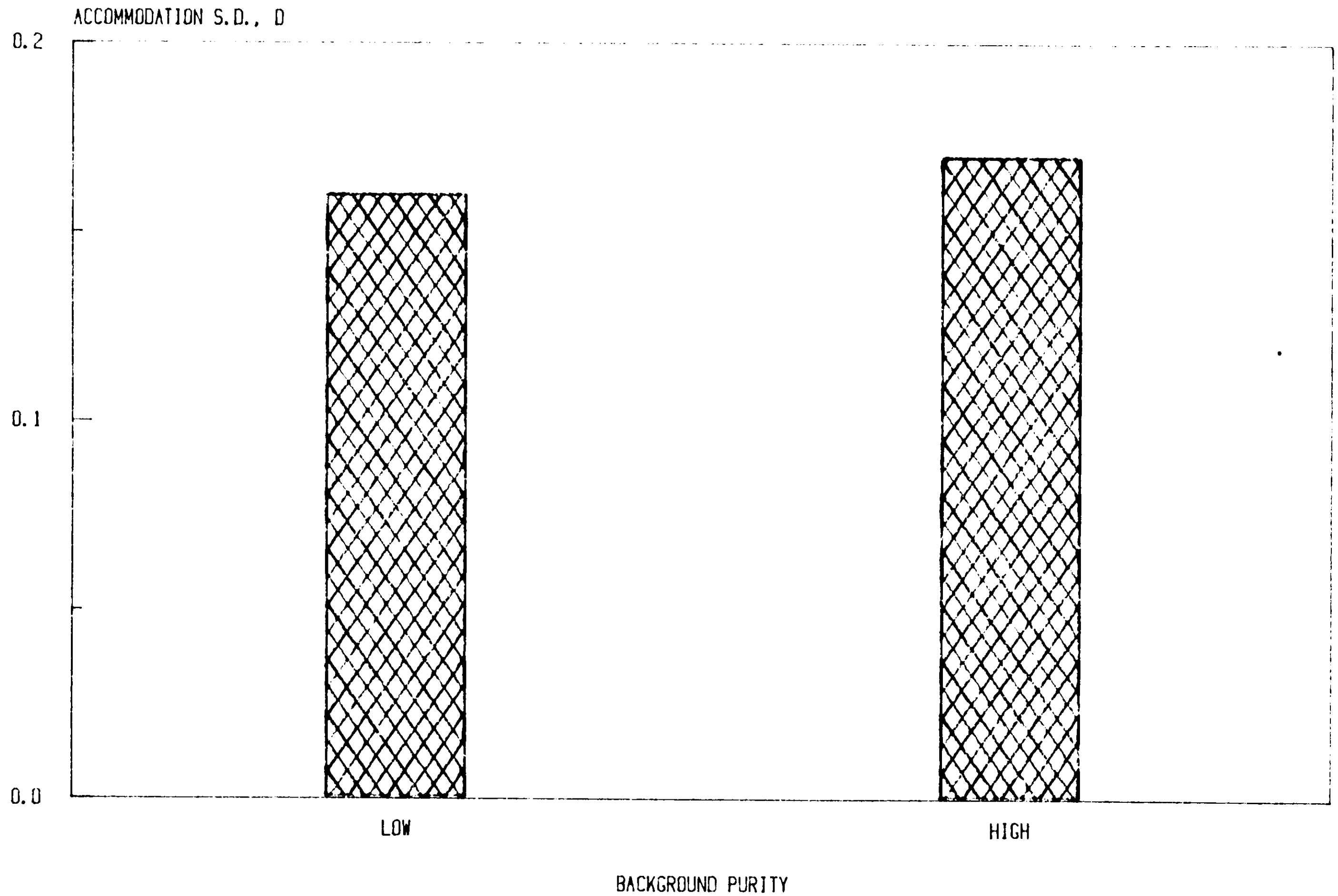

Figure 35. Yellow foreground-background purity effect on standard deviation of accommodation.

stability of accommodation was greater when the yellow target was observed against a low purity background.

Red. No significant effects were found when chromatic targets were observed on red backgrounds. When red targets were observed, however, the background wavelength (p = 0.0001) as well as the interaction between the background wavelength and background purity (p = 0.0364) affected the stability of the observers' accommodation response. The variability in accommodation to red targets presented on a blue background (0.21 D) is greater than when the red target is presented on a cyan (0.17 D), magenta (0.17 D), green (0.15 D), or yellow (0.14 D) background. Also, compared to a green or yellow background, the variability to cyan and magenta backgrounds is greater. These data are presented in Figure 36.

Analysis of the BW X BP interaction indicates that accommodation variability to red targets is significantly affected by the wavelength of the high purity backgrounds. As displayed in Figure 37, the standard deviation of accommodation to red targets on high purity yellow or green background (0.13 D and 0.14 D, respectively) was the lowest and do not significantly differ. The accommodation stability to red targets on magenta or cyan background does not significantly differ from each other but is significantly larger than the value obtained with yellow or green backgrounds. The largest variability, 0.24 D, occurs when red targets are observed on high purity blue backgrounds. This result indicates the variability in the mean accommodation response

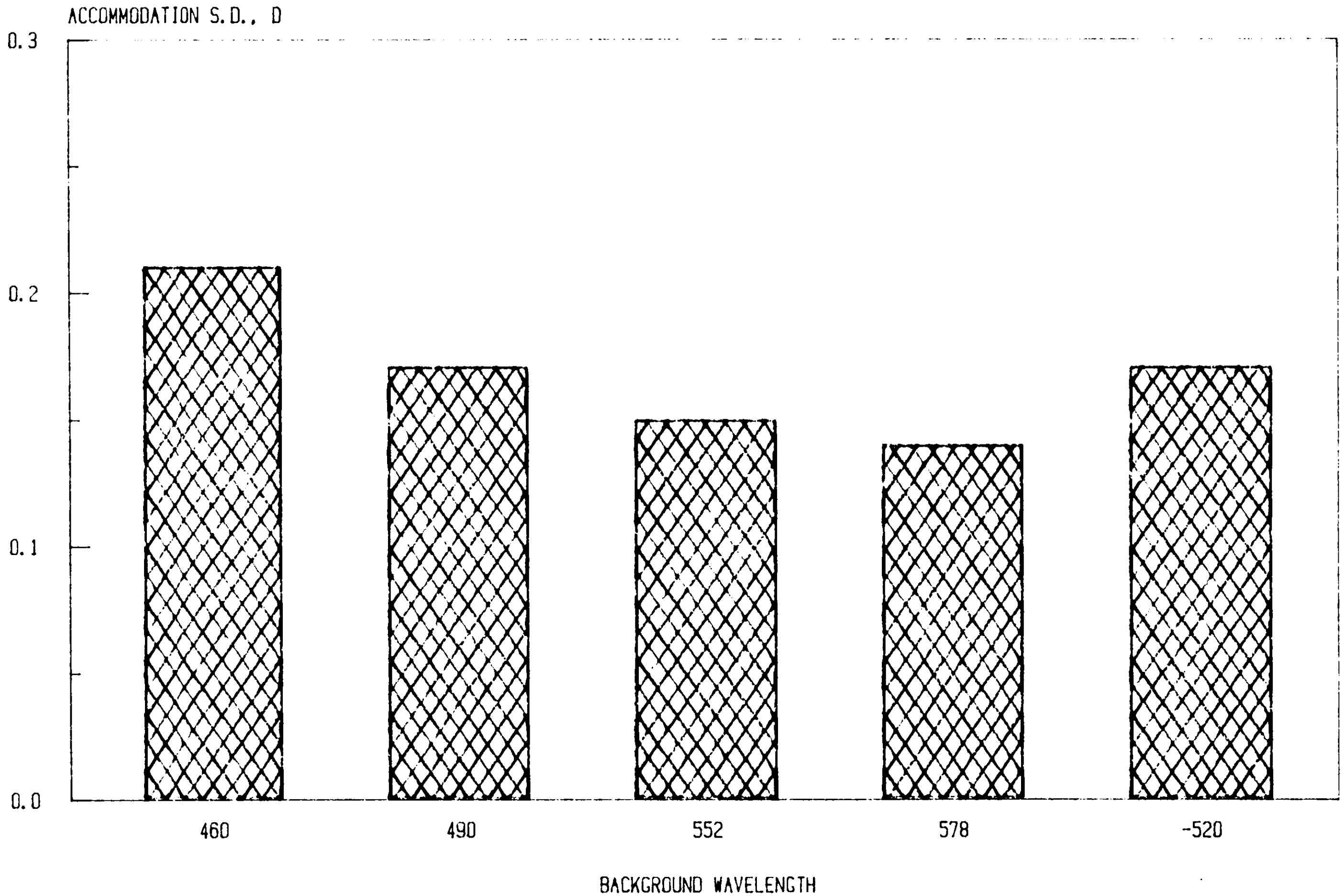

Figure 36. Red foreground-background wavelength effect on standard deviation of accommodation.

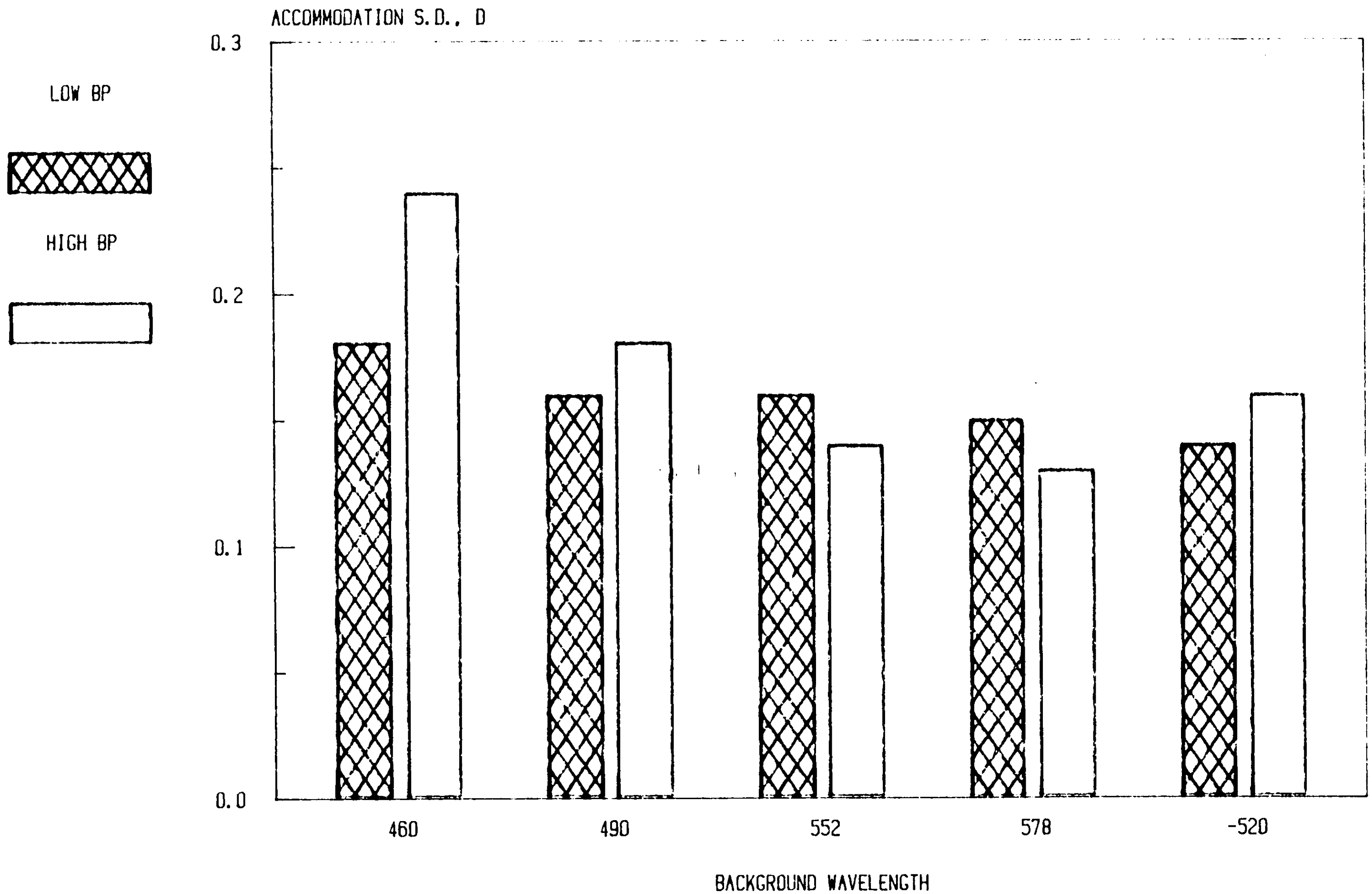

Figure 37. Red foreground-BW X BP effect on standard deviation of accommodation.

for the target/background combination with the most widely separated wavelengths is the largest obtained.

Magenta. No significant differences with respect to the observers' standard deviation of accommodation were found with magenta backgrounds or foregrounds.

Achromatic. The analysis of variance performed with achromatic backgrounds yields no significant results with respect to the standard deviation in the subjects' accommodation to chromatic targets. When achromatic targets were presented on chromatic backgrounds, the background wavelength ($p = 0.0485$), the background purity ($p = 0.0084$), and interaction between the background wavelength and foreground purity ($p = 0.0141$) were found to affect the observers' stability of accommodation. The standard deviation in mean accommodation to achromatic targets on blue backgrounds of 0.20 D is similar to that for yellow and red at 0.17 D, but significantly different from that obtained for cyan, magenta, and green backgrounds. The stability of accommodation is not significantly different among yellow, red, cyan, magenta, and green backgrounds. The effect of background wavelength is depicted in Figure 38. The analysis indicates the standard deviation of accommodation is lower (0.16 D) for backgrounds of low purity than for high background purity (0.18 D). This effect is illustrated in Figure 39.

An investigation of the BW X FP interaction indicates that the stability of the observers' accommodation response to achromatic

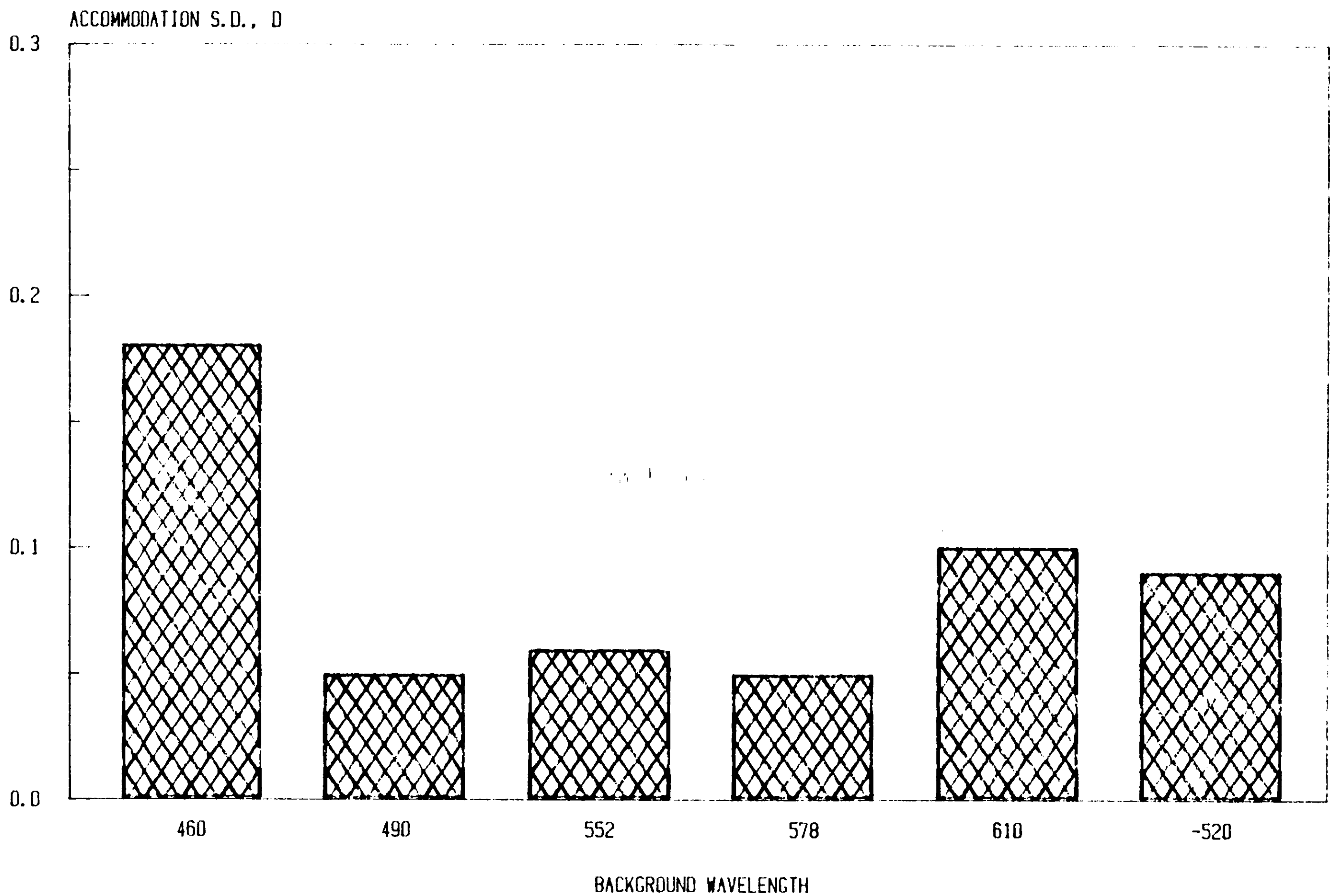

Figure 38. Achromatic foreground-background wavelength effect on standard deviation of accommodation.

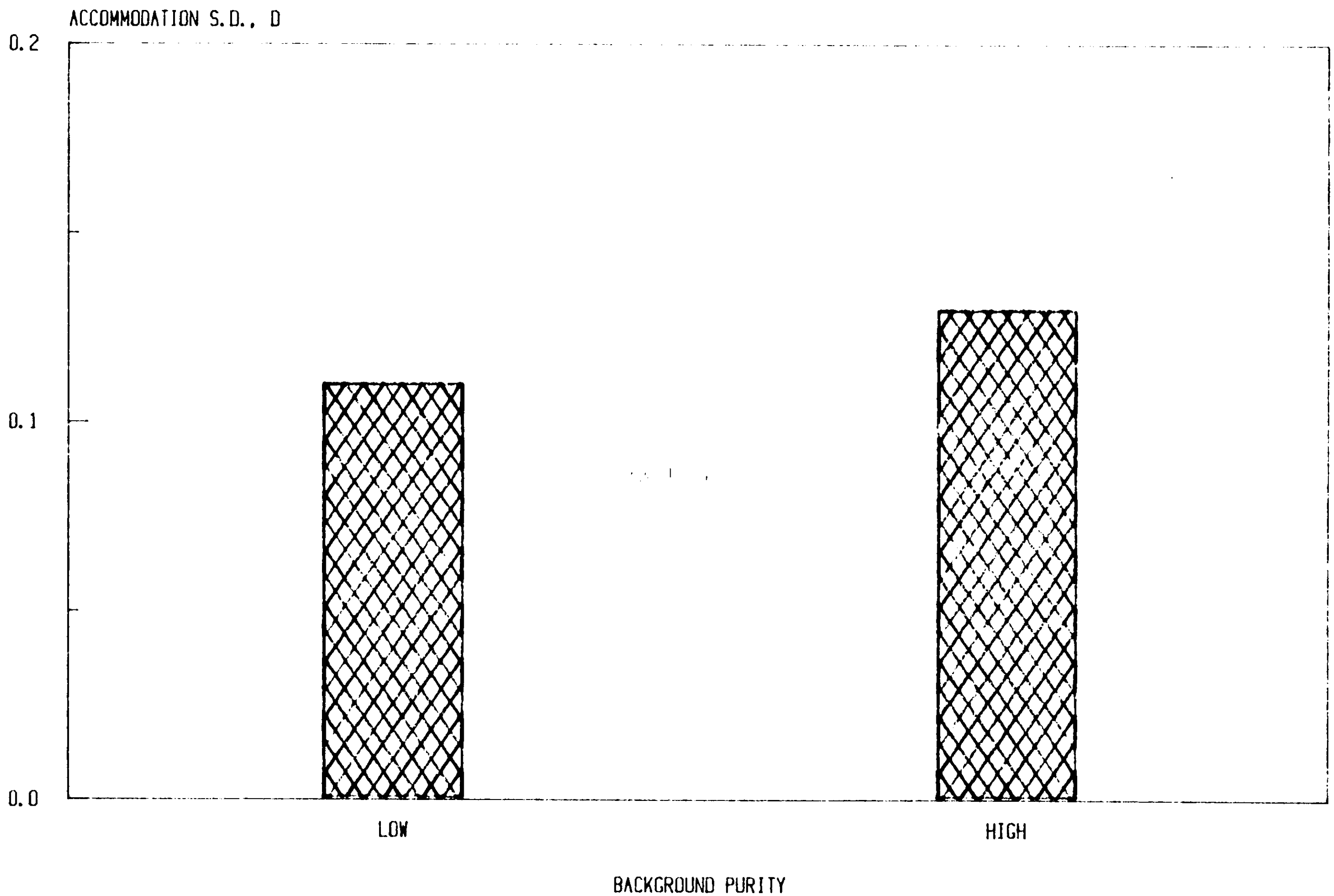

Figure 39. Achromatic foreground-background purity effect on standard deviation of accommodation.

targets is affected by background wavelength at both levels of foreground purity (Figure 40). When the target is white, accommodation is less stable on blue backgrounds than for all other backgrounds, among which there are no significant differences. The standard deviation of accommodation to black targets on chromatic backgrounds is lowest for green or cyan backgrounds (0.15 D), which differs from the 0.18 D and the 0.19 D values obtained with red and blue backgrounds, but is not significantly different from magenta and yellow backgrounds. However, the variability in accommodation on red backgrounds is not significantly different from cyan, magenta, and yellow The values for blue background does not differ significantly from magenta, yellow, or red backgrounds.

Summary. The results of the analysis of the stability of the observers' accommodation response indicate that for most target/background combinations, the variability in the observers' refraction about the mean is consistent with her depth of focus. The one exception is when targets were observed on high purity blue backgrounds. Here the values were generally larger than those obtained for all other target/background combinations. These results indicate that the high purity blue background may have acted to disrupt the observers' accommodation response.

Experiment Two. An analysis of variance was performed on experiment two for all dependent measures. In contrast to experiment one, the full factorial design permitted the examination of the interaction between foreground and background wavelength. Experiment

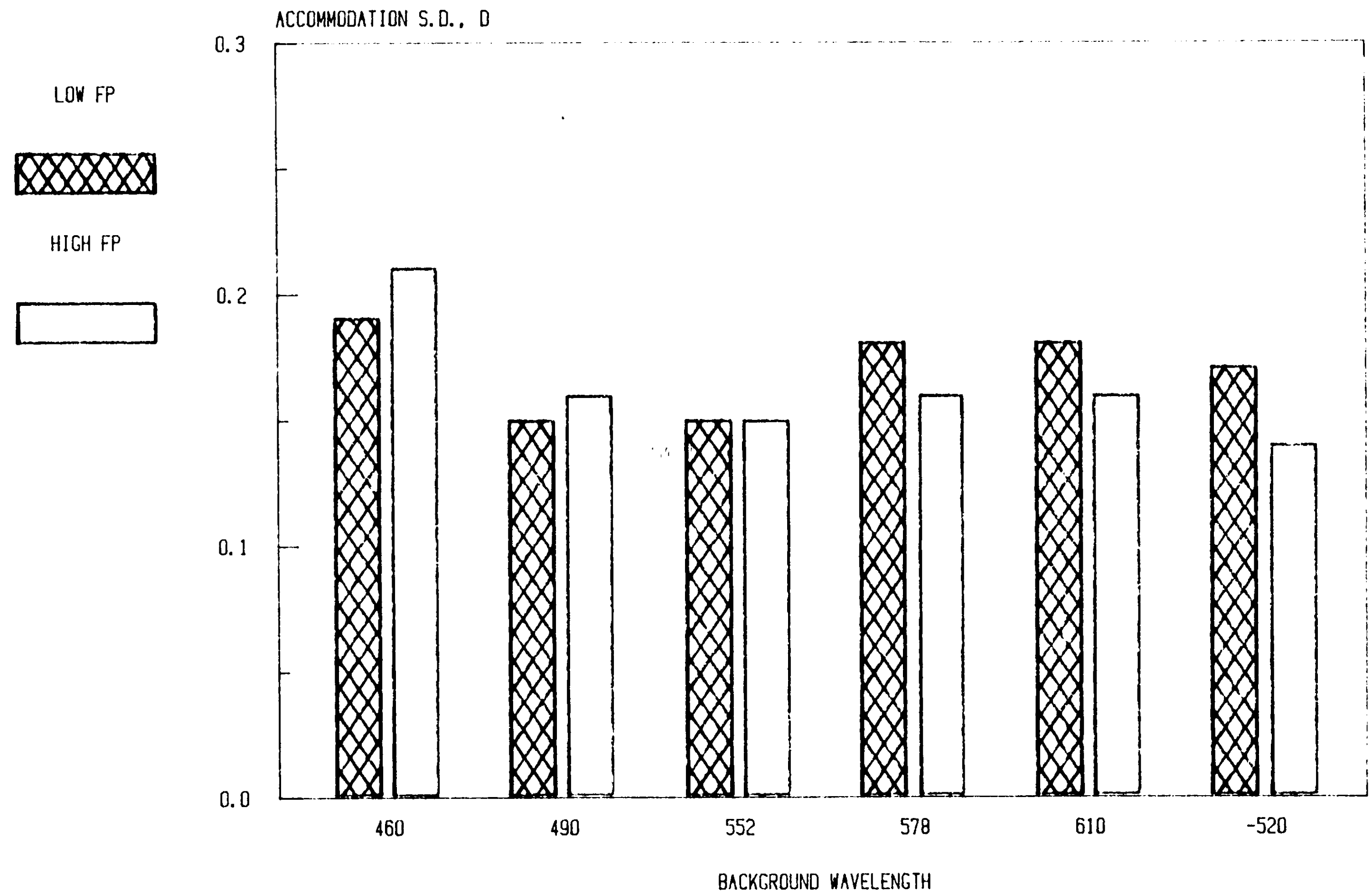

Figure 40. Achromatic background-BW X FP effect on standard deviation of accommodation.

two also contained one full replicate of the task variable, the number of matches within the column of six numeral pairs. The results of these analyses are summarized below.

Experiment Two-Average Dioptric Power. The analysis of variance using the observers' average accommodation to the presented stimulus conditions yielded no significant independent factors.

Experiment Two-Standard Deviation of Dioptric Power. When the observers' stability of accommodation was investigated with the stimuli used in experiment two, foreground wavelength ($p = 0.0345$) and the interaction among background wavelength, background purity, and foreground purity ($p = 0.0398$) were found to significantly affect the observers' response. The standard deviation in mean accommodation to blue targets was 0.16 D, which was significantly different than that for green, yellow, or magenta targets, which did not significantly differ. The main effect of foreground wavelength is illustrated in Figure 41.

The BW X BP X FP interaction is plotted in Figure 42. Analyses of this interactions indicates that the variability of the accommodation response is only affected across background wavelength when low purity characters are displayed on high purity backgrounds. Under these conditions, the standard deviation of the accommodation response to targets displayed on high purity cyan backgrounds (0.17 D) is significantly greater than the values obtained for red (0.15 D), or achromatic (0.14 D) backgrounds, for which, there was a significant difference.

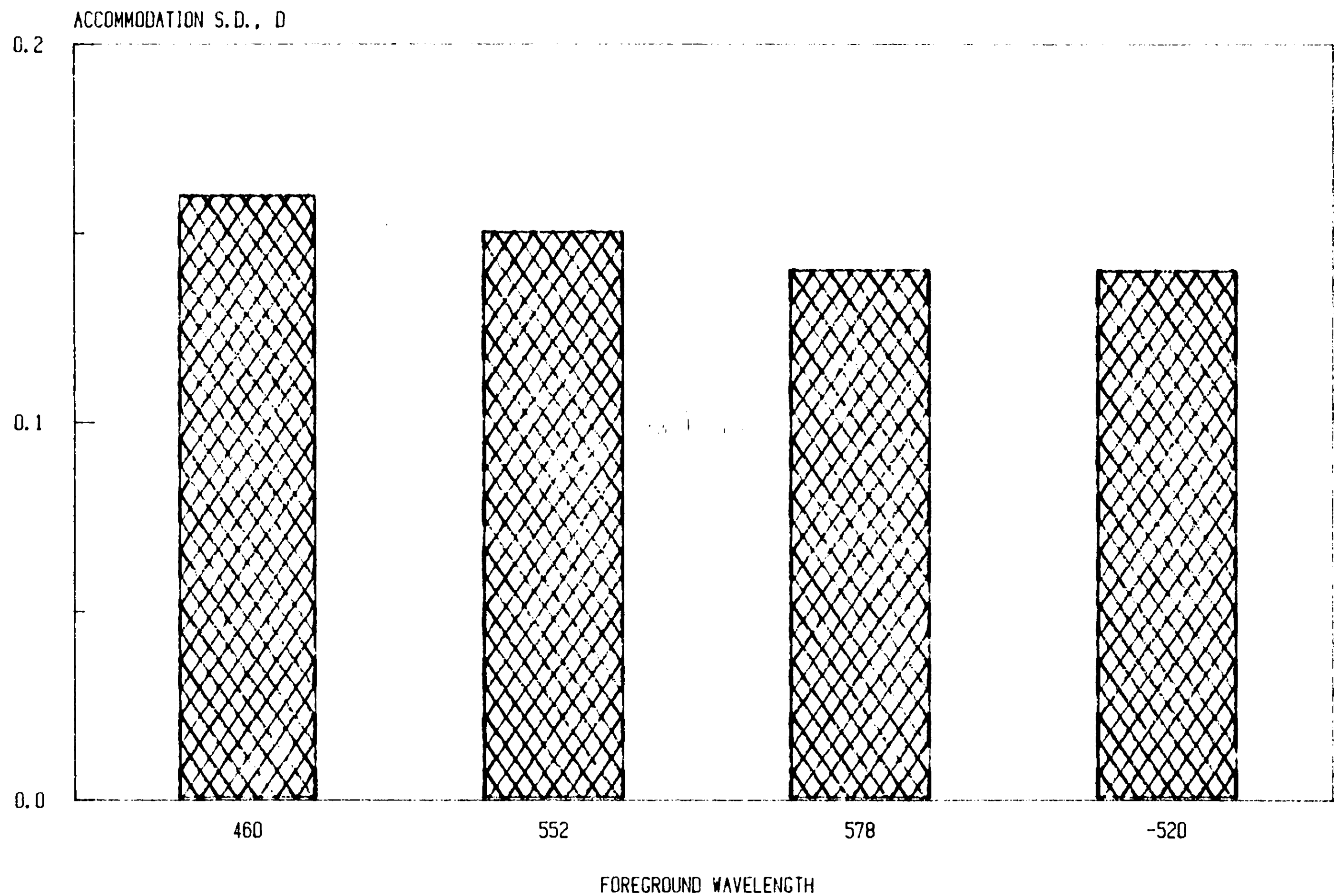

Figure 41. Experiment 2-Foreground wavelength effect on standard deviation of accommodation.

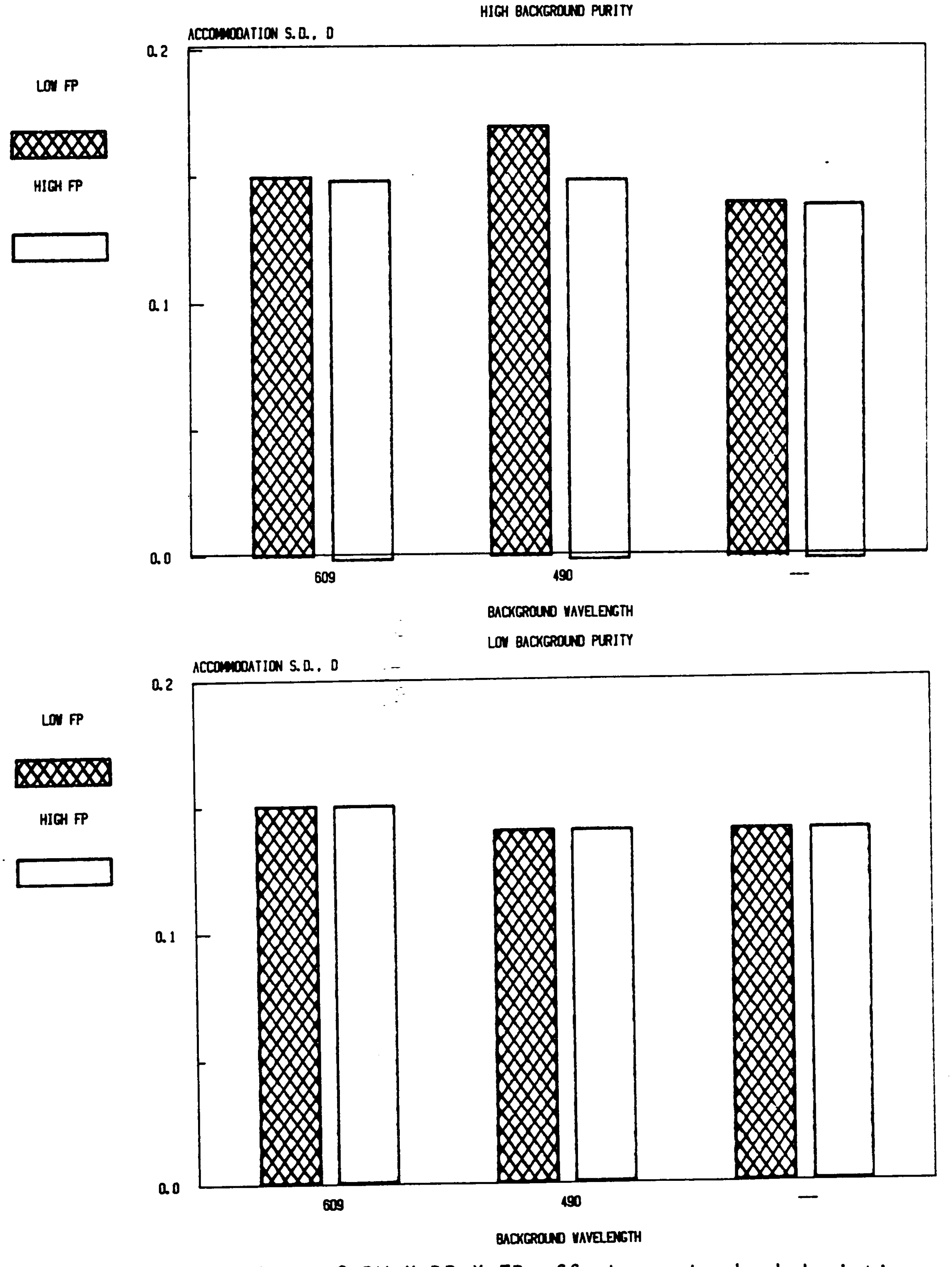

Figure 42. Experiment 2-BW X BP X FP effect on standard deviation of accommodation.

The analyses of the data in experiment two provide some support to the concern that chromatic aberration can affect an observer's accommodation stability as demonstrated by the significant effects of foreground wavelength and the BW X BP X FP interaction. While the effect is present, the magnitude of the changes (+0.17 D) exhibited by the observers in this study do not indicate major problems in terms of accommodation stability for observers in a multicolor CRT environment.

Task Speed. The analysis of variance investigating the effect of the independent variables on task speed was performed by first including the task variable, the number of matches in the task stimulus. Results of that analysis demonstrated that there was no significant effect due to the number of pairs in the column ($p = 0.1137$). This suggested that the task essentially required an exhaustive search by the subject and, as a consequence, a second ANOVA was run collapsing the data from experiment two over the number of pairs in the task stimulus.

Significant main effects on task speed include background wavelength ($p = 0.0015$), foreground wavelength (0.0002), and foreground purity ($p = 0.0001$). Significantly better task speeds (0.34) were obtained with red and achromatic backgrounds when compared to cyan backgrounds (0.26). The data for the BW main effect are plotted in Figure 43.

Tasks composed of blue characters were performed significantly faster (0.36) than those of magenta characters (0.32), which

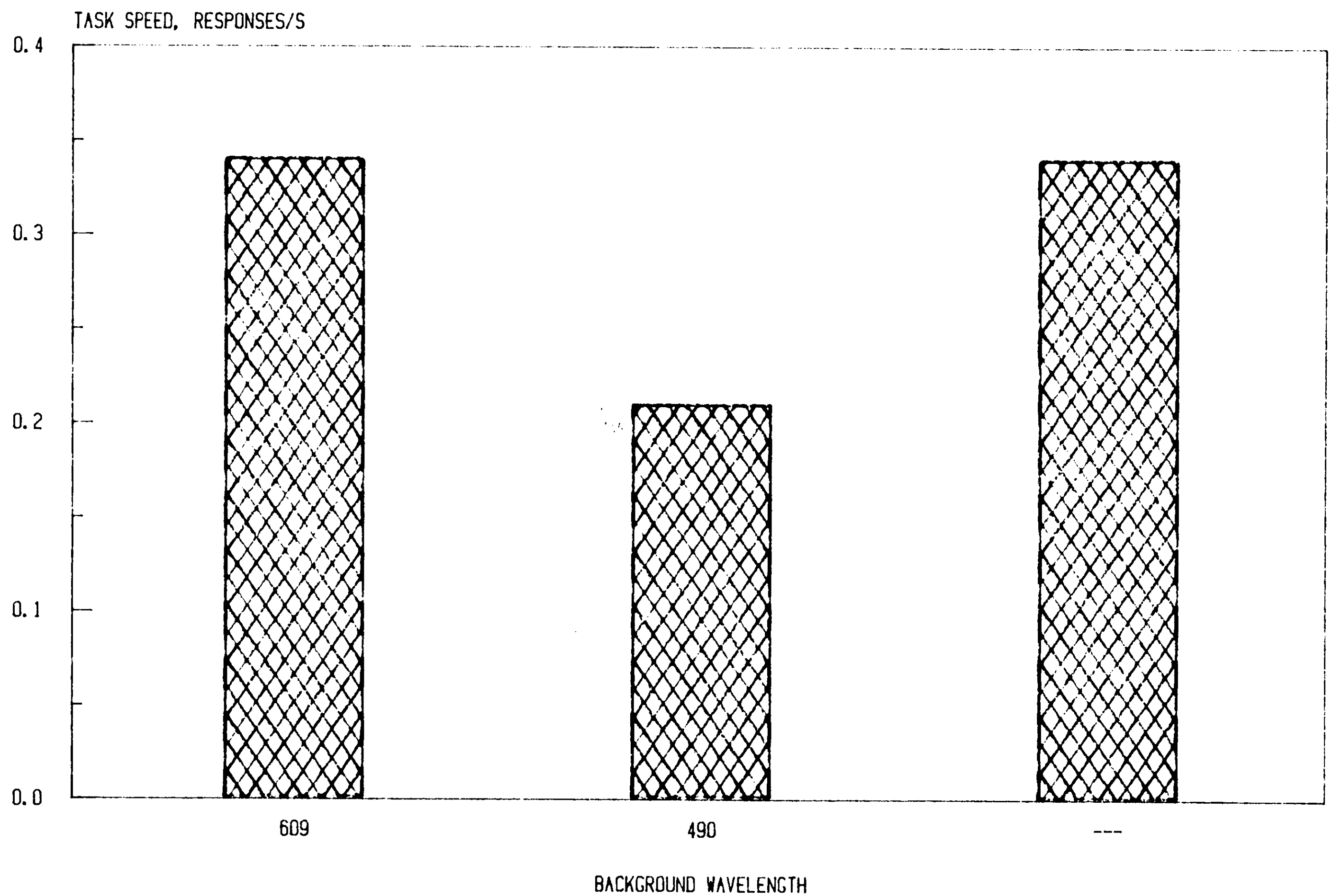

Figure 43. Experiment 2-background wavelength effect on task speed.

resulted in better performance than those tasks whose foregrounds were green (0.30) or yellow (0.29). Figure 44 illustrates this effect.

The last of the significant main effects concerns the effect of foreground purity on task performance and is shown in Figure 45. Task speeds are significantly faster with high purity targets (0.34) than with low purity targets (0.29).

Several two-way interactions were obtained in the analysis of variance. Background wavelength combined with foreground wavelength to affect task speed ($p = 0.0001$). These data are plotted in Figure 46. When the targets were observed on red backgrounds, performance was poorest with magenta targets (0.24); better task speeds resulted when green or yellow targets were observed; and task speed was highest when the target was blue (0.41). Task performance for targets observed on cyan backgrounds can be summarized as follows: green targets resulted in the lowest task speeds (0.15); task speed increased with yellow and blue targets (0.24 and 0.30 respectively), but no performance differences were found between these two target wavelengths; and task speed was significantly faster when magenta targets were observed against cyan backgrounds (0.36) than for other target/background combinations with cyan backgrounds. No differences in task speed across all foreground wavelengths were found with achromatic backgrounds. These results taken together suggest that the color contrast between the foreground and background may have affected task speed.

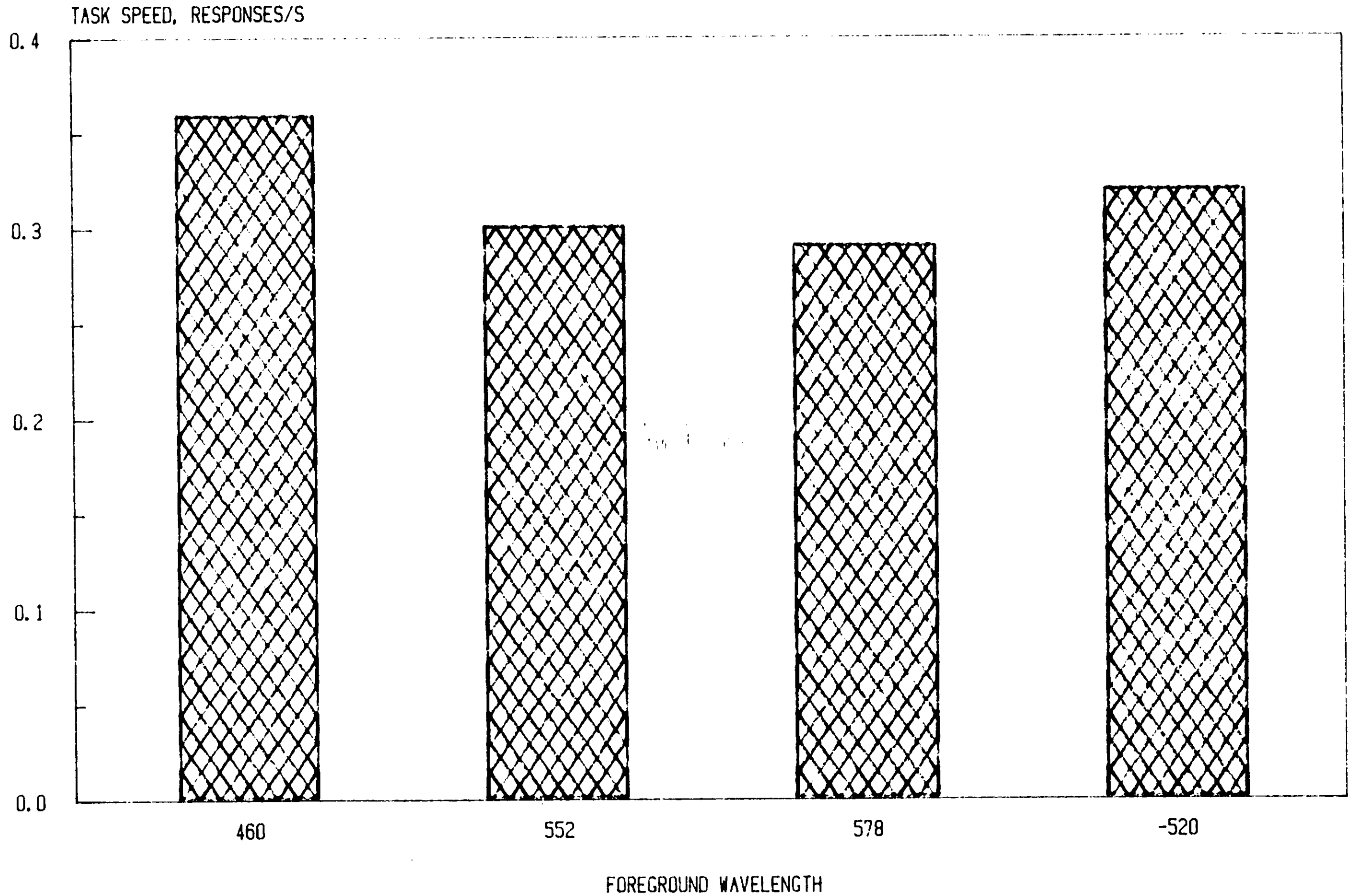

Figure 44. Experiment 2-foreground wavelength effect on task speed.

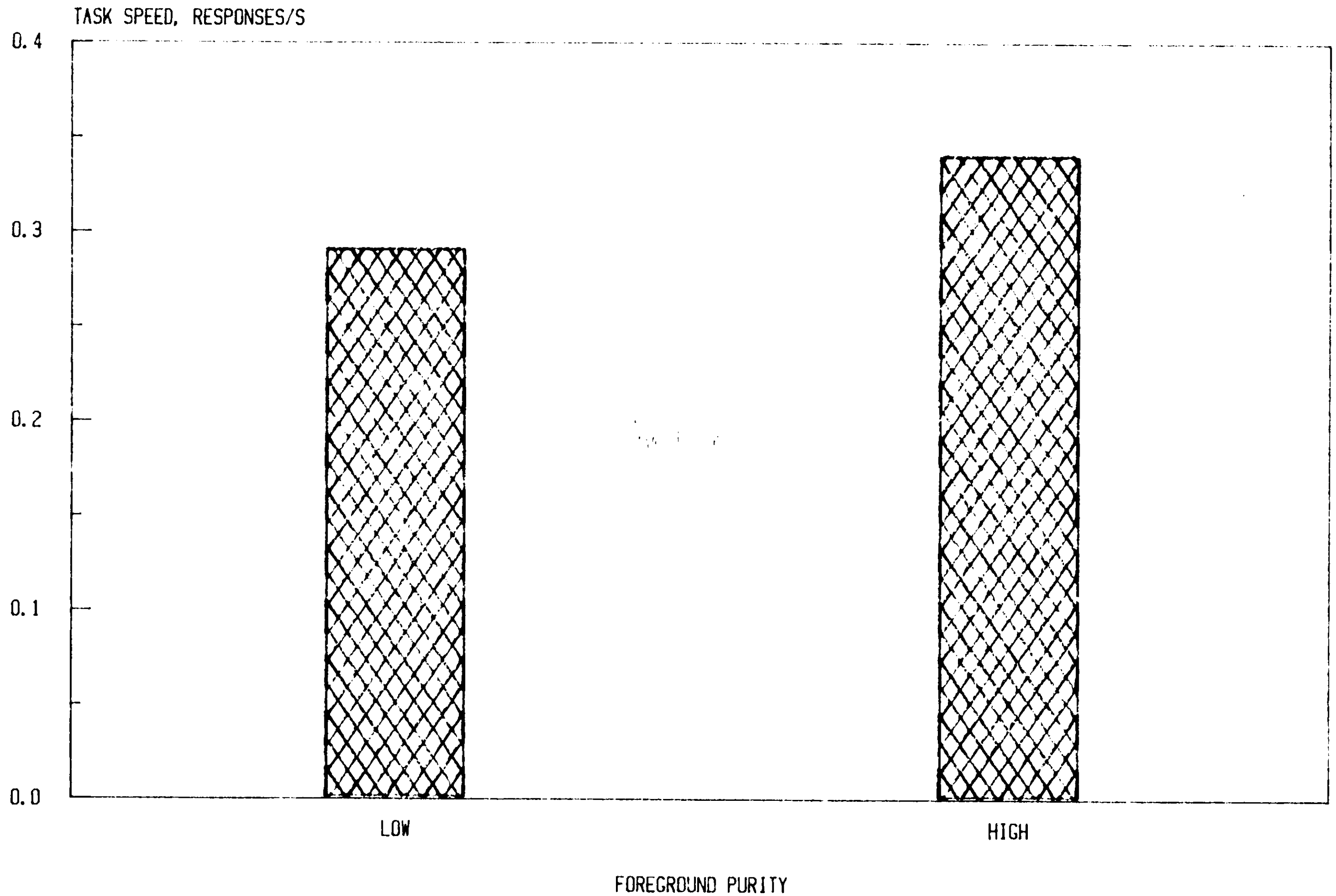

Figure 45. Experiment 2-foreground purity effect on task speed.

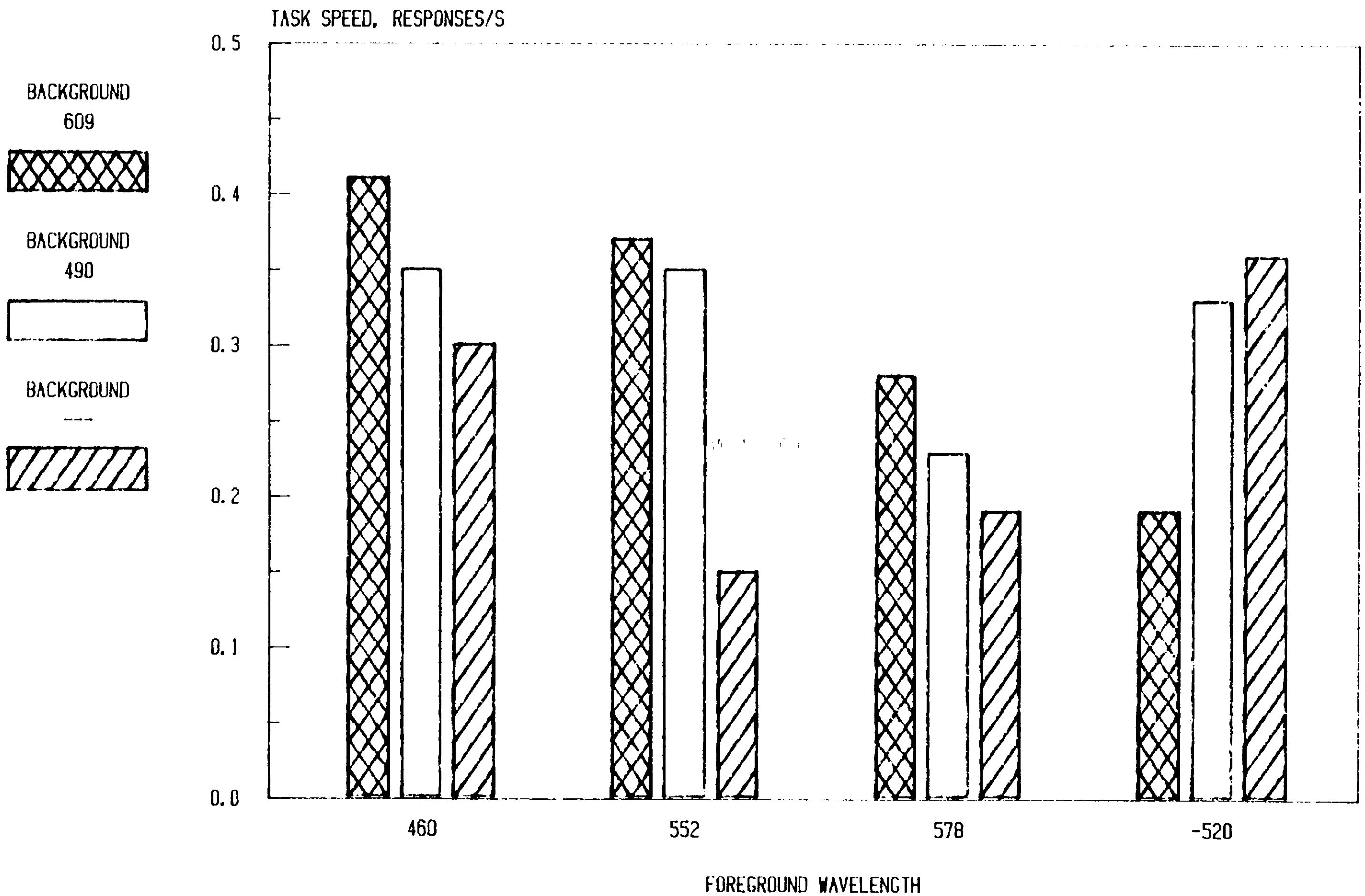

Figure 46. Experiment 2-BW X FW effect on task speed.

Background wavelength combines with background purity to significantly affect task speed (p = 0.0012). For high purity backgrounds, the achromatic, white, and cyan backgrounds result in poorer task performance than that obtained with a red background. The data are plotted in Figure 47. At low purity, cyan and red backgrounds result in significantly poorer task performance than do black backgrounds. The differential task speeds across background wavelength appear to be caused by two distinct contrast effects. At high purity, the task speed is a function of chromatic contrast, whereas at low purity the effect is more a function of the luminance difference between the black background and the targets which the observer is viewing.

Task performance is affected by the interaction between background purity and foreground wavelength (p = 0.0001). Significant differences were found at both high and low background purities; however, an examination of the means for the low purity background did not find the locus of the effect. When targets are displayed on high purity backgrounds, there are significant differences among all foreground wavelengths. The data show that a task speed ordering was blue, 0.37; magenta, 0.32; green, 0.33; and yellow, 0.31. These data are plotted in Figure 48.

Background wavelength interacts with foreground purity to significantly affect task speed (p = 0.0072). The analyses indicate that background wavelength acts to affect task speed at both levels of foreground purity. At high foreground purity task

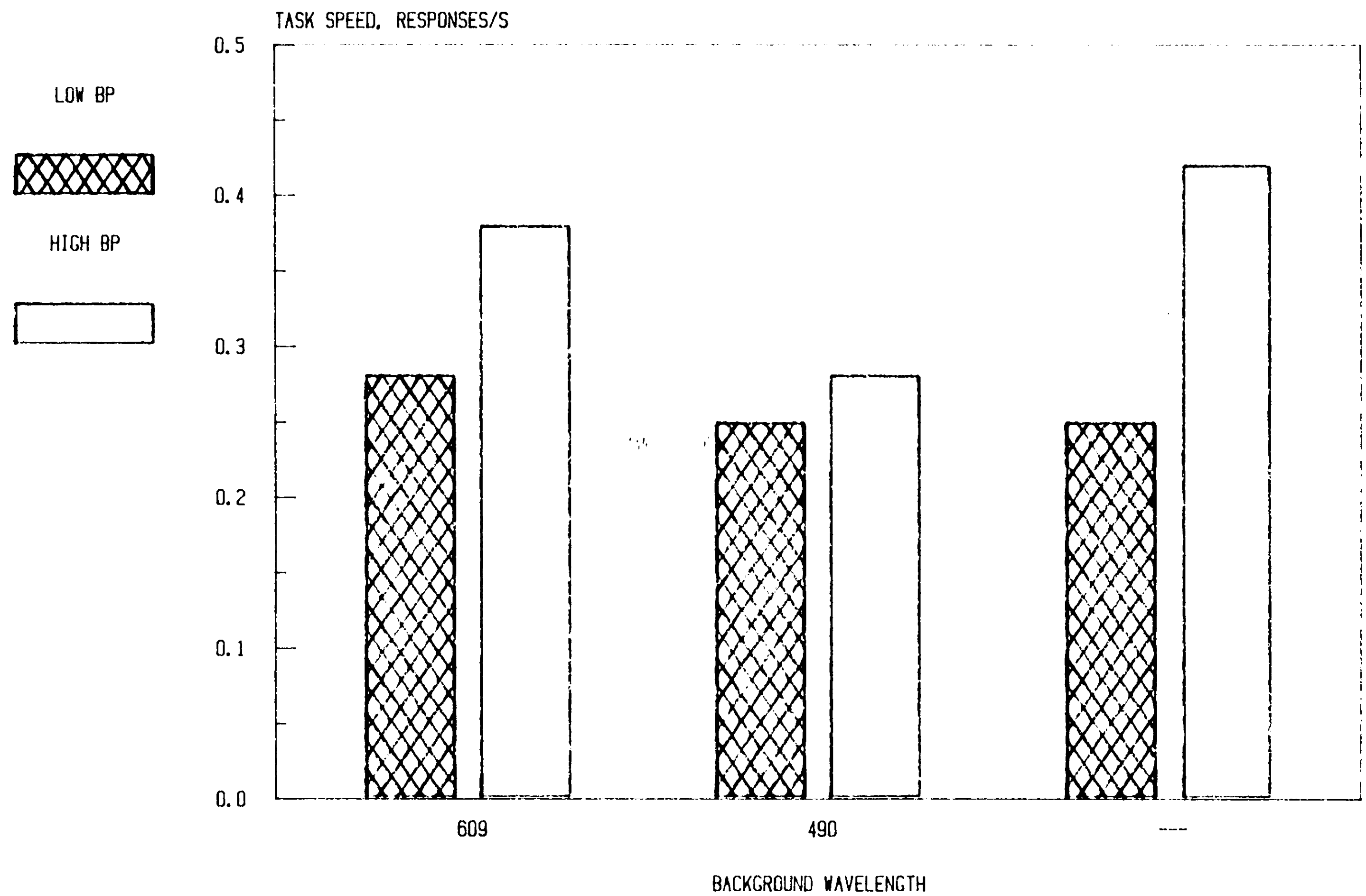

Figure 47. Experiment 2-BW X BP effect on task speed.

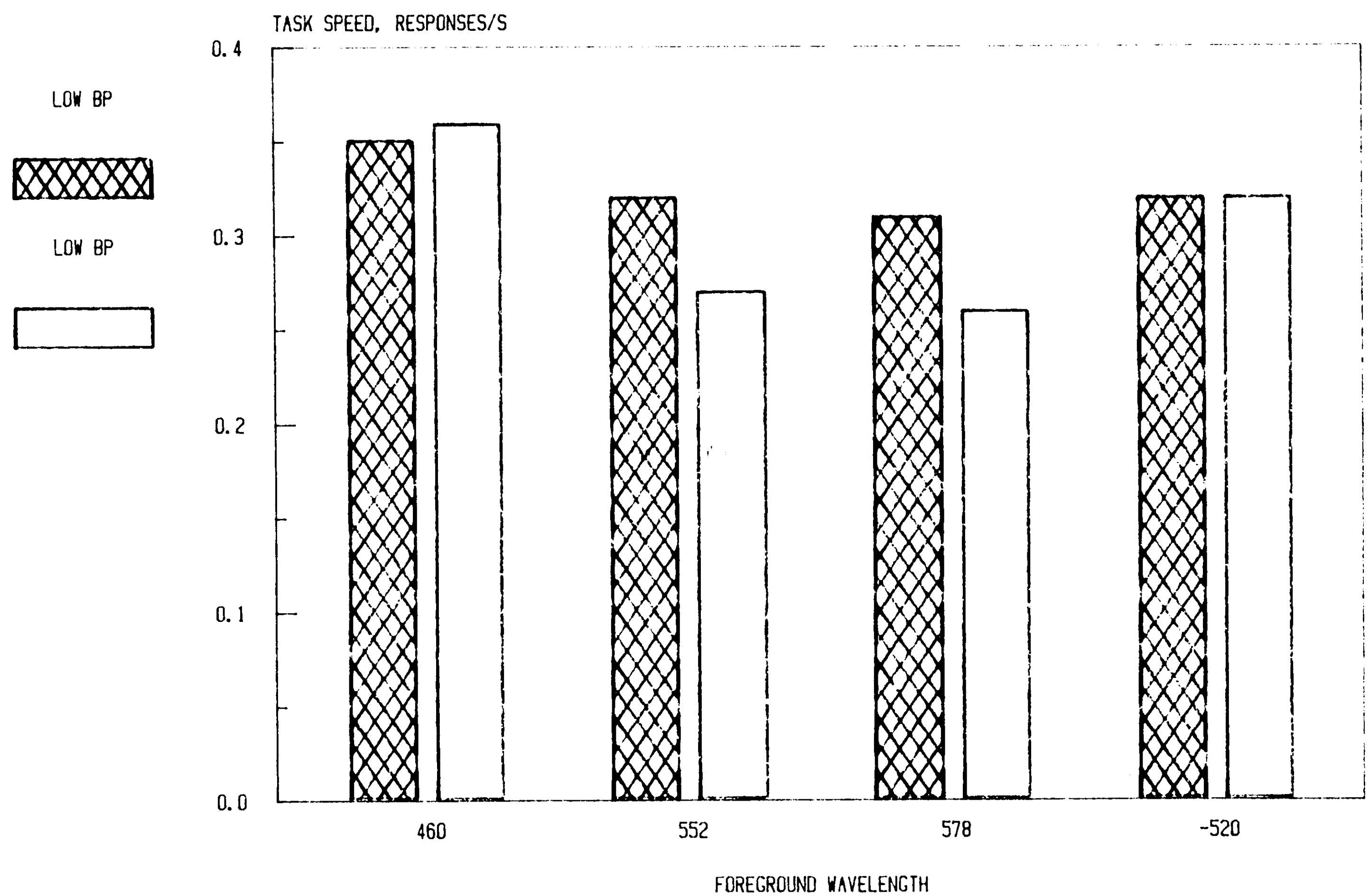

Figure 48. Experiment 2-BP X FW effect on task speed.

performance is significantly worse for cyan backgrounds (0.24) than is performance on red (0.34) or achromatic (0.36) backgrounds, which do not significantly differ. At low foreground purity similar results are obtained (Figure 49).

The last of the significant two-way interactions combines the effects of foreground wavelength and foreground purity ($p = 0.0002$) to affect task speed. No significant effects across foreground wavelength were found for low purity targets, but when high purity targets were observed, task performance for green and yellow targets resulted in significantly lower task times than for either magenta or blue characters. Task speed was significantly greater with magenta targets (0.34) and further improved with blue targets (0.42). Figure 50 illustrates FW X FP interaction. Task speed for high purity magenta targets is significantly different from that with high purity blue targets.

Consistent with the results of Lippert (1984), the analyses of the two-way interactions clearly demonstrate that color contrast plays an important role in determining task performance in a visual task where the targets differ only from the backgrounds in chrominance. The effect of chromatic contrast is not only evidenced by the effect of the differing foreground or background hues, but also in the demonstrated relationship of the purity of the foreground or background to the color combinations presented. The effect of luminance contrast on task speed was also demonstrated throughout the analyses of these two-way interactions.

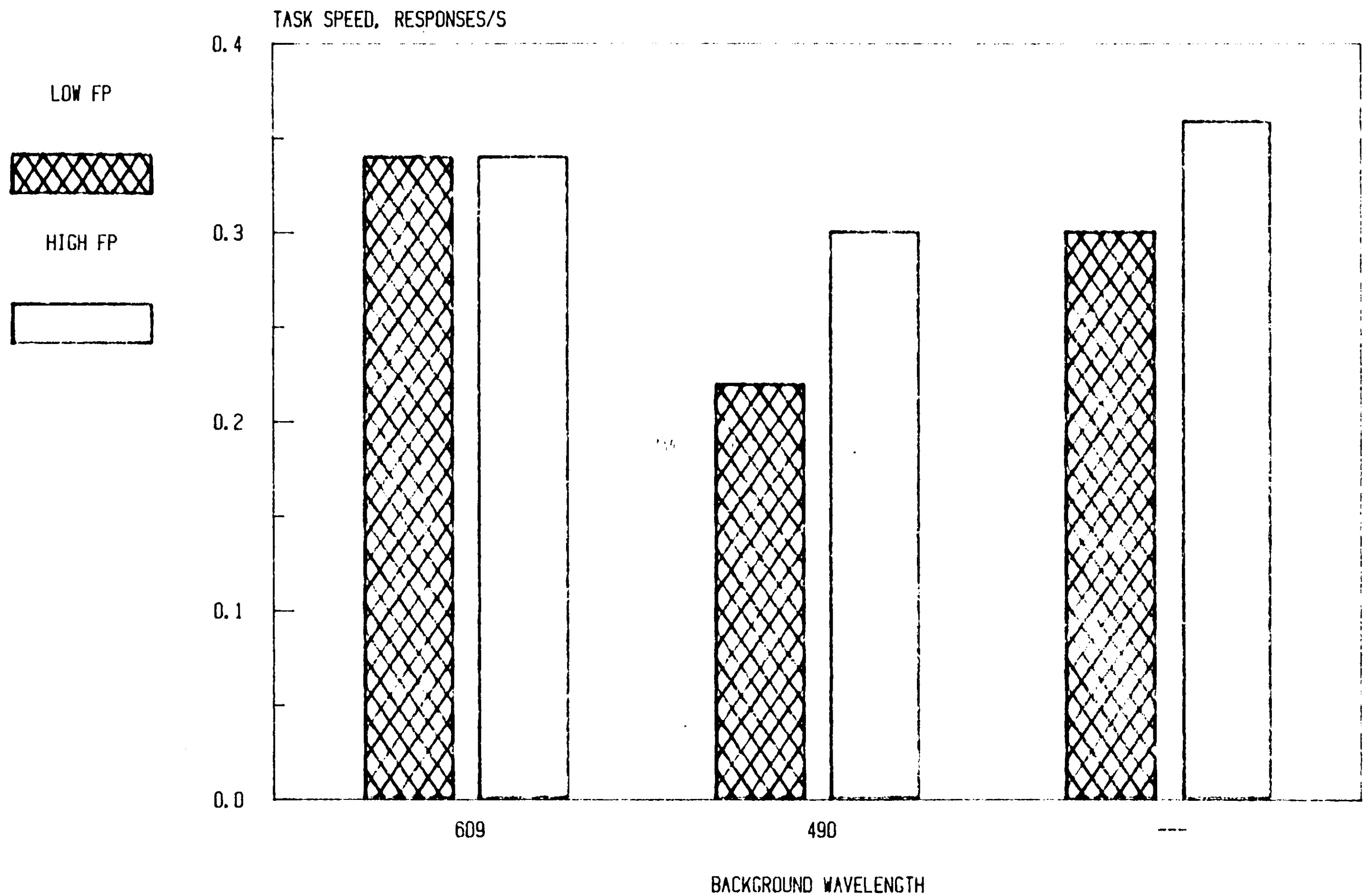

Figure 49. Experiment 2-BW X FP effect on task speed.

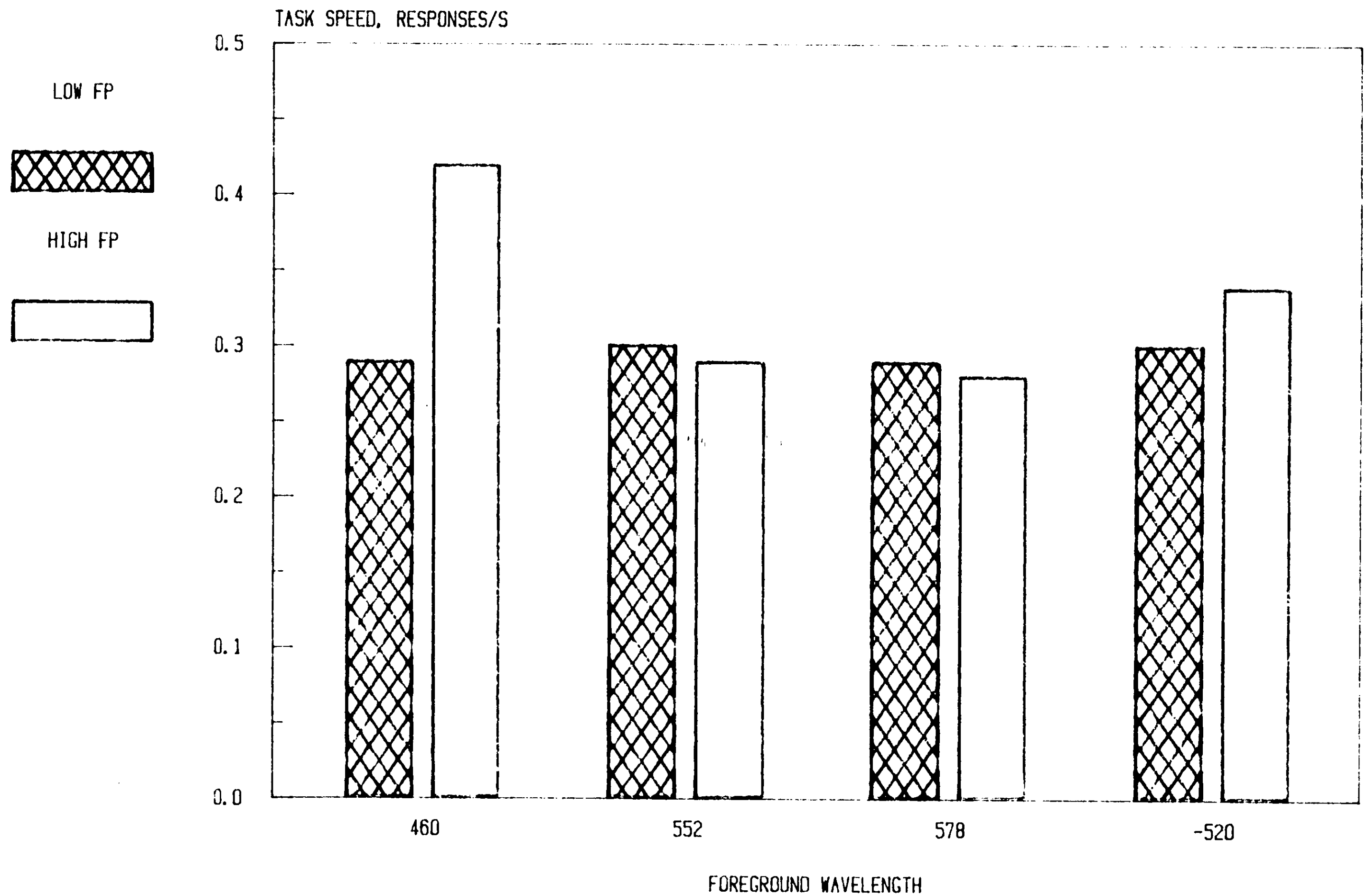

Figure 50. Experiment 2-FW X FP effect on task speed.

Several higher order effects resulted from the analysis of task speed in experiment two. Each significant three-way interaction will be discussed.

Background wavelength combined with foreground wavelength and background purity to produce an effect on task speed ($p = 0.0012$). Post hoc analyses of the BW X BP X FW interaction indicate significant results for each combination of background wavelength and foreground purity across foreground wavelength with the exception of the achromatic background at low purity. When the background is a high purity red, task performance is significantly lower for magenta targets than for yellow, green, or blue targets, which are not significantly different from each other. Performance with high purity cyan backgrounds was lowest for green foregrounds, yellow targets yielded significantly faster task speeds, and the best performance occurred with blue and magenta, which were not significantly different.

Task speed for white backgrounds was lowest with yellow characters, which was significantly different from the performance with magenta, green, or blue backgrounds. For low purity red backgrounds, magenta characters produced task speeds that were significantly slower than task speed attained with yellow targets, and this performance was not as good as that obtained with green or blue targets. Lastly, for low purity cyan backgrounds, green and yellow targets result in the poorest performance, blue characters resulted in significantly better performance, and magenta characters yielded the highest task speeds. These data are plotted in Figure 51.

Several effects may be inferred from the analyses. At high background purity, a pure color contrast effect emerges for each background wavelength against each foreground hue. At low purity, the effect of color contrast can be seen for the red or cyan backgrounds, but a different response occurs for the achromatic background that cannot be attributed to color contrast. The task speed for the low purity achromatic background is flat across all foreground wavelengths. This suggests some performance ceiling and can be most readily attributed to the luminance difference between the low luminance achromatic, black, background and the target field displayed. The contribution of luminance contrast to the performance of the task tended to conceal any effect color contrast may have had for these conditions. The BW X FW X FP interaction is plotted in Figure 52. For characters of high purity, a general color contrast effect obtains. The exception to this is the asymptotic performance resulting from observing a blue target across all backgrounds for the blue target, task speed for all background is 0.42.

Analyses show that mean performance is affected in the following manner: for red backgrounds, task speed is greatest with green and blue characters, significantly lower for yellow targets, and lowest for magenta targets; for cyan backgrounds, green characters result in the lowest levels of performance, yellow

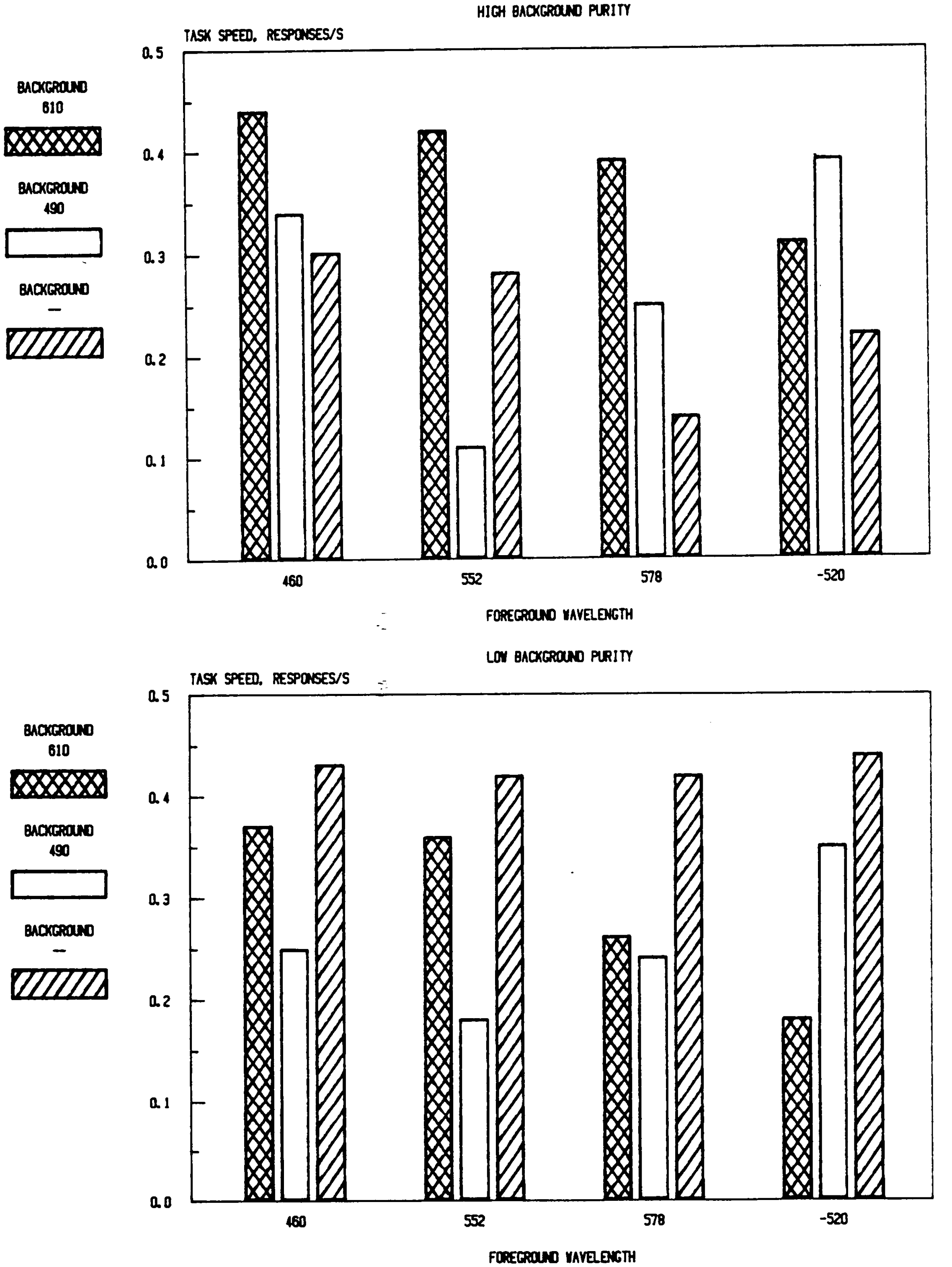

Figure 51. Experiment 2-BW X BP X FW effect on task speed.

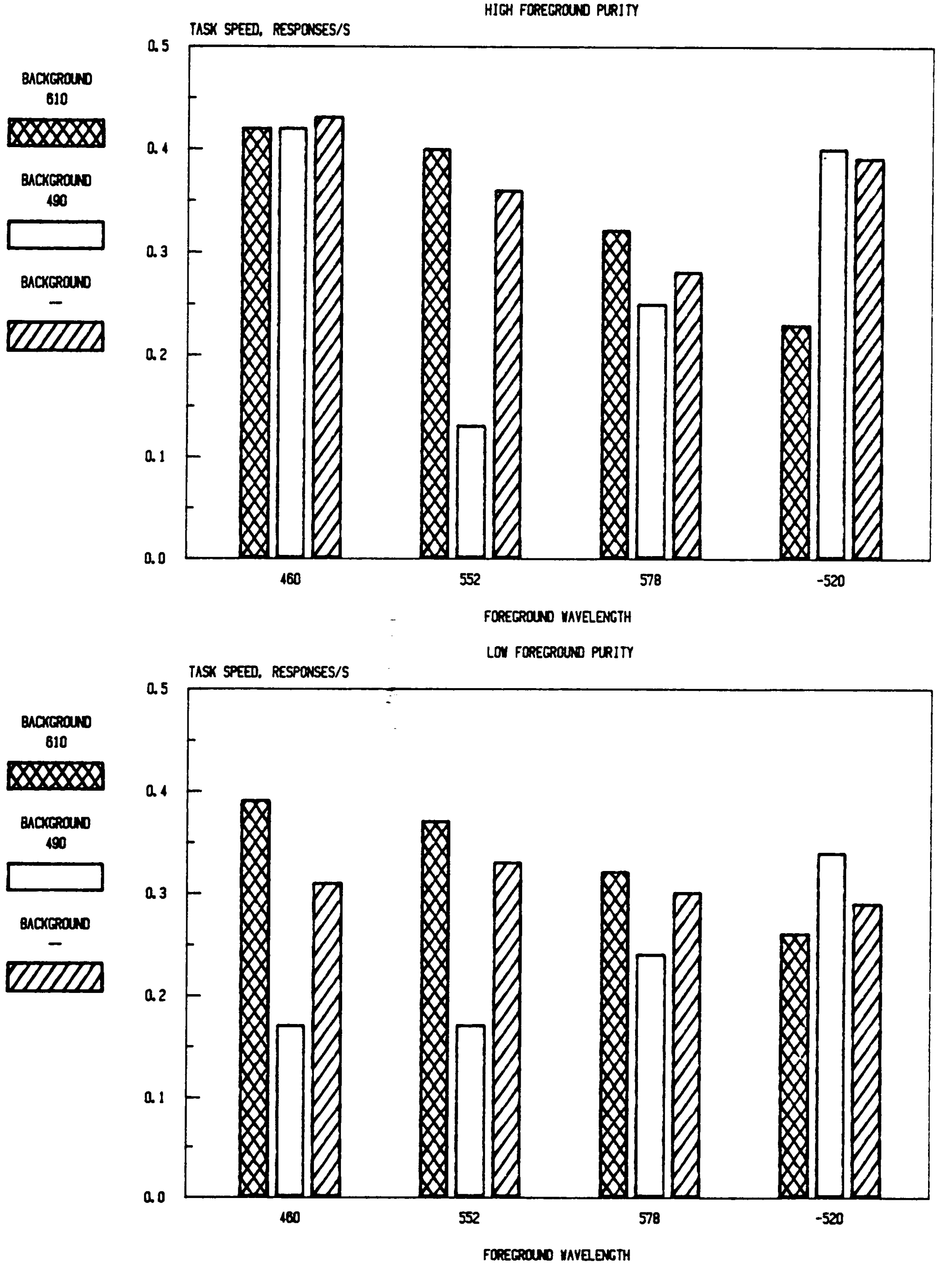

Figure 52. Experiment 2-BW X FW X FP effect on task speed.

characters result in significantly better performance, and the best performance results from blue targets presented on cyan backgrounds; for white backgrounds, yellow targets resulted in task speeds that were significantly lower than those obtained with all other foregrounds. All of these results indicate a role for chromatic contrast in affecting task performance.

At low purity, the effect of chromatic contrast on task speed appears to be less prominent than with high purity targets. The effect is evidenced with blue and cyan backgrounds, but is less pronounced with the achromatic targets. Results of the analyses indicate for that red backgrounds, yellow and magenta foregrounds result in the lowest task speeds and green and blue targets result in better performance, but it is not significantly better than performance with yellow targets. Low purity blue and green characters result in the lowest task speeds when the background is cyan, and better performance results with yellow and magenta targets which are not significantly different. No significant differences were found with low purity characters across foreground wavelength when the background is achromatic.

The final three-way interaction involves the effects of background wavelengths, background purity, and foreground purity on task speed. Figure 53 is a plot of the BW X BP X FP interaction. The plot illustrates the relation between foreground and background purity across background wavelength. At high background purity, the red background results in significantly better

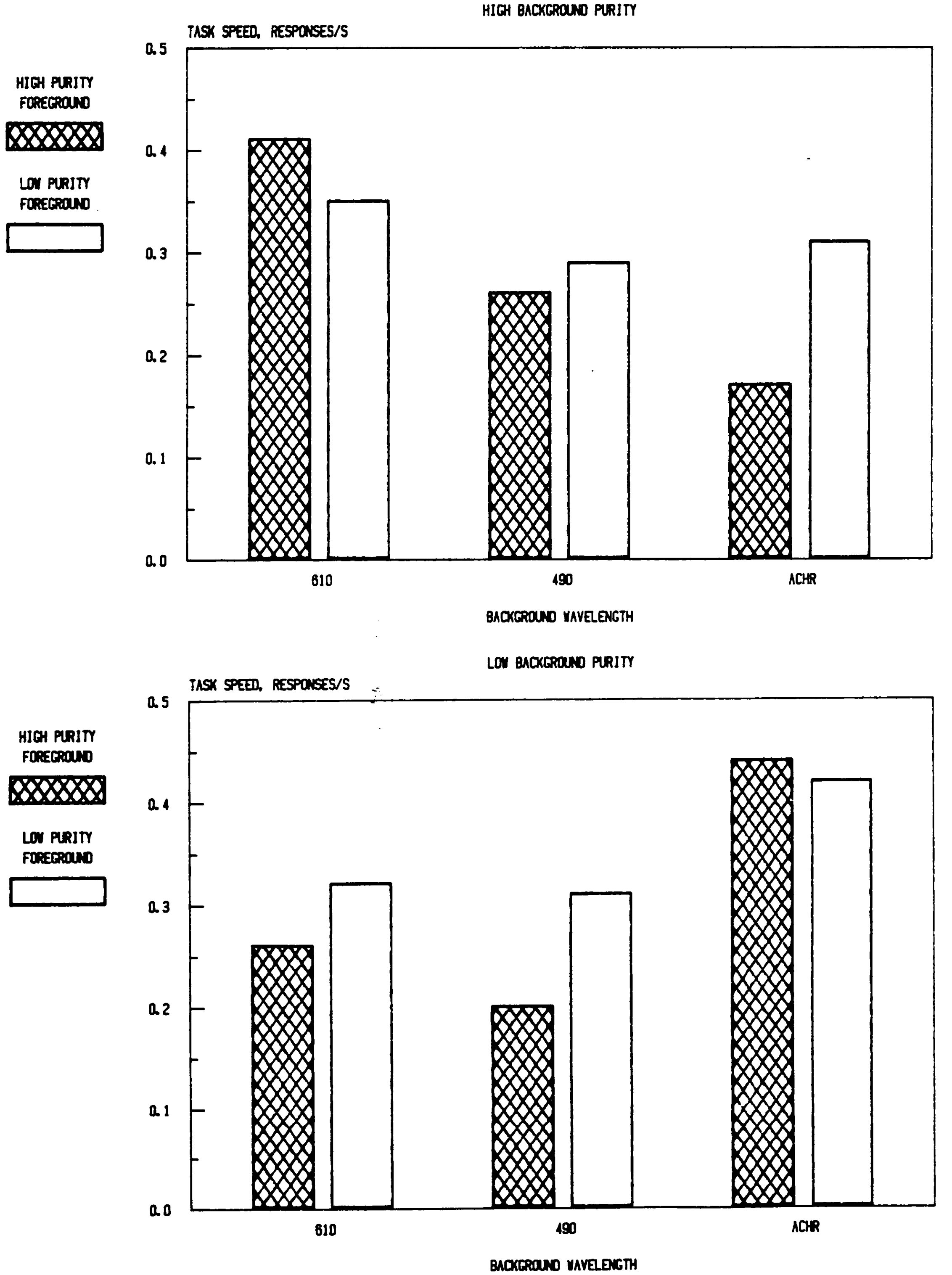

Figure 53. Experiment 2-BW X BP X FP effect on task speed.

performance at both high and low foreground purities. At high foreground purity there is no significant difference between the performance obtained with cyan or achromatic background, whereas with low purity characters, the achromatic background results in significantly poorer performance. The relatively poor performance resulting from displaying low purity targets on a white background can be explained in terms of the color contrast between the target and background. For backgrounds of low purity, the overwhelming effect is one of luminance contrast as indicated by the performance resulting from displaying targets of either purity on a black background.

At either foreground purity, the performance with the low purity achromatic background is significantly better than with backgrounds of other wavelengths. Lastly, when low purity characters are displayed on a low purity background, better performance results from red backgrounds than from cyan backgrounds.

In summary, each of the three-way interactions adds evidence to support the hypothesis that chromatic contrast can significantly affect performance in this type of visual task. Additionally, the plots of the BW X BP X FP and the BP X FW X FP interactions support the very important role that luminance contrast can play in a visual performance task where task speed is the measure of interest.

<u>Regression Analyses</u>

The analysis of variance demonstrated that the observer's accommodation, as indicated by the mean level of accommodation and the stability of accommodation, and performance in a visual task are both significantly affected by those parameters which combine to produce color contrast between the target and surround. However, the factorial combinations of background wavelength, foreground wavelength, background purity, and foreground purity provide little information about the quantity of color contrast inherent in the observed stimulus.

Fortunately, uniform color spaces have been developed to provide a unitary metric that can be used to describe the total contrast that is exhibited between a target and its background. These metrics consider the luminance and chrominance of the target and background separately and then calculate the Euclidian distance between the foreground and background to produce a measure of effective contrast. This calculated distance has been denoted the color difference between the two fields.

Two such uniform color spaces, the CIE $L^*u^*v^*$ (Wyszecki and Stiles, 1982) and Yu'v' (Lippert, 1984) will be used to qualify the effective color contrast between the target and background of the stimuli presented to the observers in this study. These quantities may be defined as follows:

$$DELUV = \left[(L^*_B - L^*_F)^2 + (u^*_B - u^*_F)^2 + (v^*_B - v^*_F)^2\right]^{0.5} \quad (2)$$

where:

L^* = the lightness of the background and foreground, respectively,

u^* = the transformation of the x coordinate of the CIE 1931 chromaticity diagram for the 1976 uniform color space,

and

v^* = the transformation of the y coordinate of the CIE 1931 chromaticity diagram for the 1976 uniform color space.

Development of the CIE $L^*u^*v^*$ uniform color space has been defined by Wyszecki and Stiles (1982).

$$Yu'v' = \left[(Y_B - Y_F)^2 + (u'_B - u'_F)^2 + (v'_B - v'_F)^2\right]^{0.5} \qquad (3)$$

where:

Y = the luminance of the displayed foreground or background,

u' = a transformation of the x coordinate for the 1931 CIE chromaticity diagram,

and

v' = a transformation of the y coordinate for the 1931 CIE chromaticity diagram.

The development of the Yu'v' uniform color space was described by Lippert (1984). Color differences as calculated by these two uniform color models will be used to quantify the amount of total contrast in each target background combinations.

In order to investigate further the relationship between the effective contrast and the accommodation and performance measures collected in this experiment, regression analyses were performed to determine the amount of variance that can be explained by the color space difference between the target and background.

There was also an interest in relating the observers' accommodation response to performance in a visual task. Regressions were performed to determine if a relationship between either of the two accommodation measures and task speed exists.

Means across all subjects were used as data for all regression analyses performed.

Accommodation Measures. Data from experiment one were used for all regression analyses involving the accommodation measures. A summary of the regression analyses performed to determine the least-squares best-fit linear relationship between several measures and the observers' mean accommodative response and the stability of the accommodation response is contained in Table 1.

Neither of the uniform color models provides a good empirical fit for the accommodation data collected in this experiment. The inability of either of the models to explain the variance in the data did not seem consonant with the analysis of variance, where many effects due to those parameters which affect color contrast were significant. A closer look at the ANOVA results suggested that the purity of the background or foreground might be instrumental in driving accommodation. No relationship of this type

TABLE 1

REGRESSION SUMMARY - ACCOMMODATION MEASURES

Model	R2	p
AD = 0.0414 + 0.0007 DELUV	0.0540	0.0324
AD = 0.0575 + 0.0040 YUV	0.0022	0.6721
AD = 0.02831 + 0.869 PURITY	0.0283	0.0750
AD = 0.0325 + 0.1341 BLUE	0.5779	0.0041
SD = 0.1301 + 0.0008 DELUV	0.2064	0.0583
SD = 0.1389 + 0.0013 YUV	0.0992	0.0033
SD = 0.1494 + 0.0312 PURITY	0.1400	0.2310
SD = 0.1409 + 0.0817 BLUE	0.8023	0.0001

was obtained either, but a further inspection of the results suggested that the amount of blue in the background could be influencing the observer's accommodation response.

To investigate this effect, the blue content of the background as indicated by the proportion of the z chromaticity coordinate was regressed to determine if a relationship between the accommodation response and the blueness of the background existed. Results of the regression analyses indicate that when the response is averaged over foreground wavelength approximately 58% of the variance associated with the observers' mean accommodation level can be explained and over 80% of the variance in the stability of the observers' accommodation can be explained with this one variable.

No relationship was found in regression analyses that attempted to relate the accommodation measures to task speed in the performance task (Table 2).

Task Speed. The analysis of variance demonstrated a very consistent and very strong effect of color contrast on the subjects' task speed. Independent regression analyses were run for the data collected in the two experiments to explore the relationship between task speed and the effective color contrast of the stimulus. Table 3 summarizes these analyses. The empirical fit of the data to the CIE $L^*u^*v^*$ and the Yu'v' color models indicates that much of the variance in performance over the target background combinations could be explained by varying amounts of color contrast in the stimulus. The linear model utilizing the

TABLE 2

REGRESSION SUMMARY TASK SPEED vs ACCOMMODATION

Exp.	Model	R2	p
2	TS = 0.3577 + 0.0577 AD	0.0479	0.0322
2	TS = 0.3612 - 0.2050 SD	0.0742	0.1316
2	TS = 0.3140 + 0.0094 BLU	0.0035	0.8544

TABLE 3

REGRESSION SUMMARY - TASK SPEED vs COLOR DISTANCE

Exp.	Model	R2	p
1	TS = 0.1865 + 0.0048 DELUV	0.5014	0.0001
1	TS = 0.0411 + 0.0158 DELUV - 0.0002 DELUV2	0.6591	0.0001
2	TS = 0.145 + 0.0064 DELUV	0.6290	0.0001
2	TS = 0.0035 + 0.0176 DELUV - 0.0002 DELUV2	0.7658	0.0001
1	TS = 0.1120 + 0.0085 DELUV; (DELUV < 40)	0.5866	0.0001
2	TS = 0.1164 0.0185 DELUV; (DELUV < 40)	0.7139	0.0001
1	TS = 0.2330 + 0.0143 YUV	0.2693	0.0001
2	TS = 0.2023 + 0.0191 YUV(40)	0.3435	0.0001
1	TS = 0.1831 + 0.1414 YUV(5.3)	0.5499	0.0001
1	TS = 0.0474 + 0.4552 YUV(5.3) - 0.1404 YUV2(5.3)	0.6819	0.0001
2	TS = 0.1499 + 0.1739 YUV(5.3)	0.6691	0.0001
2	TS = 0.0120 + 0.5018 YUV(5.3) - 0.1169 YUV2(5.3)	0.7890	0.0001

TABLE 3

REGRESSION SUMMARY - TASK SPEED (CONTINUED)

Exp.	Model	R2	p
1	TS = 0.1467 + 0.1927 YUV(5.3)		
	(YUV(5.3) < 1.6)	0.6064	0.0001
1	TS = 0.0272 + 0.5104		
	YUV(5.3) - 0.1702 YUV2(5.3)	0.6575	0.0001
2	TS = 0.1199 + 0.2294 YUV(5.3)	0.7223	0.0001
	(YUV(5.3) < 1.6)		
2	TS = 0.0044 + 0.57720		
	YUV(5.3) - 0.1891 YUV2(5.3)	0.7714	0.0001
	(YUV(5.3) < 1.6)		

CIE $L^*u^*v^*$ uniform color space resulted in an $R^2 = 0.5014$ for experiment one and $R^2 = 0.6290$ for experiment two. Utilizing Lippert's Yu'v' modeling with the 40 weighting he found to be optimal for reading numeral strings, an R^2 of 0.2693 and 0.3435 was obtained for experiment one and two, respectively. Lippert (1984b) suggested that weighting of the Yu'v' color difference metric may be dependent upon the task being performed. Therefore, the model weightings were optimized for the matching task performed in this study and the regression analyses were performed a second time. Results of the Yu'v' with an optimal weighting of 5.3 were an R^2 = 0.5499 for experiment one and $R^2 = 0.6691$ for experiment two. The reduction in the explained variance for experiment one may be due to the confounding of task with target/background combination and the expanded range of stimuli.

The data from both experiments were plotted and a strong second order effect was suggested (Figures 54, 55, 56 and 57). Regression analyses were performed to determine if a quadratic equation would provide a better empirical fit for the data. Results of second order regression modeling, as indicated in Table 3, indicated R^2 of 0.6591 and 0.7658 for experiments one and two, respectively, using the CIE $L^*u^*v^*$ uniform color model, and 0.6819 and 0.7890 for experiments one and two using Yu'v'.

Plots of the second order regression equations (Figures 54, 55, 56 and 57) suggested that color contrast was important in determining the task performance only for a portion of the range of

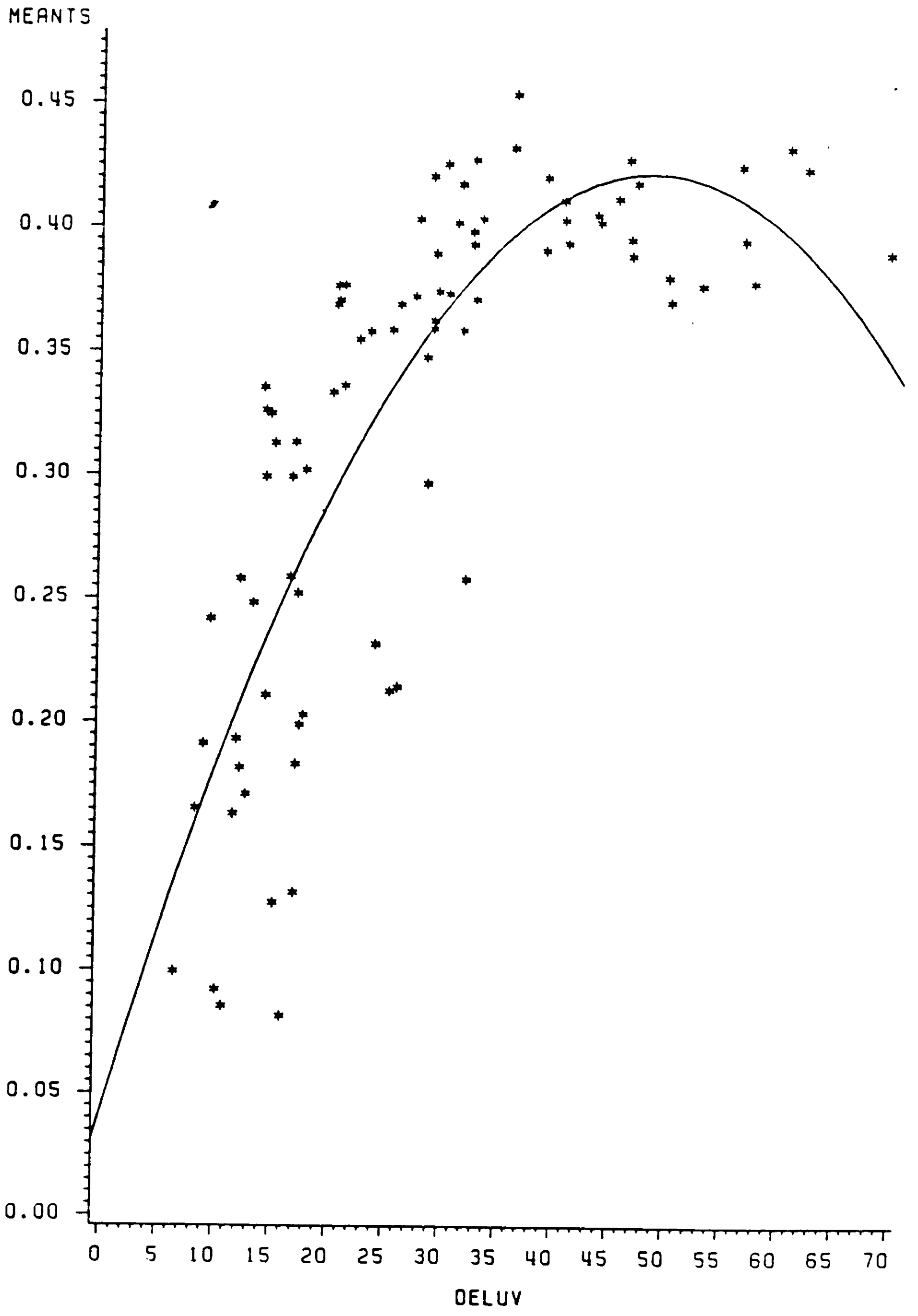

Figure 54. Experiment 1-TS-vs-color difference CIE $L^*u^*v^*$.

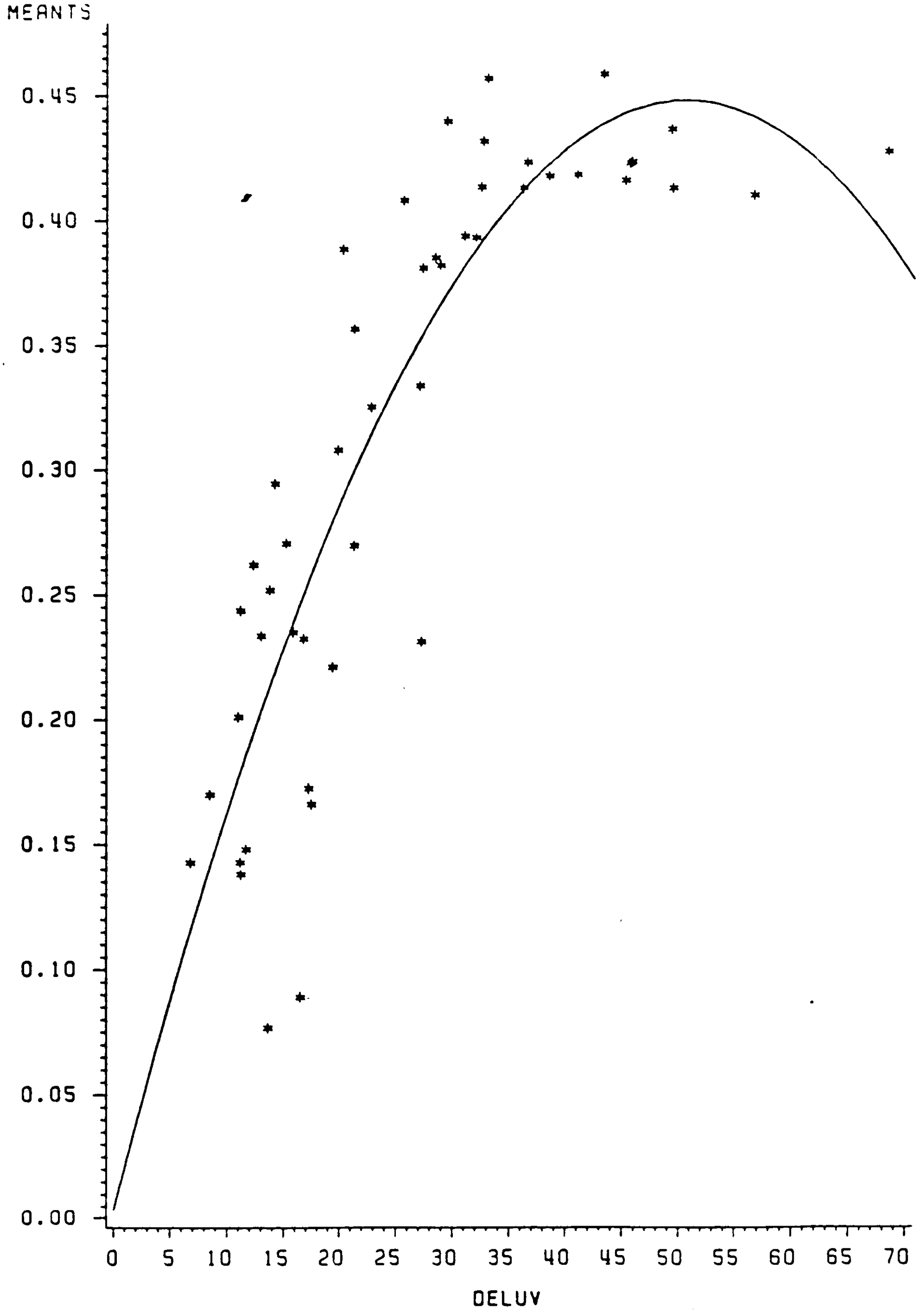

Figure 55. Experiment 2-TS-vs-color difference CIE $L^*u^*v^*$.

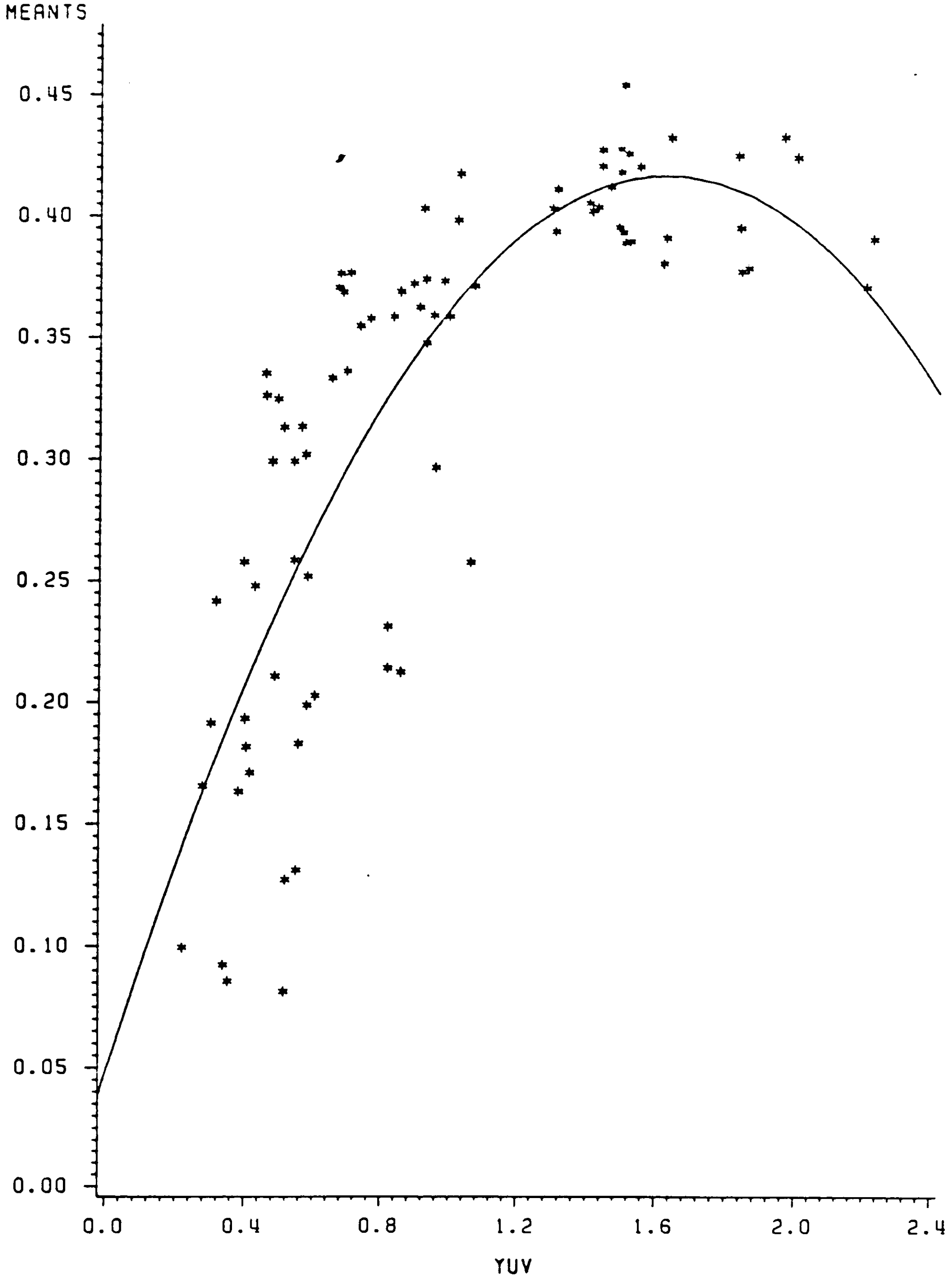

Figure 56. Experiment 1-TS-vs-color difference Yu'v'.

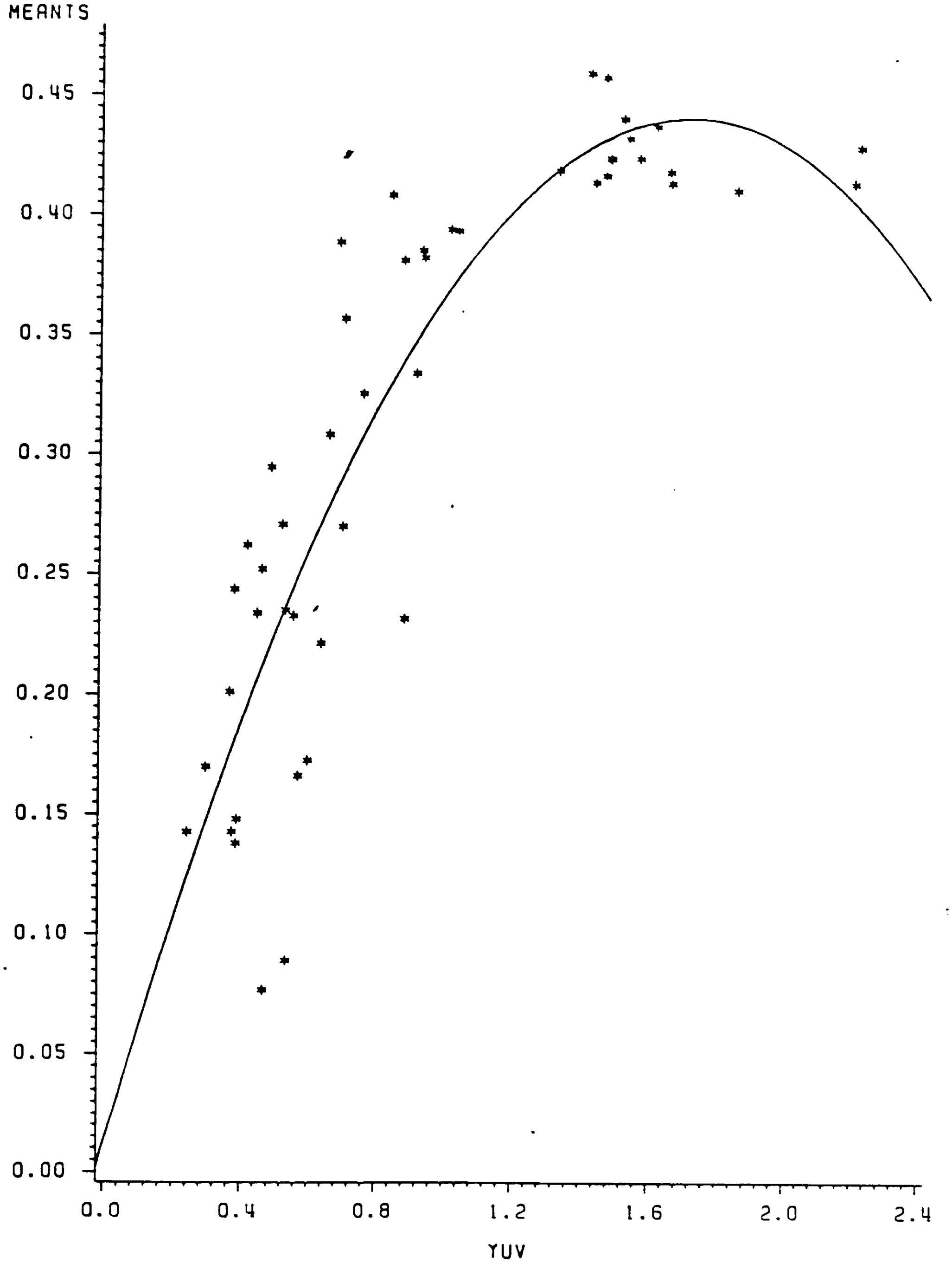

Figure 57. Experiment 2-TS-vs-color difference Yu'v'.

contrasts investigated in the study, after which task performance did not improve with increasing effective color contrast between the target and the surround. Regression analyses were run to determine where this ceiling effect takes place. This point was selected as the place where the second order function no longer significantly added to the explained variance.

The ceiling effect was not the same for the two color models used to determine effective color contrast. Color contrast as calculated by the CIE $L^*u^*v^*$ exhibited the ceiling effect at approximately a color difference of 40 units. Using only the conditions for which the color difference is less than 40 units, the explained variance for the linear model was equal to 0.5866 for experiment one and 0.7139 for the second experiment. No significant improvement resulted from adding another predictor to the regression equation. Improvement in the linear regression for the Yu'v' color model occurred until Yu'v' equaled about 1.6 units. The R^2 for the linear model in this case was 0.6064 and 0.7223 for experiments one and two, respectively. The second order effects never quite disappeared in the Yu'v' model, and the second order model accounted for 65.75% of the variance of experiment one and 77.14% of the variance in experiment two.

DISCUSSION

The experiments in this research were designed to investigate the observers' continuous accommodation response to characters presented on a multicolor CRT and further to relate the accommodation response to task performance. A secondary goal of the research was to determine if color contrast, as quantified by color difference modeling, is related to the observers' performance in a visual task.

The data that were collected suggest that there is little doubt that the chromaticities of the target, background, or target/background combination significantly affect the observers' mean accommodation response. Results of the analysis of variance indicate that higher purity colors presented on the multicolor CRT on either the background or foreground result in higher accommodation amplitude. Also, the high purity blue background results in a greater accommodation response from the observer. However, no uniform results across all target/background combinations emerged that would aid in the prediction of the observers' accommodation response given a particular combination. The results of experiment one indicate that the observers' accommodation response to targets that vary from their backgrounds only in terms of chromaticity, purity, or chromaticity and purity is a much more complex phenomenon than can be explained by the simple parameters controlled in this study. Support for the complexity of the mechanisms involved in the accommodation response under conditions of color contrast is demonstrated by the lack of an identifying relationship between the chromaticity coordinates of the target and background and the mean accommodation response (R^2 = 0.17). The inability to reject the null hypothesis for any of the independent factors in experiment adds to the ambiguity concerning the stimulus for accommodation when only chromatic contrast exists between the target and surround.

Perhaps the inability to determine how color acts to drive the accommodation system when viewing characters presented on a multicolor CRT results from the range of refraction required of the observers to perform the tasks in the experiments. Mean accommodation levels required of the observer's ranged from -0.21 D to 0.42 D. The 0.63 D range of accommodation required of the observers in this study is small when compared to the 10 diopter range of most young observers. This suggests that the multicolor CRT does not provide a strong stimulus for accommodation. Bedford and Wyszecki (1957) reported a 1.25 diopter change in accommodation response over the range of dominant wavelengths used as stimuli in this study. The nature of the differences in the stimuli may be responsible for the disparity in the amplitude of change when compared to the Bedford and Wyszecki data. The stimuli generated by the phosphors in the multicolor CRT are relatively wideband when compared to monochromatic stimuli. As a result, the human visual system will respond to the radiant energy across a wider band rather than the narrower band inherent in the monochromatic illuminants used in the earlier studies. The effect of the response over a broader band is an attenuation in the amplitude of the response at either end of the spectrum. There is, however, good agreement in the direction of accommodation between the studies; that is, observers were myopic to light of less than 578 nm dominant wavelength when viewed against a black background, and hyperopic to light greater than 578 nm dominant wavelength viewed under similar conditions.

The accommodation response data in the present study are consistent with the findings of Murch (1982) for those conditions where chromatic targets were observed on black backgrounds for both the direction and amplitude of change. Murch displayed a field of Xs on a multicolor CRT with a black background. These results are interesting because the construction of the stimuli and the data collection apparatus in the two experiments differed. These data, therefore, suggest that the results obtained using either the infrared optometer, as was the case in this study, or the laser optometer, as in the Murch study, will be similar.

A major difference in the present study and earlier research is that chromatic targets were not only observed against black backgrounds, but the observer was required to view chromatic characters on chromatic backgrounds. In these cases, the foreground and background only differed in wavelength and purity. There was no luminance modulation between the target and surround. The result of viewing targets under conditions where there is no luminance contrast is that rather than obtaining positive and negative refraction around stimuli with dominant wavelength 578 nm, most target/background combinations were focused in front of the image plane. These data are not explained in terms of the effects of chromatic aberration when the fixation point is displayed on a black field. The implication is that when there is no luminance contrast between the target and the surround, the effect of chromatic aberration on the refraction of the eye is to drive the visual system to a positive accommodation.

Among the independent variables, no one factor or combination of factors seems to affect uniformly the observers' accommodation level. However, it was noticed that target combinations with the high purity blue background consistently resulted in high accommodation amplitudes when compared to the other target/background combinations. Regression analysis confirmed a relationship between the amount of blue, as quantified by the z chromaticity coordinate, and the amplitude of the accommodation response (R^2 = 0.58). Since most of the target/background combinations resulted in positive accommodation values, it is suspected that blue may be acting as an anchor in some contrast mechanism. As the amount of blue becomes greater, there is a push away from the negative accommodation response to light of shorter wavelengths resulting in more positive accommodation as the background becomes more blue.

A major purpose of this study was to determine if there is a relationship between the amount of color contrast in the target/background combination and the amplitude of the mean accommodation response. No such relationship was demonstrated in this research. The observers' mean accommodation response was regressed against the amount of color contrast, as quantified using color difference modeling, to determine the strength of the relationship between the two variables. As reported, less than 7% of the variance in mean accommodation could be explained by the color difference between the target and the background.

The practical significance of the change in the accommodation amplitude as a result of observing characters of different colors on backgrounds of different colors lies in the relationship of the magnitude of the change to the observer's depth of field. If the change in the amplitude of the observer's refraction exceeds her depth of field, then refocusing is indicated; however, if the change is within the depth of field, no refocusing should be required to maintain proper focus on the target/background combination. Using the +/- 0.18 D depth of field for a 5 nm pupil and the 0.63 D range of refraction demonstrated in the study, it is obvious that some refocusing is required to maintain sharp focus. The data suggest that the target/background combinations with high purity blue backgrounds and a large color difference between the target and background should be avoided if it is desirable to provide stimuli that do not require refocusing. Additionally, the blue target on a black background requires refocusing relative to the achromatic target/background condition. All other combinations of foreground and background are within the nominal depth of field used in the study and do not indicate a requirement for refocusing.

The standard deviation of the observers' accommodation response was calculated as a measure of the variance in accommodation. High values indicate that there is more variability about the mean accommodation response than lower values. In this manner, the stability of the accommodation response, how tightly the observer can maintain steady state focus on the target/background combination, was assessed. It was hypothesized that lower variability in the accommodation response would indicate that the target/background combination provided a better stimulus for accommodation.

The purity of the foreground or background consistently affected the stability of the accommodation response. Normally, the low purity target or background resulted in lower variability in the mean accommodation response. Analysis of the interactions between foreground purity and background purity indicated that those target/background combinations with low purity in the target and background resulted in lower variability in the mean accommodation response. That is, better stability resulted from low contrast target conditions. These results are not consistent with the above hypothesis. The implication is that the stability measure did not act as an indicator of image quality, as might have been expected from the work of Bour (1981), but rather acted as measure of accommodative effort. This inference was supported by unsolicited comments from observers who spoke of the difficulty of obtaining and maintaining focus on the low contrast targets.

Inspection of the results of the analysis of variance again showed that the observer's response to targets on high purity blue backgrounds was greater than that of other target/background combinations. Regression analysis demonstrated a strong relationship between the blue content in the background of the stimuli and the variability in the accommodation response. Using the z chromaticity coordinate as the only predictor, an R^2 of 0.80 was obtained. These data were not consistent with the hypotheses offered at the beginning of this study.

Owens (1980) indicated that the mechanisms that are responsible for visual contrast resolution are instrumental in the control of the accommodation system. His hypothesis is supported by much of the research that has explored how the variables which affect the contrast of a target, the target luminance, spatial frequency, and contrast, also affect the accuracy of the accommodation system. Each of these studies has found that as the luminous contrast of the target relative to the surround is reduced, the ability of the observer to obtain focus accurately and maintain focus on an object or an image is degraded. Bour (1981) demonstrated that the stability of the accommodation response is related to the luminance modulation of the observed image. In an effort to determine if a similar result is obtained when there is chrominance contrast but no luminance contrast, the standard deviation of the mean accommodation response was correlated with the color distance between the target and background as quantified by the two uniform color models used in the study. Intuitively, it was thought that if there is large contrast between the target and surround, the variability of accommodation should be small indicating a good stimulus for accommodation. The regression analyses performed did not support a relationship between color contrast and variability in the accommodation response.

Two reasons may be given for the lack of a relationship between the stability measure and the color contrast in the target/background condition. The first is that there was not a lot of variability in the stability of accommodation from stimulus condition to stimulus condition; thus, the uniformity of accommodation across all of the conditions tends negate any proportional relationship between image quality and the stability of accommodation. Secondly, the disruption in accommodation due to the high purity blue background provided several high contrast target/surround conditions where the variability in the accommodation was very high. Together, these two factors make the target's effective contrast a very poor predictor of accommodation stability when viewing chromatic targets on chromatic backgrounds.

The magnitude of the variability of the accommodation to the targets presented in this study is on the same order that has been previously reported (Alpern, 1960; and Bour. 1981). The range of variability was from 0.15 D to 0.35 D. However, these results do not agree with the latest study of accommodation stability which used an optometer and data collection technique very similar to the one used here. Rupp, McVey, and Taylor (1984) report r.m.s deviation in the mean accommodation response of approximately 0.1 D. These results were obtained with observers focusing on targets with luminous contrast and are not too different from the results obtained here when chromatic targets were observed on black backgrounds.

The stability data point out an important role for luminance contrast when attempting to obtain accurate focus on an image displayed on a CRT. These data support the statement of Wolfe and Owens (1981), who said that luminous modulation is not only a sufficient stimulus for accommodation, but is a necessary condition, if it were not for the fact that the observers in this study did obtain and maintain focus on isoluminant stimuli.

What then is the stimulus for accommodation where there is chrominance contrast but no luminous contrast? Since the regression analysis demonstrated that no relationship exists between color contrast and either of the accommodation measures, perhaps the stimulus is not a function of color or luminance, but a function of the brightness of the target/background combination. While the foreground and background were isoluminant, there were brightness differences among the stimulus combinations. These differences were most noticeable where the stimulus contained a high purity background. Thus, it is proposed that in the absence of luminous contrast, the accommodation may be driven by brightness contrast, the psychophysical correlate to luminance contrast.

No relationships were found between either of the accommodation measures and visual task performance. While it was found that color contrast between the target and surround significantly affected task speed and that the color difference calculated with either of the uniform color spaces was highly correlated to task performance, these effects were not demonstrated to be related to an observer's accommodative state. Without a link to the stimulus for accommodation, that component of the scene which causes the eye's refraction to change so that focus can be obtained and maintained, we do not know why the subjects performed better on some target/background combinations than others. It is a certainty that luminance contrast played no role in determining whether a target/background combination resulted in good task performance except in those trials where luminance contrast was available as a stimulus. In those trials where luminance contrast existed, performance was uniformly good. However, high color difference with no luminance contrast resulted in similarly good performance levels. Although no link between accommodation and task performance was found, the relationship between color difference and task performance infer that an appropriate stimulus for accommodation was provided even in the absence of luminance contrast.

A related result from the analyses of task speed involved the relationship between the color difference as calculated from the CIE $L^*u^*v^*$ uniform color space or the Yu'v' uniform color space. Previous work (Lippert, 1984; Post, 1983) had attempted to find a relationship between task performance in a numeral string reading task and color difference as modeled by the CIE $L^*u^*v^*$ color model. Their findings concluded that, although some of the variance in reading speed could be explained by the color difference between the target and background, most of the variance was explained by the task variable, that is, the number of digits to be read. Lipppert's Yu'v' model of color difference performed better than the CIE $L^*u^*v^*$ model, but major portions of the variance in reading speed were still explained by the task variable. In contrast, the analyses in this research show no significant effects due to the number of matched digits in the task and that color differences play a major role in determining task speed. The results are most likely resultant of the isoluminant nature of the stimuli presented and the particular task being performed. Both linear and quadratic models involving color difference, calculated using either method, explained major portions of the variance in task speed. The second order effect suggests a ceiling effect beyond which more color contrast, as indicated by color difference, would no longer effect an improvement in performance. These values were found to be a distance of 40 units for the CIE $L^*u^*v^*$ model and 1.6 units for the Yu'v' model.

Both models performed well in predicting task speed under the isoluminant conditions in the study. While the CIE $L^*u^*v^*$ did not perform as well as the optimized Yu'v' model, its origin is more widely known and can be more generally applied to performance modeling. The usefulness of the Yu'v' appears to be linked to the appropriate weighting of the u' and v' and the weightings seem to be particularly specific to the task and the conditions of the environment being modeled. To be widely used, a foundation must be built upon which the weightings can be based, such that the models derived from the Yu'v' color space can be used for predictive work in a design environment.

SUMMARY

In this study, the background wavelength, background purity, foreground wavelength, and foreground purity of stimuli presented on a multicolor CRT were manipulated to determine the effect of simultaneously viewing targets of one chromaticity against backgrounds of another chromaticity on an observer's accommodation response. A link between the observer's accommodation response and task performance was also sought.

The data collected in this study suggest that the target and background chromaticities do not combine in any simple way such that the observer's refraction, given a target/background combination, can be predicted. The analysis of variance showed that stimuli created with the high purity blue backgrounds resulted in accommodation amplitudes that were greater than the accommodation to all other combinations of targets and backgrounds. A high correlation between the accommodation response and the blueness in the background support this result. No other uniform results were found and no relationship between the accommodation amplitude and the amount of color contrast in the target was supported by the data collected in the experiments. The amplitude of the response to the stimuli presented in this research does not indicate major problems with respect to refocusing requirements.

The stability of the accommodation response was found not to be related to the amount of color contrast in the target/background combination. Thus, color contrast as a measure of the image quality

can not be used to predict the appropriateness of the target/background combination as a stimulus for accommodation. As with the mean accommodation response, the amount of blueness in the background of the stimulus was highly correlated with the stability measure.

It was proposed that rather than the color, luminance contrast, or color contrast between the target and surround driving accommodation under isoluminant conditions, the stimulus for the accommodation response might be the brightness difference between the target and the background. The suggestion is that the accommodation system is using the psychophysical correlate of the luminance contrast in its absence.

Neither of the accommodation measures correlated well with performance in the visual task presented in the experiments.

Color difference modeling provided an excellent empirical fit for the task performance data collected in this research. Performance improvement is directly related to the color difference between the target and the background, but for only a portion of the combinations tested, after which no performance gains are realized with increasing color contrast. That is, the increase in task speed with color difference becomes asymptotic, as might be expected.

The research described in this dissertation indicates that visual accommodation to characters displayed on a multicolor CRT can impose situations which would require an observer to refocus. However, the requirement to refocus is not large and was found to exist only for those foreground/background combinations that included a high purity blue background. The data suggest accommodation amplitudes and variability to characters displayed on high purity blue backgrounds are high when compared with other target/background combinations and that a high purity blue should be avoided as a background in the design of display screens if at all possible. It is also indicated that foreground/background combinations can be selected that will provide for optimal performance and not require the observer to refocus.

The data reported here in no way exhaustively describe the observer's accommodation response under conditions of color contrast. Suggestions for future research would include placement of the display at the observers' dark focus to remove any errors in refraction due to over or under accommodation about the dark focus, and the measurement of the observers' empty field response at each wavelength and purity so that a better idea of the contrast effects under conditions of isoluminance can be gained. Also, one might brightness match the stimuli and then replicate this study to determine if brightness was being used as a stimulus for accommodation by the observers in this study.

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APPENDIX A

STIMULUS CHROMATICITIES

TABLE A-1

CHROMATICITIES - EXPERIMENT 1

Wavelength (nm)	Purity	Luminance (cd/m2)	X	Y
464	0.93	1.5015	0.1483	0.0735
455	0.43	1.3889	0.2479	0.2058
491	0.35	1.4447	0.2346	0.3435
489	0.13	1.4111	0.2850	0.3352
550	0.67	1.5068	0.3188	0.5839
555	0.36	1.4424	0.3383	0.5839
576	0.74	1.4611	0.4642	0.4638
581	0.42	1.4085	0.4126	0.4195
610	0.85	1.5388	0.6040	0.3405
610	0.46	1.4815	0.4817	0.3462
-525	0.61	1.4811	0.3846	0.2114
-514	0.32	1.4070	0.3667	0.2687
Achromatic	White	1.4099	0.3639	0.3412
Achromatic	Black	0.0000	0.3639	0.3412

CHROMATICITY PLOT EXPERIMENT I

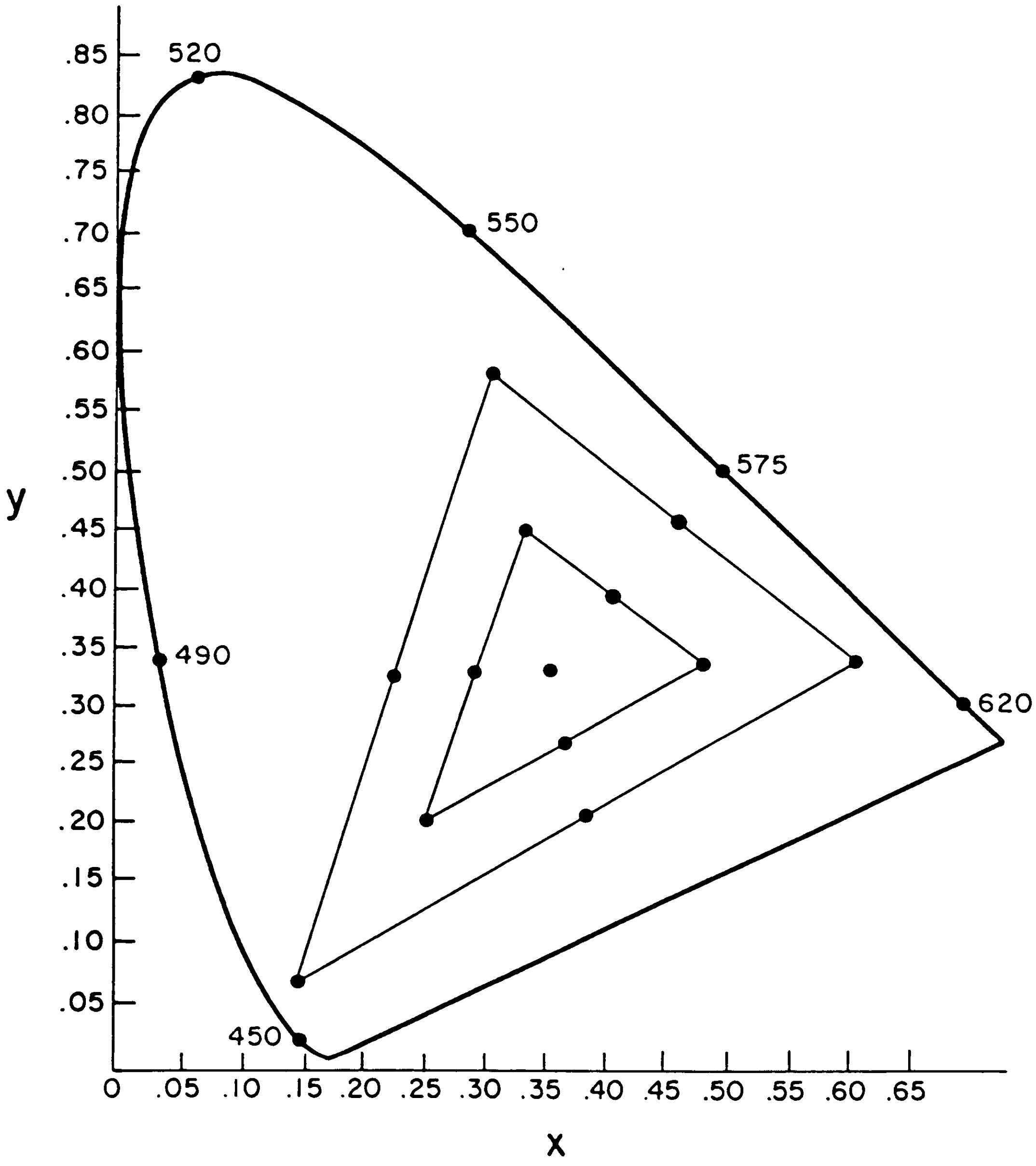
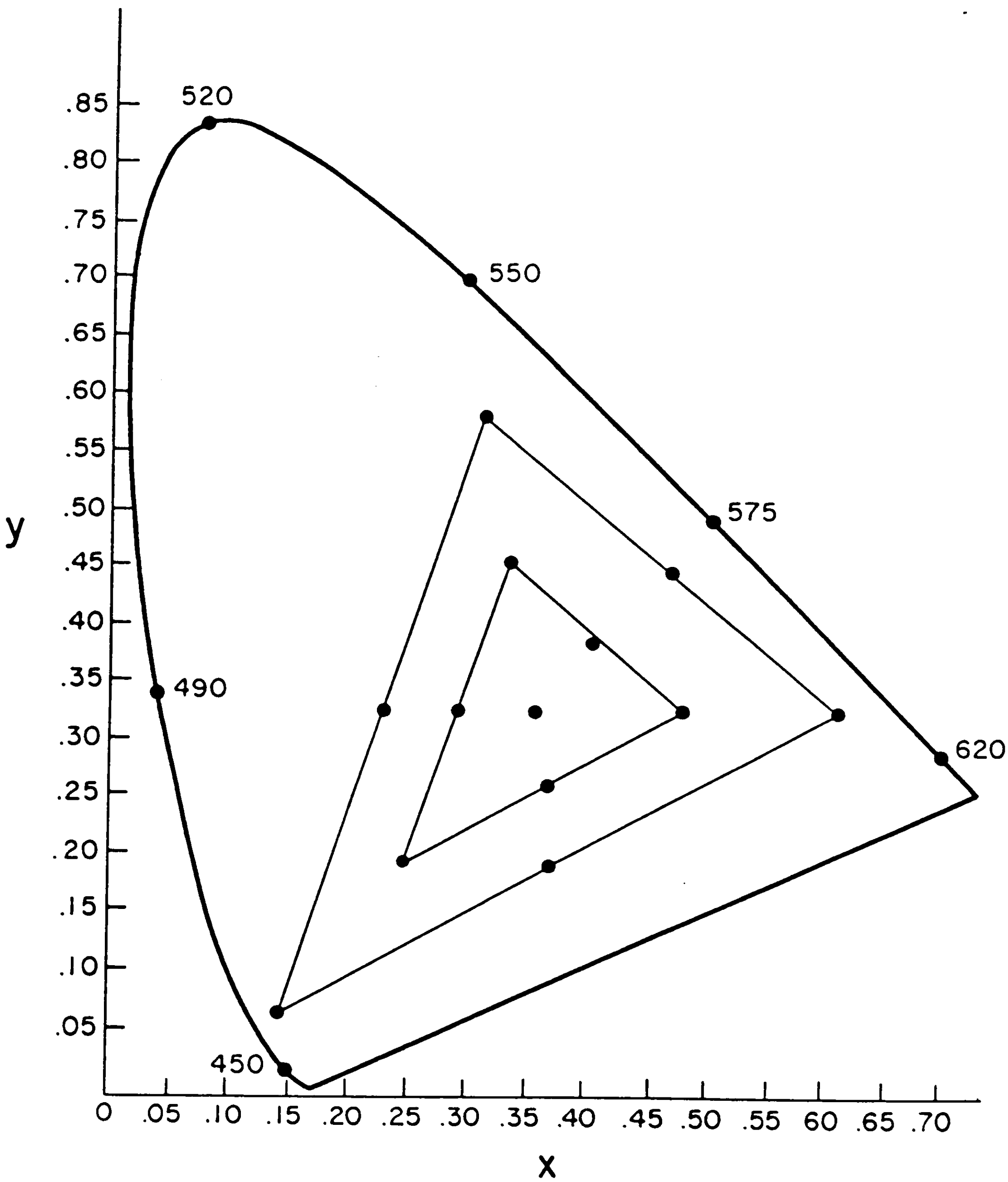


TABLE A-2

CHROMATICITIES - EXPERIMENT 2

Wavelength (nm)	Purity	Luminance (cd/m2)	X	Y
467	0.91	1.4993	0.1480	0.0751
455	0.45	1.3930	0.2403	0.2134
492	0.35	1.4346	0.2318	0.3393
492	0.15	1.4025	0.2871	0.3303
550	0.67	1.5265	0.3227	0.5839
555	0.38	1.4673	0.3309	0.4729
576	0.76	1.5203	0.4599	0.4689
581	0.39	1.4460	0.3986	0.4247
609	0.88	1.4968	0.6077	0.3415
609	0.46	1.4395	0.4774	0.3543
-535	0.61	1.4982	0.3699	0.2019
-518	0.32	1.4033	0.3728	0.2756
Achromatic	White	1.3534	0.3861	0.3427
Achromatic	Black	0.0000	0.3861	0.3427

CHROMATICITY PLOT EXPERIMENT 2



APPENDIX B

SUBJECT BIOGRAPHICAL DATA SHEET

BIOGRAPHICAL DATA

NAME: ______________________________

AGE: ______________________________

VISUAL ACUITY:	LEFT	RIGHT	BOTH
NEAR:	_____	_____	_____
FAR:	_____	_____	_____

COLOR VISION: MISSES _______

PREGNANT: _______

EYETRACKER SETTINGS

X:_______________ Y:_______________ Z:_______________

V4 OUTPUT:____________

OPTOMETER SETTINGS

NUMBER 5:(MAX 4.65) ___________

NUMBER 6:(MAX 5.10) ___________

VOLTAGE OUT (BLACK ON WHITE):__________

APPENDIX C

INFORMED CONSENT

INFORMED CONSENT FORM

TITLE OF STUDY: Accommodation during color contrast

INVESTIGATOR: Daniel T. Donohoo,
IEOR graduate student

PROJECT DIRECTOR: Dr. Harry Snyder, 961-5358

IRB CHAIRMAN: Mr. C. D. Waring, 961-5283

I, ______________________________ (print name), have agreed to participate in this experiment. I have been informed of the nature of the experiment and all questions have been answered to my satisfaction. I understand that the SRI eyetracker uses a near infrared source of illumination. I have no reason to expect that I will suffer any adverse effect as a result of my participation and I recognize my responsibility to inform the researcher of any medical problems which may arise during the experiment. I understand that no compensation or medical treatment is available if injury should occur during the experiment. I understand that I may terminate my participation at any time for any reason and that, if I do so, I will be paid only for the time that I have participated. I understand that I may also withdraw my data from the study for any reason. I also understand that information collected during this experiment will remain confidential with regard to my identity and that my identity will not be released to any other person or group without my prior written consent.

Lastly, I understand that I may request to see the results of the experiment.

(signed) ______________________

(date) ______________________

APPENDIX D

INSTRUCTIONS TO THE SUBJECTS

INSTRUCTIONS TO SUBJECTS

EXPERIMENT 1

Experiment 1 requires you to perform the following task. You are to observe the crosshair displayed on the color CRT and bring the crosshair into focus. When focus has been obtained on the crosshair, depress the leftmost button the the keypad located on the right arm of the chair. Depressing this button is your signal that you are ready for the visual task to begin, and it will cause the visual task display to be presented. A few seconds may lapse between the depression of the button and the task presentation. You must continue to press the pushbutton throughout the task presentation.

Your task is to determine as quickly as you can the number of pairs in which the first number matches the second number. As soon as you have made this determination release the leftmost pushbutton. The target will extinguish and you will be presented with an interstimulus display. At this time you need to indicate the number of matching pairs in the column of six pairs by depressing the appropriate pushbutton the the keypad: the leftmost pushbutton corresponds to one match, the second button two matches, the third button three matches and the rightmost pushbutton four matches this selection ends a task trial. For example; observe the following column of number pairs:

0 0

1 2

3 4

5 5

6 7

8 9

In this column there are two pairs in which the first number matches the second number. After releasing the leftmost pushbutton to indicate that you knew the number of matches in the column, you would depress the second pushbutton indicating two matches.

You will be given breaks periodically during the experimental session, however, if you need to get off the bite bar for any reason during the experiment, just indicate this to me and the experiment will be stopped.

APPENDIX E

SUMMARY ANOVA TABLES

TABLE E-1

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR BLUE BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.4257		
Within				
Foreground Wavelength (FW)	4	0.0621	2.48	0.0854
FW X S	16	0.0250		
Background Purity (BP)	1	0.1860	2.17	0.2151
BP X S	4	0.0859		
BP X FW	4	0.0130	0.56	0.6951
BP X FW X S	16	0.0232		
Foreground Purity(FP)	1	0.0092	1.51	0.2866
FP X S	4	0.0061		
FW X FP	4	0.0431	2.28	0.1059
FH X FP X S	16	0.0189		
BP X FP	1	0.0662	6.29	0.0662
BP X FP X S	4	0.0105		
BP X FW X FP	4	0.0490	2.70	0.0683
BP X FW X FP X S	16	0.0182		

TABLE E-2

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR BLUE FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.5262		
Within				
Background Wavelength (BW)	4	0.0061	0.34	0.8500
BW X S	16	0.0182		
Background Purity (BP)	1	0.0007	1.69	0.2640
BP X S	4	0.0004		
BW X BP	4	0.0089	1.15	0.3703
BW X BP X S	16	0.0077		
Foreground Purity (FP)	1	0.0312	2.61	0.1815
FP X S	4	0.0120		
BW X FP	4	0.0030	0.23	0.9189
BH X FP X S	16	0.0132		
BP X FP	1	0.0117	2.42	0.1950
BP X FP X S	4	0.0048		
BW X BP X FP	4	0.0107	1.93	0.1549
BW*BP*FP*S	16	0.0055		

TABLE E-3

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR CYAN BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.4795		
Within				
Foreground Wavelength (FW)	4	0.0145	0.86	0.5095
FW X S	16	0.0169		
Background Purity (BP)	1	0.0077	0.99	0.3771
BP X S	4	0.0077		
BP X FW	4	0.0015	0.26	0.8999
BP X FW X S	16	0.0058		
Foreground Purity (FP)	1	0.0109	12.81	0.0232
FP X S	4	0.0008		
FW X FP	4	0.0060	0.36	0.8350
FW X FP X S	16	0.0169		
BP X FP	1	0.0097	4.90	0.0912
BP X FP X S	4	0.0020		
BP X FW X FP	4	0.0116	1.15	0.3678
BPX FW X FP X S	16	0.0101		

TABLE E-4

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR CYAN FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.3721		
Within				
Background Wavelength (BW)	4	0.0195	1.73	0.1935
BW X S	16	0.0113		
Background Purity (BP)	1	0.0044	0.29	0.6210
BP X S	4	0.0154		
BW X BP	4	0.0278	2.27	0.1063
BW X BP X S	16	0.0122		
Foreground Purity (FP)	1	0.0226	1.46	0.2930
FP X S	4	0.0154		
BW X FP	4	0.0067	0.81	0.5359
BW X FP X S	16	0.0082		
BP X FP	1	0.0253	7.03	0.0569
BP X FP X S	4	0.0036		
BW X BP X FP	4	0.0162	2.21	0.1144
BW X BP X FP X S	16	0.0073		

TABLE E-5

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR GREEN BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.4438		
Within				
Foreground Wavelength (FW)	4	0.0013	0.11	0.9778
FW X S	16	0.0121		
Background Purity (BP)	1	0.0135	3.95	0.1178
BP X S	4	0.0034		
BP X FW	4	0.0182	2.80	0.0614
BP X FW X S	16	0.0065		
Foreground Purity (FP)	1	0.0107	1.80	0.2503
FP X S	4	0.0059		
FW X FP	4	0.0040	0.29	0.8808
FW X FP X S	16	0.0137		
BP X FP	1	0.0015	0.40	0.5592
BP X FP X S	4	0.0038		
BP X FW X FP	4	0.0176	2.73	0.0658
BP X FW FP X S	16	0.0064		

TABLE E-6

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR GREEN FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.5653		
Within				
Background Wavelength (BW)	4	0.0133	0.92	0.4750
BW X S	16	0.0145		
Background Purity (BP)	1	0.0452	5.38	0.0812
BP X S	4	0.0084		
BW X BP	4	0.0102	0.77	0.5597
BW X BP * S	16	0.0133		
Foreground Purity (FP)	1	0.0072	3.30	0.1432
FP X S	4	0.0022		
BW X FP	4	0.0022	0.22	0.9206
BW X FP X S	16	0.0099		
BP X FP	1	0.0049	0.50	0.5194
BP X FP X S	4	0.0098		
BW X BP X FP	4	0.0087	0.79	0.5483
BW X BP X FP X S	16	0.0440		

TABLE E-7

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR YELLOW BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.5279		
Within				
Foreground Wavelength (FW)	4	0.0072	2.12	0.1259
FW X S	16	0.0034		
Background Purity (BP)	1	0.0007	0.20	0.6756
BP X S	4	0.0033		
BP X FW	4	0.0053	0.60	0.6684
BP X FW X S	16	0.0088		
Foreground Purity (FP)	1	0.0085	2.28	0.2055
FP X S	4	0.0038		
FW X FP	4	0.0114	1.12	0.3819
FW X FP X S	16	0.0102		
BP X FP	1	0.0001	0.06	0.8252
BP X FP X S	4	0.0021		
BP X FW X FP	4	0.0169	4.08	0.0182
BP X FW X FP X S	16	0.0041		

TABLE E-8

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR YELLOW FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.7324		
Within				
Background Wavelength (BW)	4	0.0046	0.48	0.7481
BW X S	16	0.0096		
Backgrund Purity (BP)	1	0.0187	0.49	0.5228
BP X S	4	0.0382		
BW X BP	4	0.0048	0.41	0.7997
BW X BP X S	16	0.0116		
Foreground Purity (FP)	1	0.0077	0.33	0.5984
FP X S	4	0.0237		
BW X FP	4	0.0302	1.18	0.3576
BW X FP X S	16	0.0257		
BP X FP	1	0.0105	0.96	0.3829
BP X FP X S	4	0.0110		
BW X BP X FP	4	0.0399	4.21	0.0161
BW X BP X FP X S	16	0.0095		

TABLE E-9

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR RED BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.5915		
Within				
Foreground Wavelength (FW)	4	0.0204	2.42	0.0907
FW X S	16	0.0084		
Background Purity (BP)	1	0.0382	4.75	0.0947
BP X S	4	0.0080		
FW X BP	4	0.0162	2.32	0.1011
FW X BP X S	16	0.0070		
Foreground Purity (FP)	1	0.0060	0.26	0.6349
FP X S	4	0.0227		
FW X FP	4	0.0109	0.83	0.5226
FW X FP X S	16	0.0130		
BP X FP	1	0.0063	1.00	0.3739
BP X FP X S	4	0.0064		
FW X BP X FP	4	0.0026	0.39	0.8103
FW X BP X FP X S	16	0.0065		

TABLE E-10

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR RED FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.3759		
Within				
Background Wavelength (BW)	4	0.0598	6.67	0.0023
BW X S	16	0.0090		
Background Purity (BP)	1	0.0736	9.94	0.0344
BP X S	4	0.0074		
BW X BP	4	0.0317	3.33	0.0364
BW X BP X S	16	0.0381		
Foreground Purity (FP)	1	0.0017	0.17	0.7046
FP X S	4	0.0103		
BW X FP	4	0.0093	0.74	0.5776
BW X FP X S	16	0.0126		
BP X FP	1	0.0099	8.64	0.0424
BP X FP X S	4	0.0011		
BW X BP X FP	4	0.0232	1.42	0.2717
BW X BP X FP X S	16	0.0163		

TABLE E-11

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR MAGENTA BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.6109		
Within				
Foreground Wavelength (FW)	4	0.0081	0.83	0.5237
FW X S	16	0.0098		
Background Purity (BP)	1	0.0518	269.41	0.0001
BP X S	4	0.0002		
FW X BP	4	0.0146	1.76	0.1869
FW X BP X S	16	0.0083		
Foreground Purity (FP)	1	0.0236	1.45	0.2951
FP X S	4	0.0163		
FW X FP	4	0.0046	0.40	0.8081
FW X FP X S	16	0.0115		
BP X FP	1	0.0075	1.22	0.3308
BP X FP X S	4	0.0061		
BP X FW X FP	4	0.0090	0.91	0.4809
BP X FW X FP X S	16	0.0098		

TABLE E-12

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR MAGENTA FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.5228		
Within				
Background Wavelength (BW)	4	0.1290	13.91	0.0001
BW X S	16	0.0093		
Background Purity (BP)	1	0.0193	1.61	0.2729
BP X S	4	0.0120		
BW X BP	4	0.0193	1.63	0.2147
BW X BP X S	16	0.0118		
Foreground Purity (FP)	1	0.0677	11.02	0.0294
FP X S	4	0.0062		
BW X FP	4	0.0111	1.00	0.4358
BW X FP X S	16	0.0111		
BP X FP	1	0.0007	0.14	0.7260
BP X FP X S	4	0.0052		
BW X BP X FP	4	0.0152	3.46	0.0323
BW X BP X FP X S	16	0.0044		

TABLE E-13

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR ACHROMATIC BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.3674		
Within				
Foreground Wavelength (FW)	5	0.0258	5.91	0.0016
FW X S	20	0.0044		
Background Purity (BP)	1	0.3789	2.81	0.1693
BP X S	4	0.1351		
FW X BP	5	0.0189	3.06	0.0327
FW X BP X S	20	0.0062		
Foreground Purity (FP)	1	0.0084	2.86	0.1660
FP X S	4	0.0029		
FW X FP	5	0.0077	0.87	0.5177
FW X FP X S	20	0.0088		
BP X FP	1	0.0223	3.79	0.1233
BP X FP X S	4	0.0059		
BP X FW X FP	5	0.0115	1.30	0.3036
BP X FW X FP X S	20	0.0089		

TABLE E-14

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR ACHROMATIC FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.4319		
Within				
Background Wavelength (BW)	5	0.0508	12.84	0.0001
BW X S	20	0.0040		
Background Purity (BP)	1	0.0205	1.50	0.2885
BP X S	4	0.0137		
BW X BP	5	0.0330	1.32	0.2968
BW X BP X S	20	0.1253		
Foreground Purity (FP)	1	0.0082	0.45	0.5394
FP X S	4	0.0183		
BW X FP	5	0.0033	0.25	0.9374
BW X FP X S	20	0.0134		
BP X FP	1	0.0193	0.96	0.3822
BP X FP X S	4	0.0200		
BW X BP X FP	5	0.0043	0.30	0.9077
BW X BP X FP X S	20	0.0114		

TABLE E-15

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR BLUE BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0504		
Within				
Foreground Wavelength (FW)	4	0.0157	6.65	0.0024
FW X S	16	0.0024		
Background Purity (BP)	1	0.0223	6.31	0.0659
BP X S	4	0.0035		
FW X BP	4	0.0134	4.74	0.0103
FW X BP X S	16	0.0028		
Foreground Purity (FP)	1	0.0071	6.20	0.0675
FP X S	4	0.0012		
FW X FP	4	0.0050	2.35	0.0983
FW X FP X S	16	0.0021		
BP X FP	1	0.0002	0.06	0.8232
BP X FP X S	4	0.0038		
BP X FW X FP	4	0.0039	1.91	0.1583
BP X FW X FP X S	16	0.0021		

TABLE E-16

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR BLUE FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0910		
Within				
Background Wavelength (BW)	4	0.0010	0.42	0.7936
BW X S	16	0.0023		
Background Purity (BP)	1	0.0002	0.09	0.7799
BP X S	4	0.0023		
BW X BP	4	0.0019	1.89	0.1613
BW X BP X S	16	0.0010		
Foreground Purity (FP)	1	0.0025	1.91	0.2396
FP X S	4	0.0013		
BW X FP	4	0.0026	3.92	0.0211
BW X FP X S	16	0.0006		
BP X FP	1	0.0003	0.08	0.7858
BP X FP X S	4	0.0034		
BW X BP X FP	4	0.0001	0.15	0.9608
BW X BP X FP X S	16	0.0008		

TABLE E-17

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR CYAN BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0602		
Within				
Foreground Wavelength (FW)	4	0.0010	0.37	0.8243
FW X S	16	0.0027		
Background Purity (BP)	1	0.0012	3.08	0.1542
BP X S	4	0.0004		
BP X FW	4	0.0005	0.65	0.6335
BP X FW X S	16	0.0008		
Foreground Purity (FP)	1	0.0017	0.94	0.3862
FP X S	4	0.0018		
FW X FP	4	0.0003	0.29	0.8797
FW X FP X S	16	0.0011		
BP X FP	1	0.0016	2.20	0.2119
BP X FP X S	4	0.0007		
BP X FW X FP	4	0.0018	1.27	0.3240
BP X FW X FP X S	16	0.0014		

TABLE E-18

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR CYAN FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0697		
Within				
Background Wavelength (BW)	4	0.0234	6.09	0.0036
BW X S	16	0.0038		
Background Purity (BP)	1	0.0211	8.80	0.0413
BP X S	4	0.0024		
BW X BP	4	0.0086	5.69	0.0048
BW X BP X S	16	0.0015		
Foreground Purity (FP)	1	0.0005	0.66	0.4632
FP X S	4	0.0008		
BP X FP	4	0.0046	2.74	0.0653
BW X FP X S	16	0.0017		
BP X FP	1	0.0002	0.14	0.7251
BP X FP X S	4	0.0014		
BW X BP X FP	4	0.0015	0.87	0.5047
BW X BP X FP X S	16	0.0017		

TABLE E-19

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR GREEN BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0672		
Within				
Foreground Wavelength (FW)	4	0.0018	1.49	0.2510
FW X S	16	0.0012		
Background Purity (BP)	1	0.0001	0.07	0.8073
BP X S	4	0.0009		
BP X FW	4	0.0010	0.85	0.5154
BP X FW X S	16	0.0012		
Foreground Purity (FP)	1	0.0034	8.25	0.0453
FP X S	4	0.0004		
FW X FP	4	0.0029	1.57	0.2305
FW X FP X S	16	0.0019		
BP X FP	1	0.0017	0.59	0.4861
BP X FP X S	4	0.0029		
BP X FW X FP	4	0.0008	0.55	0.6985
BP X FW X FP X S	16	0.0015		

TABLE E-20

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR GREEN FOREGROUNDS TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0467		
Within				
Background Wavelength (BW)	4	0.0023	0.89	0.4919
BW X S	16	0.0026		
Background Purity (BP)	1	0.0080	11.06	0.0292
BP X S	4	0.0007		
BW X BP	4	0.0012	1.09	0.3963
BW X BP X S	16	0.0011		
Foreground Purity (FP)	1	0.0007	5.91	0.0719
FP X S	4	0.0001		
BW X FP	4	0.0013	0.68	0.6160
BW X FP X S	16	0.0020		
BP X FP	1	0.0003	0.56	0.4962
BP X FP X S	4	0.0005		
BW X BP X FP	4	0.0007	0.66	0.6283
BW X BP X FP X S	16	0.0011		

TABLE E-21

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR YELLOW BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0748		
Within				
Foreground Wavelength (FW)	4	0.0023	1.13	0.3779
FW X S	16	0.0020		
Background Purity (BP)	1	0.0006	0.48	0.5285
BP X S	4	0.0013		
FW X BP	4	0.0013	2.02	0.1401
FW X BP X S	16	0.0006		
Foreground Purity (FP)	1	0.0015	0.65	0.4651
FP X S	4	0.0023		
FW X FP	4	0.0014	0.77	0.5633
FW X FP X S	16	0.0018		
BP X FP	1	0.0012	23.17	0.0086
BP X FP X S	4	0.0000		
BP X FW X FP	4	0.0004	0.19	0.9406
BP X FH X FP X S	16	0.0021		

TABLE E-22

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR YELLOW FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0651		
Within				
Background Wavelength (BW)	4	0.0091	3.48	0.0315
BW X S	16	0.0026		
Background Purity (BP)	1	0.0029	8.48	0.0436
BP X S	4	0.0003		
BW X BP	4	0.0007	0.32	0.8603
BW X BP X S	16	0.0022		
Foreground Purity (FP)	1	0.0001	0.05	0.8364
FP X S	4	0.0022		
BW X FP	4	0.0014	1.46	0.2590
BW X FP X S	16	0.0009		
BP X FP	1	0.0028	2.71	0.1751
BP X FP X S	4	0.0010		
BW X BP X FP	4	0.0032	1.43	0.2701
BW X FP X FP X S	16	0.0023		

TABLE E-23

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR RED BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0898		
Within				
Foreground Wavelength (FW)	4	0.0012	0.64	0.6433
FW X S	16	0.0019		
Background Purity (BP)	1	0.0036	2.82	0.1683
BP X S	4	0.0013		
BP X FW	4	0.0025	1.99	0.1454
BP X FW X S	16	0.0013		
Foreground Purity (FP)	1	0.0015	1.21	0.3331
FP X S	4	0.0013		
FW X FP	4	0.0006	0.60	0.6687
FW X FP X S	16	0.0011		
BP X FP	1	0.0005	0.75	0.4359
BP X FP X S	4	0.0007		
BP X FW X FP	4	0.0008	0.55	0.7009
BP X FW X FP X S	16	0.0015		

TABLE E-24

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR RED FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0677		
Within				
Background Wavelength (BW)	4	0.0228	12.58	0.0001
BW X S	16	0.0012		
Background Purity (BP)	1	0.0026	2.54	0.1866
BP X S	4	0.0010		
BW X BP	4	0.0053	6.38	0.0029
BW X BP X S	16	0.0008		
Foreground Purity (FP)	1	0.0004	0.20	0.6767
FP X S	4	0.0021		
BW X FP	4	0.0007	0.55	0.6987
BW X FP X S	16	0.0012		
BP X FP	1	0.0009	1.99	0.2311
BP X FP X S	4	0.0005		
BW X BP X FP	4	0.0018	0.97	0.4497
BW X BP X FP X S	16	0.0018		

TABLE E-25

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR MAGENTA BACKGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0782		
Within				
Foreground Wavelength (FW)	4	0.0007	0.71	0.5981
FW X S	16	0.0010		
Background Purity (BP)	1	0.0090	6.95	0.0578
BP X S	4	0.0013		
FW X BP	4	0.0004	0.48	0.7530
FW X BP X S	16	0.0009		
Foreground Purity (FP)	1	0.0002	0.91	0.3931
FP X S	4	0.0002		
FW X FP	4	0.0010	0.93	0.4732
FW X FP X S	16	0.0011		
BP X FP	1	0.0026	4.57	0.0994
BP X FP X S	4	0.0006		
BP X FW X FP	4	0.0001	0.04	0.9968
BP X FW X FP X S	16	0.0013		

TABLE E-26

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR MAGENTA FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0638		
Within				
Background Wavelength (BW)	4	0.0012	0.44	0.7770
BW X S	16	0.0028		
Bakcground Purity (BP)	1	0.0003	0.41	0.5574
BP X S	4	0.0007		
BW X BP	4	0.0018	1.42	0.2721
BW X BP X S	16	0.0013		
Foreground Purity (FP)	1	0.0061	4.46	0.1022
FP X S	4	0.0014		
BW X FP	4	0.0019	0.84	0.5219
BW X FP X S	16	0.0023		
BP X FP	1	0.0003	0.08	0.7908
BP X BP X S	4	0.0040		
BW X BP X FP	4	0.0012	0.73	0.5842
BW X BP X FP X S	16	0.0016		

TABLE E-27

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION OF ACCOMMODATION FOR ACHROMATIC BACKGROUND TRIALS.

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0675		
Within				
Foreground Wavelength (FW)	5	0.0011	1.83	0.1519
FW X S	20	0.0006		
Background Purity (BP)	1	0.0030	1.13	0.3473
BP X S	4	0.0027		
FW X BP	5	0.0003	0.44	0.8160
FW X BP X S	20	0.0006		
Foreground Purity (FP)	1	0.0008	0.62	0.4745
FP X S	4	0.0013		
FW X FP	5	0.0006	0.85	0.5289
FW X FP X S	20	0.0006		
BP X FP	1	0.0001	0.06	0.8189
BP X FP X S	4	0.0010		
BP X FW X FP	5	0.0013	1.82	0.1542
BP X FW X FP S	20	0.0007		

TABLE E-28

ANALYSIS OF VARIANCE SUMMARY OF STANDARD

DEVIATION OF ACCOMMODATION FOR ACHROMATIC FOREGROUND TRIALS

Source	df	MS	F	p
Between				
Subjects(S)	4	0.0797		
Within				
Background Wavelength (BW)	5	0.0076	2.73	0.0489
BW X S	20	0.0028		
Background Purity (BP)	1	0.0115	23.44	0.0084
BP X S	4	0.0005		
BW X BP	5	0.0042	2.21	0.0936
BW X BP X S	20	0.0019		
Foreground Purity (FP)	1	0.0005	0.12	0.7426
FP X S	4	0.0037		
BW X FP	5	0.0023	3.79	0.0141
BW X FP X S	20	0.0006		
BP X FP	1	0.0002	0.25	0.6424
BP X FP X S	4	0.0009		
BP X BP X FP	5	0.0023	1.78	0.1627
BW X BP X FP X S	20	0.0013		

TABLE E-29

ANALYSIS OF VARIANCE SUMMARY OF MEAN ACCOMMODATION FOR EXPERIMENT 2

Source	df	MS	F	p
Between				
Subjects(S)	3	0.2409		
Within				
Background Wavelength (BW)	2	0.1046	2.37	0.1746
BW X S	6	0.0442		
Foreground Wue (FW)	3	0.0040	0.96	0.4536
FW X S	9	0.0042		
BW X FW	6	0.0066	1.30	0.3060
BW X FW X S	18	0.0051		
Background Purity (BP)	1	0.1033	2.15	0.2390
BP X S	3	0.0481		
BW X BP	2	0.0278	1.25	0.3517
BW X BP X S	6	0.0222		
BP X FW	3	0.0048	2.32	0.1437
BP X FW	9	0.0021		
BW X BP X FW	6	0.0039	0.54	0.7715
BW X BP X FW X S	18	0.0073		

TABLE E-29

ANALYSIS OF VARIANCE SUMMARY OF MEAN

ACCOMMODATION FOR EXPERIMENT 2 (CONTINUED)

Source	df	MS	F	p
Foreground Purity (FP)	1	0.0000	0.01	0.9272
FP X S	3	0.0008		
BW X FP	2	0.0013	0.20	0.8261
BW X FP X S	6	0.0064		
FW X FP	3	0.0055	1.16	0.3768
FW X FP X S	9	0.0048		
BW X FW X FP	6	0.0044	1.94	0.1288
BW X FW X FP X S	18	0.0023		
BP X FP	1	0.0050	0.66	0.4770
BP X FP X S	3	0.0075		
BW X BP X FP	2	0.0015	0.50	0.6311
BW X BP X FP X S	6	0.0029		
BP X FW X FP	3	0.0023	0.44	0.7316
BP X FW X FP X S	9	0.0053		
BW X BP X FW	6	0.0020	0.51	0.7942
BW X BP X FW X S	18	0.0039		

TABLE E-30

ANALYSIS OF VARIANCE OF STANDARD DEVIATION

OF ACCOMMODATION FOR EXPERIMENT TWO

Source	df	MS	F	p
Between				
Subjects(S)	3	0.0683		
Within				
Background Wavelength (BW)	2	0.0016	0.90	0.4549
BW X S	6	0.0018		
Foreground Wavelength (FW)	3	0.0011	4.49	0.0345
FW X S	9	0.0003		
BW X FW	6	0.0006	0.56	0.7543
BW X FW X S	18	0.0010		
Background Purity (BP)	1	0.0029	5.71	0.0968
BP X S	3	0.0005		
BW X BP	2	0.0015	1.10	0.3918
BW X BP X S	6	0.0014		
BP X FW	3	0.0002	0.36	0.7814
BP X FW X S	9	0.0006		
BW X BP X FW	6	0.0003	0.73	0.6348
BW X BP X FW X S	18	0.0004		

TABLE E-30

ANALYSIS OF VARIANCE SUMMARY OF STANDARD DEVIATION

OF ACCOMMODATION FOR EXPERIMENT 2 (CONTINUED)

Source	df	MS	F	p
Foreground Purity (FP)	1	0.0000	0.07	0.8089
FP X S	3	0.0005		
BW X FP	2	0.0003	0.69	0.5387
BW X FP X S	6	0.0005		
FW X FP	3	0.0007	1.53	0.2729
FW X FP X S	9	0.0005		
BW X FW X FP	6	0.0005	1.60	0.2034
BW X FW X FP X S	18	0.0003		
BP X FP	1	0.0003	0.99	0.3923
BP X FP X S	3	0.0003		
BW X BP X FP	2	0.0006	5.79	0.0398
BW X BP X FP X S	6	0.0001		
FW X BP X FP	3	0.0001	0.23	0.8712
FW X BP X FP X S	9	0.0006		
BW X BP X FW X FP	6	0.0002	0.74	0.6259
BW X BP X FW X FP X S	18	0.0003		

TABLE E-31

ANALYSIS OF VARIANCE SUMMARY OF TASK SPEED

ACCOMMODATION FOR EXPERIMENT 2

Source	df	MS	F	p
Between				
Subjects(S)	3	0.3220		
Within				
Background Wavelength (BW)	2	0.1113	22.99	0.0015
BW X S	6	0.0048		
Foreground Wavelength (FW)	3	0.0478	20.77	0.0002
FW X S	9	0.0023		
BW X FW	6	0.0967	22.11	0.0001
BW X FW X S	18	0.0044		
Background Purity (BP)	1	0.0210	7.78	0.0684
BP X S	3	0.0027		
BW X BP	2	0.3374	25.42	0.0012
BW X BP X S	6	0.0131		
BP X FW	3	0.0146	36.71	0.0001
BP X FW X S	9	0.0004		
BW X BP X FW	6	0.0166	6.11	0.0012
BW X BP X FW X S	18	0.0027		

TABLE E-31

ANALYSIS OF VARIANCE SUMMARY OF TASK SPEED

ACCOMMODATION FOR EXPERIMENT 2 (CONTINUED)

Source	df	MS	F	p
Foreground Purity (FP)	1	0.0876	67.66	0.0038
FP X S	3	0.0013		
BW X FP	2	0.0177	12.51	0.0072
BW X FP X S	6	0.0014		
FW X FP	3	0.0442	20.34	0.0002
FW X FP X S	9	0.0022		
BW X FW X FP	6	0.0200	7.33	0.0004
BW X FW X FP X S	18	0.0027		
BP X FP	1	0.0009	0.72	0.4584
BP X FP X S	3	0.0012		
BW X BP X FP	2	0.0753	29.35	0.0008
FW X BP X FP X S	6	0.0026		
FW X BP X FP	3	0.0027	1.45	0.2921
FW X BP X FP X S	9	0.0019		
BW X BP X FW X FP	6	0.0149	8.70	0.0002
BW X BP X FW X FP X S	18	0.0017		

APPENDIX F

ACCOMMODATION RESPONSE

FOR

ALL TARGETS/BACKGROUNDS

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL TARGETS/BACKGROUNDS

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
464	0.93	491	0.35	0.16	-0.18	0.44
464	0.93	489	0.13	0.09	-0.19	0.48
464	0.93	550	0.67	0.14	-0.22	0.45
464	0.93	555	0.36	0.05	-0.61	0.58
464	0.93	576	0.74	0.14	-0.76	0.46
464	0.93	581	0.42	-0.23	-1.25	0.59
464	0.93	610	0.85	0.30	0.20	0.41
464	0.93	610	0.46	0.11	-0.69	0.58
464	0.93	-525	0.61	0.19	-0.33	0.51
464	0.93	-514	0.32	0.43	0.28	0.59
464	0.93	Achro	White	0.25	-0.03	0.365
464	0.93	Achro	Black	0.23	-0.46	0.55

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
455	0.43	491	0.35	0.06	-0.17	0.38
455	0.43	489	0.13	0.13	0.04	0.20
455	0.43	550	0.67	0.06	-0.34	0.27
455	0.43	555	0.36	0.09	-0.08	0.27
455	0.43	576	0.74	0.04	-0.24	0.31
455	0.43	581	0.46	0.07	-0.24	0.42
455	0.43	610	0.85	0.11	-0.09	0.26
455	0.43	610	0.46	0.11	0.00	0.34
455	0.43	-525	0.61	0.13	-0.08	0.45
455	0.43	-514	0.32	0.14	-0.16	0.44
455	0.43	Achro	White	0.10	-0.18	0.33
455	0.43	Achro	Black	0.09	-0.39	0.46

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
491	0.35	464	0.93	0.09	-0.07	0.24
491	0.35	455	0.43	0.04	-0.26	0.37
491	0.35	550	0.67	0.08	-0.23	0.22
491	0.35	555	0.36	0.05	-0.36	0.30
491	0.35	576	0.74	0.06	-0.06	0.29
491	0.35	581	0.42	0.07	-0.32	0.27
491	0.35	610	0.85	0.02	-0.27	0.29
491	0.35	610	0.46	0.13	0.06	0.22
491	0.35	-525	0.61	0.05	-0.25	0.23
491	0.35	-514	0.32	0.02	-0.32	0.33
491	0.35	Achro	White	0.01	-0.32	0.29
491	0.35	Achro	Black	-0.03	-0.53	0.29

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
489	0.13	464	0.93	0.12	0.06	0.17
489	0.13	455	0.43	0.00	-0.18	0.16
489	0.13	550	0.67	0.06	-0.22	0.42
489	0.13	555	0.36	0.12	-0.15	0.38
489	0.13	576	0.74	0.07	-0.07	0.27
489	0.13	581	0.42	0.03	-0.41	0.36
489	0.13	610	0.85	0.11	-0.10	0.31
489	0.13	610	0.46	0.03	-0.13	0.22
489	0.13	-525	0.61	-0.03	-0.40	0.24
489	0.13	-514	0.32	0.01	-0.17	0.25
489	0.13	Achro	White	0.06	-0.13	0.29
489	0.13	Achro	Black	0.10	0.03	0.17

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
550	0.67	464	0.93	-0.01	-0.24	0.17
550	0.67	455	0.43	0.04	-0.12	0.30
550	0.67	491	0.35	0.05	-0.09	0.27
550	0.67	489	0.13	-0.04	-0.26	0.10
550	0.67	576	0.74	0.01	-0.36	0.21
550	0.67	581	0.42	0.07	-0.13	0.34
550	0.67	610	0.85	0.11	-0.22	0.42
550	0.67	610	0.46	0.03	-0.25	0.36
550	0.67	-525	0.61	0.05	-0.20	0.32
550	0.67	-514	0.32	0.04	-0.09	0.17
550	0.67	Achro	White	0.04	-0.34	0.42
550	0.67	Achro	Black	0.08	0.04	0.19

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
555	0.36	464	0.93	0.12	-0.17	0.32
555	0.36	455	0.43	0.05	-0.11	0.21
555	0.36	491	0.35	0.07	-0.06	0.28
555	0.36	489	0.13	0.12	0.03	0.25
555	0.36	576	0.74	0.06	-0.31	0.31
555	0.36	581	0.42	0.02	-0.31	0.30
555	0.36	610	0.85	0.06	-0.08	0.20
555	0.36	610	0.46	-0.02	-0.19	0.13
555	0.36	-525	0.61	0.01	-0.18	0.20
555	0.36	-514	0.32	0.04	-0.16	0.30
555	0.36	Achro	White	0.08	-0.06	0.23
555	0.36	Achro	Black	0.06	-0.22	0.19

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
576	0.74	464	0.93	0.08	-0.07	0.17
576	0.74	455	0.43	0.00	-0.33	0.23
576	0.74	491	0.35	0.02	-0.29	0.24
576	0.74	489	0.13	0.146	0.06	0.29
576	0.74	550	0.67	0.03	-0.11	0.20
576	0.74	555	0.36	0.05	-0.08	0.23
576	0.74	610	0.85	0.07	-0.25	0.43
576	0.74	610	0.46	0.03	-0.16	0.34
576	0.74	-525	0.61	-0.01	-0.19	0.24
576	0.74	-514	0.32	0.05	-0.14	0.22
576	0.74	Achro	White	0.04	-0.20	0.19
576	0.74	Achro	Black	0.05	-0.14	0.22

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
581	0.42	464	0.93	0.03	-0.20	0.16
581	0.42	455	0.43	0.06	-0.21	0.41
581	0.42	491	0.35	0.04	-0.19	0.21
581	0.42	489	0.13	0.03	-0.24	0.31
581	0.42	550	0.67	0.08	-0.13	0.28
581	0.42	555	0.36	0.01	-0.34	0.26
581	0.42	610	0.85	0.05	-0.27	0.30
581	0.42	610	0.46	0.14	-0.01	0.25
581	0.42	-525	0.61	-0.02	-0.31	0.26
581	0.42	-514	0.32	0.07	-0.21	0.32
581	0.42	Achro	White	0.10	-0.07	0.41
581	0.42	Achro	Black	0.02	-0.09	0.13

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
610	0.85	464	0.93	0.06	-0.26	0.23
610	0.85	455	0.43	0.03	-0.38	0.19
610	0.85	491	0.35	0.14	-0.14	0.31
610	0.85	489	0.13	0.13	-0.01	0.26
610	0.85	550	0.67	0.13	-0.18	0.32
610	0.85	555	0.36	0.09	-0.09	0.28
610	0.85	576	0.74	0.06	-0.21	0.22
610	0.85	581	0.42	0.09	-0.06	0.36
610	0.85	-525	0.61	0.06	-0.18	0.38
610	0.85	-514	0.32	0.12	-0.15	0.32
610	0.85	Achro	White	0.09	-0.22	0.29
610	0.85	Achro	Black	0.13	-0.10	0.28

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
610	0.46	464	0.93	0.04	-0.34	0.29
610	0.46	455	0.43	-0.01	-0.34	0.34
610	0.46	491	0.35	0.00	-0.16	0.25
610	0.46	489	0.13	0.10	-0.17	0.33
610	0.46	550	0.67	0.03	-0.22	0.22
610	0.46	555	0.36	0.00	-0.18	0.25
610	0.46	576	0.74	0.02	-0.46	0.21
610	0.46	581	0.42	0.05	-0.23	0.44
610	0.46	-525	0.61	0.11	-0.07	0.23
610	0.46	-514	0.32	0.17	-0.06	0.44
610	0.46	Achro	White	0.08	-0.15	0.34
610	0.46	Achro	Black	0.09	-0.07	0.31

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
-525	0.61	464	0.93	0.07	-0.21	0.47
-525	0.61	455	0.43	0.10	-0.07	0.39
-525	0.61	491	0.35	0.04	-0.21	0.34
-525	0.61	489	0.13	0.06	-0.04	0.28
-525	0.61	550	0.67	0.12	-0.12	0.33
-525	0.61	555	0.36	0.13	-0.14	0.38
-525	0.61	576	0.74	0.09	-0.25	0.36
-525	0.61	581	0.42	0.15	-0.01	0.45
-525	0.61	610	0.85	0.19	-0.10	0.45
-525	0.61	610	0.46	0.14	-0.08	0.36
-525	0.61	Achro	White	0.10	-0.23	0.34
-525	0.61	Achro	Black	0.15	0.05	0.26

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
-514	0.32	464	0.93	0.12	-0.23	0.39
-514	0.32	455	0.43	0.05	-0.22	0.34
-514	0.32	491	0.35	0.03	-0.12	0.24
-514	0.32	489	0.13	0.14	0.01	0.36
-514	0.32	550	0.67	0.05	-0.28	0.31
-514	0.32	555	0.36	0.08	-0.07	0.33
-514	0.32	576	0.74	0.03	-0.27	0.25
-514	0.32	581	0.42	0.07	-0.08	0.26
-514	0.32	610	0.85	0.01	-0.16	0.24
-514	0.32	610	0.46	0.10	-0.27	0.41
-514	0.32	Achro	White	0.04	-0.11	0.18
-514	0.32	Achro	Black	0.07	-0.08	0.13

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
Achro	White	464	0.93	0.09	0.00	0.31
Achro	White	455	0.43	0.01	-0.20	0.32
Achro	White	491	0.35	0.01	-0.18	0.27
Achro	White	489	0.13	0.01	-0.36	0.35
Achro	White	550	0.67	0.05	-0.15	0.42
Achro	White	555	0.36	0.06	-0.13	0.42
Achro	White	576	0.74	0.08	-0.04	0.19
Achro	White	581	0.42	0.02	-0.17	0.23
Achro	White	610	0.85	0.04	-0.32	0.34
Achro	White	610	0.46	0.06	-0.08	0.37
Achro	White	-525	0.61	0.06	-0.13	0.37
Achro	White	-514	0.32	0.09	-0.17	0.27

APPENDIX F

ACCOMMODATION RESPONSE FOR ALL

TARGETS/BACKGROUNDS (CONTINUED)

BW (nm)	BP	FW (nm)	FP	MEAN	MIN	MAX
Achro	Black	464	0.93	-0.21	-0.37	-0.08
Achro	Black	455	0.43	-0.11	-0.32	-0.01
Achro	Black	491	0.35	-0.13	-0.38	-0.05
Achro	Black	489	0.13	-0.02	-0.12	-0.05
Achro	Black	550	0.67	-0.17	-0.47	0.00
Achro	Black	555	0.36	-0.03	-0.15	0.14
Achro	Black	576	0.74	-0.01	-0.07	0.08
Achro	Black	581	0.42	-0.04	-0.19	0.05
Achro	Black	610	0.85	0.00	-0.11	0.12
Achro	Black	610	0.46	0.01	-0.19	0.09
Achro	Black	-525	0.61	0.01	-0.25	0.14
Achro	Black	-514	0.32	-0.03	-0.16	0.08
Achro	Black	Achro	White	0.00	-0.02	0.00

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ABSTRACT

ACCOMMODATION WITH DISPLAYS HAVING COLOR CONTRAST

Much concern has been expressed about the ability of the visual display terminal to provide adequate stimuli for accommodation. As a result it has been hypothesized that an observer may have to continually refocus to maintain accommodation on the display and this contributes to the visual fatigue experienced by VDT users. The increased use of multicolor CRTs in the workplace adds yet another factor, chromatic aberration, to affect the observers' accommodation to information presented on the CRT. Two experiments were run to determine the effect of viewing characters of one chromaticity and purity on a background of another chromaticity or purity or chromaticity and purity. The observer's accommodation response was continuously sampled throughout the presentation of each target/background combination. Mean accommodation response and the standard deviation of the mean accommodation response were then calculated to ascertain the effect the target background combination had on the observers' accommodation response. The observers' were also required to perform a visual performance task for each target/background combination.

The data collected indicate that chromatic characters when observed on chromatic background do not provide a strong stimulus for accommodation. Mean changes in the observers accommodation response were all within the depth of field except when characters were viewed on blue backgrounds. The variability in the observers accommodation

response was not found to be a good predictor of image quality where only color contrast exists between foreground and surround. Task performance was highly correlated with effective contrast between the target and background as quantified by uniform color space modeling.