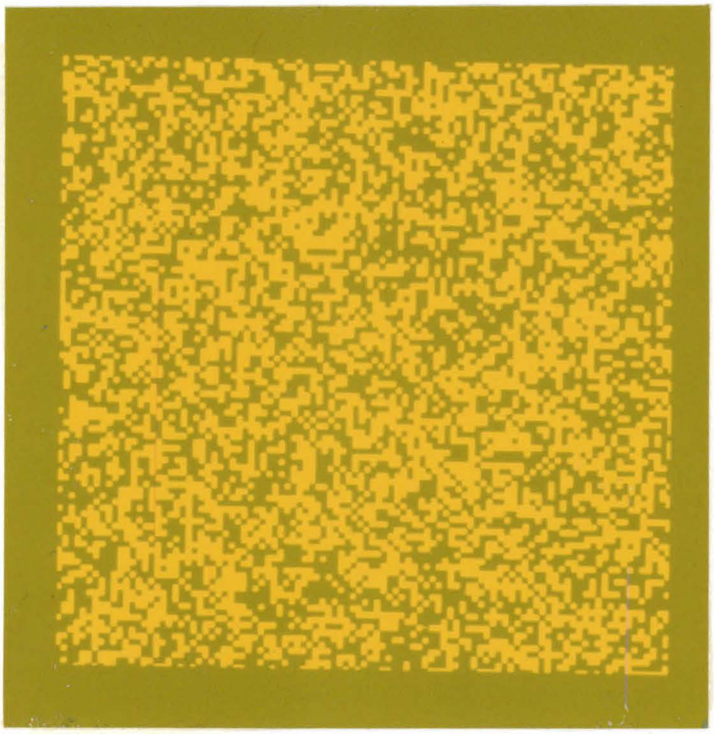

Frontispiece. A Julesz pattern in color, as used in the experiments described here. See chapter six.

THE INTERACTION OF COLOR AND LUMINANCE IN STEREOSCOPIC VISION

Thesis by

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Bela Julesz first introduced me to the marvelous things which could be done with his stereo patterns at Bell Telephone Laboratories.

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Cary Lu

ABSTRACT

Experiments are described using the random dot stereo patterns devised by Julesz, but substituting various colors and luminances for the usual black and white random squares. The ability to perceive the patterns in depth depends on a luminance difference between the colors used. If two colors are the same luminance, then depth is not perceived although each of the individual squares which make up the patterns is easily seen due to the color difference. This is true for any combination of different colors. If different colors are used for corresponding random squares between the left and right eye patterns, stereopsis is possible for all combinations of binocular rivalry in color, provided the luminance difference is large enough. Rivalry in luminance always precludes stereopsis, regardless of the colors involved.

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CHAPTER ONE

INTRODUCTION

Research in vision has almost always concentrated on isolating parameters; this has been necessary because of the complexity of the visual system. This has led to a large volume of experiments with results which are difficult to relate to one another. In recent years, as the understanding of fundamental processes of vision has improved, experiments have begun to be carried out which study the interaction of various parameters.

In this thesis, two of the major areas of vision research, traditionally carried out in isolation, are combined: binocular vision and color vision. Their interaction is mapped, with of course a restricted set of stimuli, to examine the way in which visual information due to differences in color and differences in luminance are used to perceive depth. (The term color conventionally includes hue, saturation and brightness. This is explained in Chapter 3.)

Neurophysiological and psychophysical experiments have provided a great deal of information on how the discriminations for depth and color are achieved. We now know, albeit sketchily, how the primary visual cortex receives input from both eyes and constructs the percept of three dimensional space, and how the cells receive information coded for the wavelength of light. These results will be reviewed in the first chapters.

Because of the tendency to isolate parameters in vision research, the background information in the early chapters must necessarily be difficult to tie together until the experiments are described in the later chapters.

CHAPTER TWO

THE BASIS OF BINOCULAR VISION

There are three major <u>physiological</u> cues to depth perception: the accomodation of the eyes, convergence of the eyes, and retinal disparity, that is the differences between the images of an object on the retinae. Of these, accomodation can be a monocular cue, the others binocular. Accomodation and convergence are not important factors in seeing depth; very early work by Dove, 1841, showed depth perception was readily achieved during the brief illumination of a spark, too brief for any changes in accomodation or convergence. Retinal disparity is a very important mechanism, and will now be considered in detail below.

Secondary cues, also called <u>psychological</u> or <u>familiarity</u> cues, such as perspective, size, clarity, etc. are also important in normal visual experience. These factors can be fairly simply manipulated to produce erroneous depth perception, since they are based on experience rather than fundamental physiological operations. They are discussed in Chapter 5.

Returning now to the physiological cues, if the image of an object is binocularly fused (an object as seen with two eyes is perceived as a single object) then we can construct a geometric relationship which connects all objects which, for a given convergence, can be seen as fused. This construction is known as a horopter, a curve intersecting all points which map onto corresponding points of the retinae. The correspondence of points is determined subjectively; this yields the curve shown in figure 2-1. (Purely optical considerations produce a simpler curve, the Vieth-Muller circle. For a discussion on how horopters are measured and why they do not fit the simpler Vieth-Muller circle, see Ogle, 1962.)

All objects located on the horopter are seen fused, simultaneously. The implication of this fusion is that the horopter maps those points in the retinae which correspond neurally; these are the receptors in the retinae whose responses can be made to produce a fused percept.

The horopter contains those objects in visual space perceived without retinal disparity. There is also a certain restricted region in front of and behind the horopter which is seen in single vision. The extent of this region depends on the angular field of corresponding receptors in each eye (both in the retina and further on in the visual system) and the location in the visual field. The angular field of corresponding points is larger towards the periphery of the retina because of the lower acuity off the visual axis, and thus the proportionate region of single vision is larger towards the edge of the visual field. See figure 2-2. This region of single vision is caused not only by the finite receptive fields of the receptors, but more importantly by the ability of the

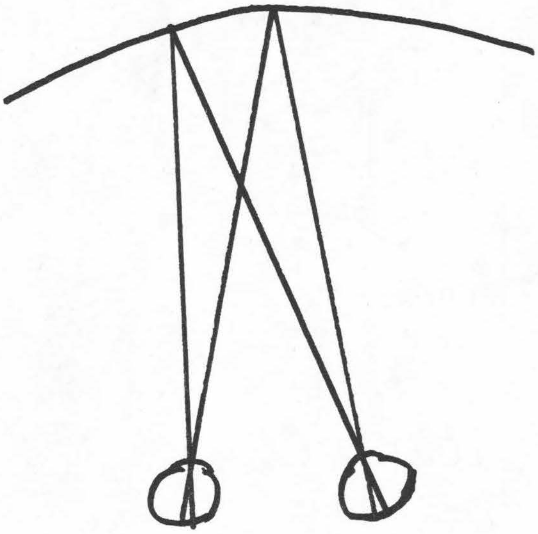

Figure 2-1. A horopter. Points on the curve map into corresponding points on the two retinae.

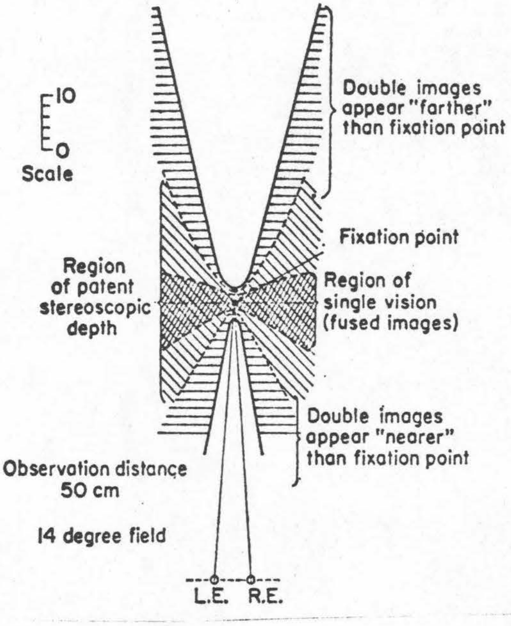

Figure 2-2. Regions of depth perception.

From Ogle (1962).

central visual system to fuse objects which are not exactly on the horopter; neural correspondence need not be exact for single vision, only close enough to be correlated between the two eyes. Differences in the correlation mean differences in disparity. Point by point remapping of these differences in disparity by the central visual system while all objects are still seen in single vision yields depth perception.

Single vision results from two mechanisms which should be distinguished. The first was mentioned above -the range of retinal disparities which permit a single percept of objects and involves a full range of depth perception with single vision.

The fusional mechanism is a second mechanism which brings about single vision and does not deal with depth but rather the permissible sloppiness in registration of the two eye images which still allows a single percept of objects. If the retinal image of one eye is rotated about the line of sight with respect to the other image and the stimuli are so constructed that rotation of one about its center only produces equivalent vertical disparities, then the depth perception mechanism is not stimulated. It is found that the disparity is compensated by an apparently central fusion mechanism, which is an example of the second type of single vision (Kertesz, 1971).

For the fusional mechanism, the retinal disparity can be about 6 min arc in central vision using point stimuli, and increases toward the periphery of the visual field. The Kertesz experiments show that the disparity compensated for by the fusional mechanism is dependent on the complexity of the patterns. The more complex the patterns (the greater the number of discrete elements in the visual field), the greater the permissible sloppiness which is compensated for centrally.

Note that this permissible sloppiness is larger than the disparities needed for depth perception. Depth can be perceived in ordinary situations with disparities of about two min arc although under some laboratory conditions, with controlled high constrast stimuli, stereoscopic acuity can reach a few seconds of arc.

The fusional mechanism is often referred to as "Panum's Fusional Area" in the vision literature. Unfortunately the term is not always used in the restricted sense described here, but for allowable binocular disparity with depth perception, (which is the first type of fusion described here). There are also many differences in the way it is measured and even how the values of the area are quoted. See Mitchell, 1966.

Referring again to figure 2-2, in front of and behind the region of single vision, there are two regions where depth is easily perceived even though double vision does occur. The visual system suppresses the conflict so that the double vision is not normally noticed. These are the regions of patent stereo vision. In front of and behind the regions of patent stereo vision, there are two more regions where double vision is perceived, yet spatial localization is still unambiguous. Finally, the remaining two regions of visual space, in front of and behind all the others, generate retinal disparities too great for unambiguous depth perception.

We may now draw up a sequence of operations (undoubtedly oversimplified, and idealized) which are performed by the visual system in depth perception:

1. An object, which is the center of attention, is located in an horopter. To do this, the visual system must fuse corresponding features from the images in each eye by appropriate convergence. This is the fusional mechanism and does not always operate correctly.
2. Other objects, on or near the horopter within the area of single vision are identified from the images in each eye, and those objects on the horopter are automatically fused by #1. Objects not on the horopter are seen in single vision, and the degree of mismatch with respect to the horopter is then used to determine location in depth.

3. Still other objects, farther away from the horopter within the area of patent stereo vision are identified, but not fused and their corresponding depth positions with respect to the horopter are determined and conflicting parts of the percept are suppressed. Suppression normally occurs to allow the maximum unambiguous percept of the object.
4. Another set of objects is identified, correlated, and localized in depth, but the disparity is too great to suppress portions of their images.
5. Other objects with very large retinal disparities are identified, but not correlated, so no localization is possible; they are perceived double.

This thesis will describe experiments which deal with points 1 and 2, where fusion of images is performed by the visual system using cues of differences in color and brightness in the images. Points 3-5 are of less direct relevance and will be mentioned again only where appropriate.

The Neurophysiology of Binocular Vision

Neurophysiology must ultimately account for or supplant points 1-5 of the previous section. There is now some tentative information about what happens.

The fusion of objects at the center of attention from the two eye images eventually results in a feature by feature matching of the images.

How the visual cortex of the cat maps the visual direction of stimulating light was shown by Hubel and Wiesel (1962), who found that the neurons in the visual cortex are organized into columns, where the cells of a particular column have the same preference for direction of movement of an edge in the visual field for maximal stimulation. The columns contain a population of cells and these cells have slightly different visual fields.

Extensions of this technique to binocular vision have led to experiments by Barlow, Blakemore and Pettigrew (1967) and Nikara, Bishop, and Pettigrew (1968) which have shown that the majority of the cells in the visual cortex of the cat are binocularly driven, responding to light stimulation in either eye in the appropriate visual direction. These cells give a greater response (measured in number of spikes per unit time) to simultaneous binocular stimulation than the sum of left and right eye monocular stimulation.

The classifications of Blakemore (1970) provide the most succinct summary of binocular vision in the cat: He reports that there are two types of columns of cells in the visual cortex. The constant depth column consists of cells having binocular receptive fields of about the same retinal disparity, which look out onto adjacent regions of visual space; these cells receive input from receptors which are grouped together on the retina. The column therefore looks out onto one segment of a horopter.

The constant direction column consists of neurons with superimposed inputs from the contralateral eye, and horizontally scattered inputs from the ipsilateral eye. Thus, these neurons "look" in a specific visual direction for the contralateral eye but at different disparities from the ipsilateral, that is, in the same direction but at differing depths.

The binocular gate neurons described by Bishop (1972) are cells which have the greatest sensitivity to accurate localization in visual space, typically responding only to binocular stimuli simultaneously presented within a 0.3 degree cone in the visual direction from each eye. Outside of this cone, the cell is inhibited when stimulated in the <u>other</u> eye within a 2 degree cone which envelopes the 0.3 degree cone. This presumably corresponds to the area around the horopter which permits single vision; for a given gate cell, objects within the 0.3 degree cone cannot be distinguished. Populations of cells each with slightly different disparities would account for depth perception within this region.

The other categories of stereosis are more difficult to attribute to known neurophysiological processes.

Psychophysical experiments depend on the percept of objects, and are very difficult to interpret in terms of the activity of particular cells in the visual cortex.

When the disparities are too large for fusion, there is at present no clear neurophysiological data which offer an explanation of the suppression of portions of an image. Cells which have been thus far analysed in terms of line detectors are too simple to identify objects. Localization of an object when it cannot be fused because of excessive disparity involves recognition of the object; simple objects such as rods can be seen double without localization, while a more familiar object, such as a pen, will be localized in space although not seen fused.

Identification of objects in two visual fields must involve higher order correlation which looks at similar features seen by populations of cells.

The neurophysiological location of these higher order complex pattern detectors is uncertain; one can at present only speculate on the way the percept of a real object is formed; as one moves on higher in the visual system from the visual cortex, and indeed at the visual cortex, no successful strategy has evolved to determine what is the maximally effective stimulus for a given cell, or what is probably more important, a given group of cells.

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CHAPTER THREE

COLOR

The concept of color has generated an enormous literature and, it seems, an even more enormous confusion. There is scarcely any facet of color which has not been subjected to conflicting study and conflicting vocabulary. The purpose of this chapter is limited to clarifying the terms used in this thesis and describing the results of research which is relevant to the experiments to be described.

There is no wholly satisfactory definition of color; the common definition is that it is the perceptual component of vision related to the wavelength of the stimulating light. However,there are many examples of situations where the "color" is not caused by the wavelengths of light, such as the many subjective color phenomena. It is not even necessary to have light in order to "see" color (phospenes, for example).

More colloquial definitions say that color is the distinctive quality of the appearance of light. This allows more clearly for whites and grays as colors. This last definition can be generalized to say that color is the psychological percept that can differentiate between two light sources (direct or indirect) aside from spatial and temporal differences.

Light sources differ by three approximately independent variables: brightness, hue, and saturation. "Brightness" refers to the perceptual response to luminance. Luminance is the physical quantity, integrated across the visible spectrum of radiant energy multiplied by the standard photopic response of the eye. In this thesis, "color" is normally considered independent of luminance or brightness; this term is used for hue and saturation only. The term color will include the neutral, or achromatic colors, white, gray, and black. Note that white, gray, and black are considered here to be the same color (different brightness) just as dark green and light green (both 512 nm) are the same color.

In some psychophysical experiments and in the descriptions of vision, there is an important distinction between the wavelengths of stimulating light (the physical parameters) and the perceived color, since there are many instances where the perceived color is only casually related to the spectral composition of the stimulus. These complications do not arise in the experiments to be described here; these experiments only require that different colors be seen distinctly and the relatively small changes in perceived color under different conditions are not important to the results (although these changes are noted where appropriate). Because of this, physical stimulus terms and perceived color names like 512 nm, green, and green light will be used interchangeably.

The surmise of Thomas Young in 1807 that color perception is dependent on three color addition in the visual system has been recently supported by experiments with the human retina. This was studied directly by microspectrophometry (Marks, Dobelle, and MacNichol, 1964; Wald, 1964) and sensory methods (Stiles, 1959).

These experiments have provided evidence for three pigments in the human fovea with responses peaked at about 445, 540, and 570 nm. This corresponds, in National Bureau of Standards nomenclature, to purplish blue, yellowish green, and yellow green respectively. These are not the blue, green and red which were expected by physiologists and psychologists in the last century, some of whom found support for their theories on the basis of the "unitary" colors--that is, colors which are perceptually "pure"--blue, green, yellow, red. DeValois,(1972) for example does not use the more common description of "Blue, green, and red" receptors, but rather "Short, medium, and long" wavelength receptors (S, M, and L receptors).

The point of all this is that while there is good physiological basis for trichromatic color theory, the form that color information takes does not appear to follow the traditional ideas of primary colors, at the level of the receptors and the neural pathways which immediately follow.

After the retina, the organization of color information in the neural pathways has mostly been found to be based on opponent-color processes, and most of the infomation has been collected in the lateral geniculate body of the monkey. (DeValois, 1972).

The term "opponent-color" was originally used by Hering in the nineteenth century to describe his theory of color vision. His concept is superficially confirmed by modern neurophysiology. The concept involves four basic colors, red, yellow, green, and blue. Pairings for complementary colors ("opponent colors") are red with green, and yellow with blue. Hering proposed that there were three types of pathways mediating color vision: one channel responding to color content in terms of redness or greeness, another in blue and yellow, and a third to changes in overall light, regardless of wavelength (aside from the fundamental spectral sensitivity of the eye). (Note that red and green are not true complementary colors.)

The six general categories of lateral geniculate body cells of DeValois fall generally into these three groups:

The first four are the "opponent-color cells" (about 70-80% of the detected cells):

1. Cells stimulated by red, inhibited by green.
2. Cells stimulated by green, inhibited by red.
3. Cells stimulated by yellow, inhibited by blue.
4. Cells stimulated by blue, inhibited by yellow.

And the remaining two are "non opponent" or achromatic cells:

5. Cells stimulated by increase in overall light intensity, inhibited by a decrease.
6. Cells stimulated by a decrease in overall light intensity, inhibited by an increase.

For each group there is a population of cells stimulated or inhibited by the appropriate colors (or changes in overall light intensity) and the degree of stimulation and inhibition varies over a wide range.

Wavelengths of light corresponding to the colors described here as red, yellow, green, and blue are: 660, 580, 510, 450 nm. (Of course there is a range of colors about each of these wavelengths which yields the same types of response .) These can be compared with the three color pigments in the retina described above. Thus the responses of the receptors are already interactive in the LGB. The evidence suggests that the red/green cells have input from L and M type cones (see above), while the blue/yellow cells have input from S and L type cones. (DeValois, 1965; Abramov, 1968)

Beyond the lateral geniculate body, there have been only a few studies; Hubel and Wiesel (1968) found that in the striate cortex of the rhesus monkey most of the cells were achromatic, and responded to the overall intensity of light, irrespective of wavelength. Only a small minority of cells, twelve out of 177, had had clear chromatic responses. Of these twelve, three had opponent-color properties, four simply responded to light of a small range of wavelengths, and the remaining five responded to moving slits of some chromatic light.

One of the problems in interpreting neurophysiological data is that the cells studied by this technique are selected by whatever recording and testing method is used; thus it is very difficult to determine what percentage of cells in the LGN or visual cortex are missed simply because of inappropriate stimuli. And, as noted in the last chapter, there is no known strategy for determining the optimum stimulus for a given cell.

Psychophysics of Color Vision

Discrimination of color is best described on the CIE triangle. The experiments conducted to produce the CIE triangle utilize a ten degree visual field (this is the 1964 system; the earlier 1931 system in current parallel use is based on a two degree visual field. For the purposes of this discussion, the differences in the resulting systems are minor). The visual field is split down the middle with the test stimulus on the left. The matching stimulus with subject control of the primary colors is on the right. After matching of the two sides is acheived, the values of the relative luminances of the primaries are transformed into coordinates of the CIE triangle.

Although it was not the original purpose of the CIE matching experiments, the technique is a test of the detection of simple or monocular contours, since matching the two sides means that the contour is not visible. (A monocular contour refers to a border in the visual field which is detected by differences in hue, saturation and/or brightness which are visible on monocular viewing. This will be distinguished from the concept of a binocular contour, described in the next chapter.)

The threshold for detection of a simple contour has been studied by MacAdam (1942) who measured the chromaticity coordinates for matching a test stimulus with a fixed stimulus. The bivariate standard deviation of the error in matching plotted about the fixed stimulus on the CIE triangle gave an ellipse which was a measure of the accuracy of matching. Points outside the ellipse indicate colors which have a high probability of being seen distinct from the fixed stimulus. This means that the border between the two sides of the visual field is perceived, thus the ellipses indirectly plot the just-noticeable-difference in the CIE triangle. See figure 3-1. The sizes and shapes of the ellipses vary because of the non uniform perceptual scaling of the CIE system.

The detection of differences in wavelength as a function of wavelength over the visible spectrum is shown in figure 3-2 (Judd, 1932). The minimum perceptible wavelength difference is less than four nanometers throughout most of

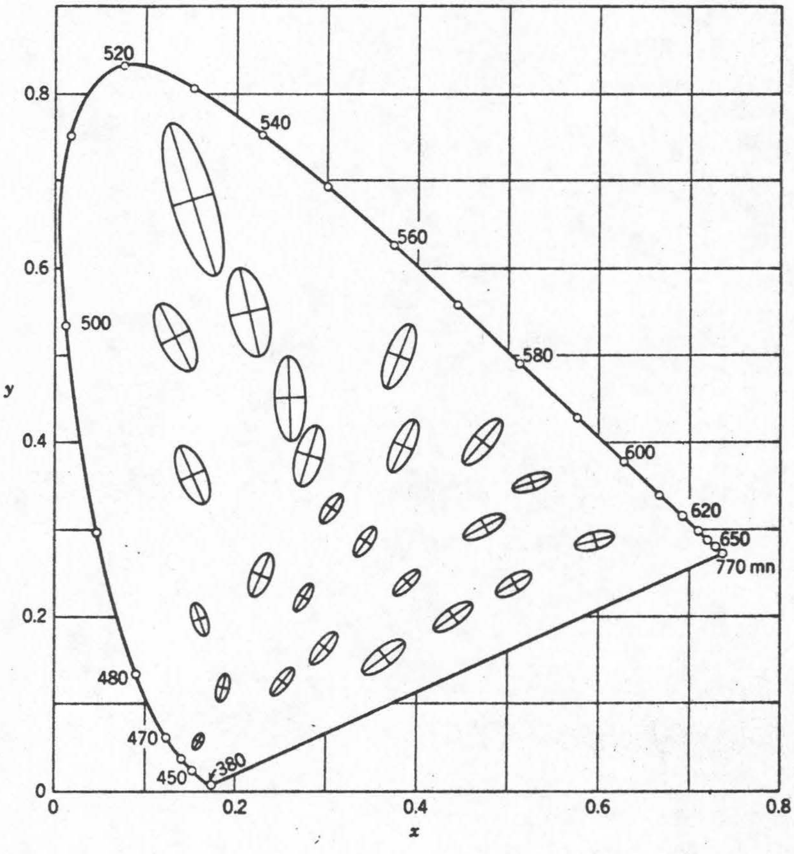

Figure 3-1. MacAdam ellipses. The ellipses are the one standard deviation just noticeable differences for variations in color about a fixed point (the center of the ellipses). The size of the ellipses is magnified ten times for clarity. From MacAdam (1942).

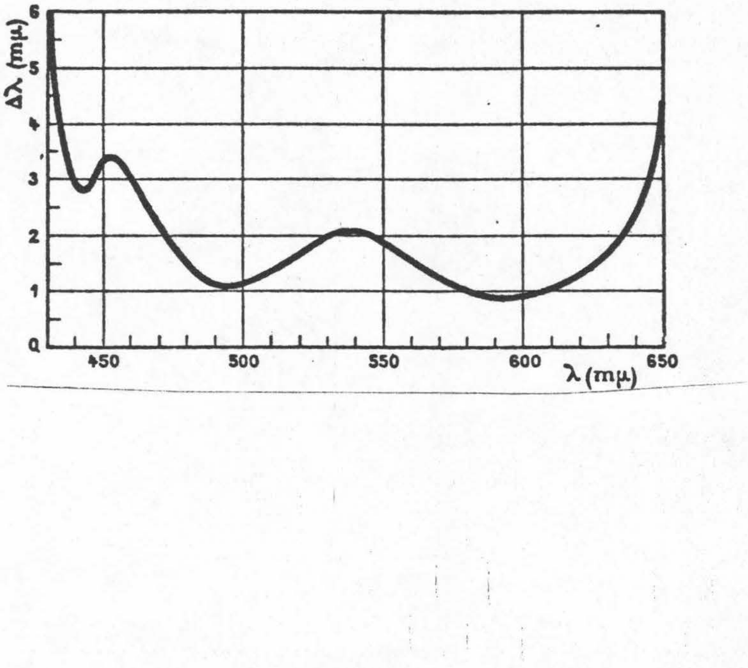

Figure 3-2. The wave length difference sensitivity throughout the spectrum. From Judd (1932).

the visible spectrum. This minimum perceptible wavelength difference corresponds to an ellipse with a cross-section of this size plotted along the spectrum locus of the CIE triangle.

The major axes of the MacAdam ellipses approximately point toward the white point on the CIE diagram. Therefore the minor axes of the ellipses are approximately the just-noticeable-differences in hue, and the major axes the just-noticeable-differences in saturation. Noting that the plot exaggerates the size of the ellipses ten times for clarity, it is apparent that the monocular perception of contours requires about 3 nanometers or less difference across a boundary in the visual field (this can be seen in figure 3-2 also) or about 5% difference in the saturation. The experiments to be reported later all use interference filters for generating colors of very high saturation, and thus the colors used are on the spectrum locus. This means that only the resolution of the eye along the hue axis is important, and the color difference between any adjacent pair of interference filters used in these experiments is always larger that the 3 nanometer just-noticeable-difference quoted (the closest separation used is 15 nanometers, except for the case of identical filters).

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CHAPTER FOUR

RANDOM DOT STEREO PICTURES

Julesz Patterns

A Julesz pattern stereo pair (Julesz, 1964) consists of two patterns (figure 4-1) each with a grid of one hundred by one hundred squares which are randomly white or black. (The size of the grid is arbitrary, as are the figures given below. The actual sizes used are chosen for convenience.) The right eye pattern is the same as the left eye pattern, except that part of the center of the left eye pattern (marked "A" in figure 4-2) is shifted four squares to the left and the opened space of 4 by 40 squares (marked y in figure 4-2) is then filled up with more random squares. Upon monocular inspection, the patterns are both random dot arrays. When viewed binocularly, the images are compared by the visual system, and those sections in which the left and right eye images match are located in the same depth. Because the correlated center 40 by 40 squares are shifted nasally with respect to the surrounding squares, the center is seen in front of the surround. If the shift is temporal then the center square is seen in the back of the surround.

This describes the basic black and white arrays as used by a number of experimenters.

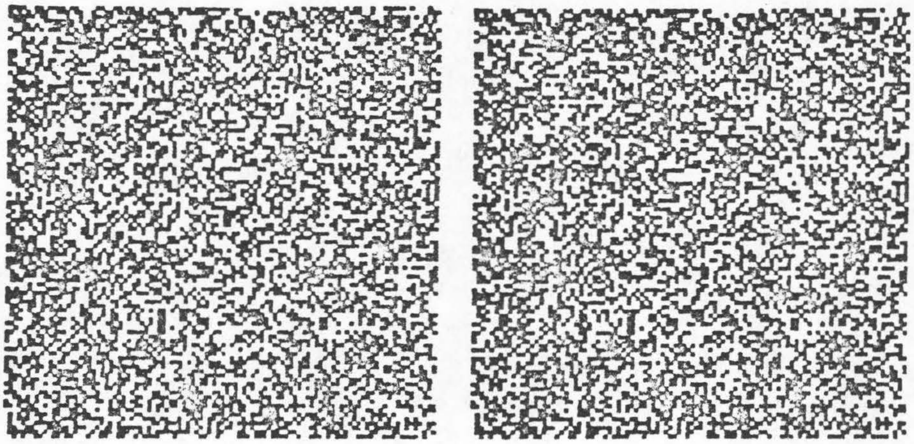


Figure 4-1. A Julesz pattern stereo pair. From Julesz (1965).

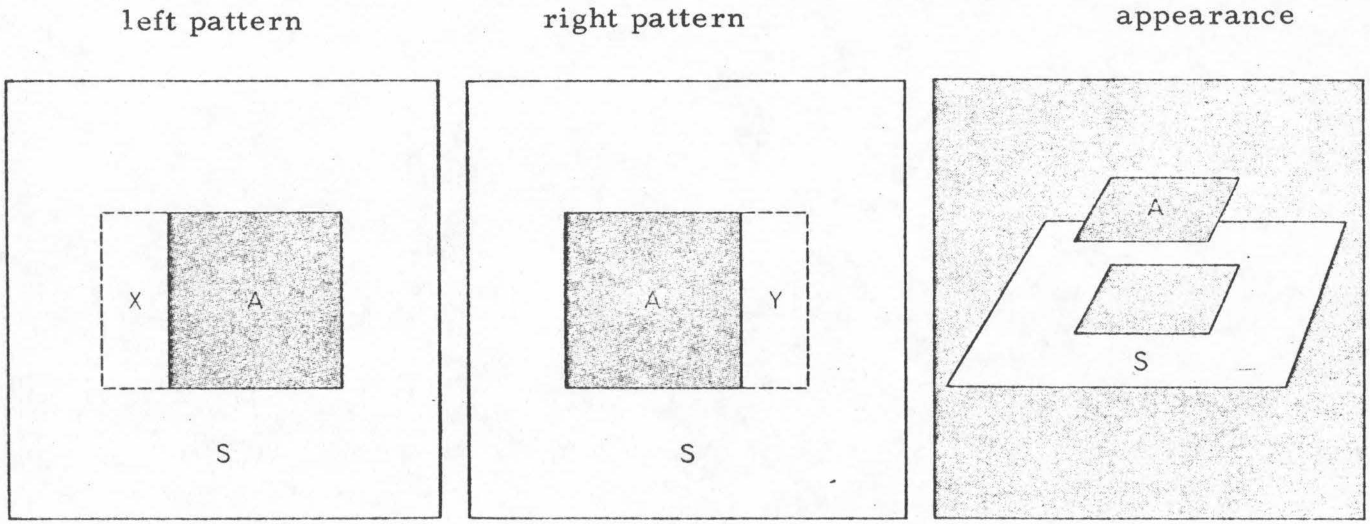


Figure 4-2. Construction of a Julesz pattern stereo pair. See text. From Julesz (1965).

Kaufman (1964) has produced a variation of the basic Julesz technique, by using typewritten letters instead of squares, and blocks of correlated letters are shifted.

The actual patterns themselves used for these experiments were produced by computer generated microfilm, using an Information International FR-80 which makes direct negative photographs of a CRT tube face. The control of the CRT is provided by a program which makes the random squares by scanning lines on the screen. A random number generator is used to select the squares which are to be black, and the center 40 by 40 square shift is achieved by manipulating arrays in the computer. A complementary or negative pattern is the same as the original pattern except that white squares are substituted in the complementary pattern for the black squares of the original, and black squares for the white. The complementary pattern is produced by inverting arrays in the computer. After this operation, the identification of which pattern is the original or positive and which one is the complementary is arbitrary.

Monocular and Binocular Contours

At this point a distinction should be made for the perception of objects which can be seen monocularly, such as the small squares of the Julesz patterns, which is simple or monocular contour detection, and perception of depth, such as seeing the 40 by 40 central square in depth. This latter perception is termed stereo or binocular contour detection, and requires central processing in the visual pathways. Monocular contour detection requires no further information than that already available at the retina of one eye.

Monocular contour detection can be divided into two types, local and global perception. Local perception is of small details, while global perception is for large areas and complex figures.

We can trace what the visual system must do in order to see the Julesz stereo pair in depth. Local perception locates the small squares; global perception of many squares determines the structure of the image which can be compared with the global perception of the other eye image. Where agreement is substantial, the images are concluded to be the same and are perceived as fused in single vision (subject, of course, to the retinal disparity limitations discussed above). After fusion is achieved, the amount of retinal disparity involved in each region where fusion occurs is computed and the differential disparity yields the depth perceived.

Several effects studied by Julesz indicate the flexibility of the global perception process as applied to his patterns.

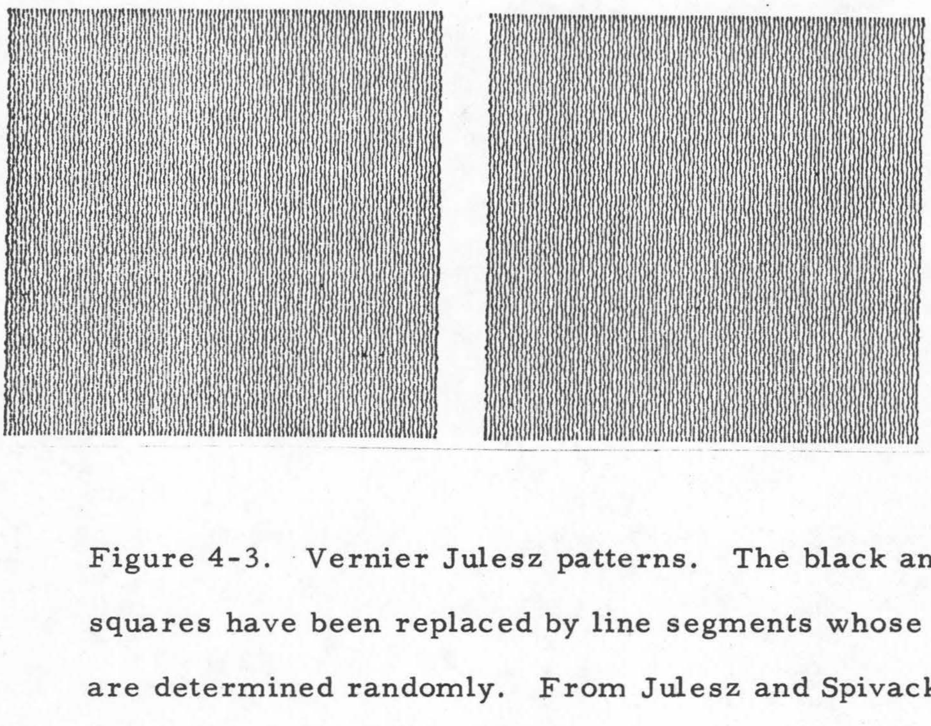
The sizes of the left and right patterns may differ by

10% or one image may be out of focus (locations of the black and white squares are still discernible) and the stereo contour is still perceived. Hence global perception operates with optical mismatch in local perception.

The left and right eye images may be adjusted so the correspondence between the two sides is 75% instead of 100%. That is, the distribution of the black and white squares no longer exactly match (aside from the center shift). For example, 25% of the squares, chosen randomly, are reversed from white to black or black to white in one image. The stereo contour is still perceived, as the global perception process looks for the statistically best matched features; here one can consider the 25% mismatch noise.

Kaufman's patterns using typewritten letters show that local perception operates on relatively complex objects (compared to the simple squares of the Julesz patterns).

The squares of the Julesz patterns can be replaced by short lines of length equal to the side of the small squares (Julesz and Spivack, 1967). These are called vernier Julesz patterns and are shown in figure 4-3. If each of the small squares of a Julesz pattern is considered ten units wide, then a white square is replaced with a vertical line in the middle of the square. (position 5) A black square is replaced by a vertical line two units to the right. (position 7) Now when the center shift is performed, the small displacements of the lines with respect to one



left pattern

right pattern

Figure 4-3. Vernier Julesz patterns. The black and white squares have been replaced by line segments whose positions are determined randomly. From Julesz and Spivack (1967).

another produce a retinal disparity separate from the center shift; 50% of the line segments in the 40 by 40 center array will have the same position in the pattern as the surround after center shift, 25% will have a small disparity corresponding to a nasal shift (positions 7 on the left with position 5 on the right) and should be seen in front of the surround and 25% have a disparity which is temporal and thus seen behind the surround (position 5 on left and position 7 on the right). However, the visual system does not perform this element by element analysis of disparities, but matches the entire 40 by 40 element region, to yield the same percept as for the standard Julesz pattern of squares, preferring global perception for depth rather than local perception. The implication is that depth is perceived by global processes which receive input from the larger area (in this case) which can be correlated.

REFERENCES

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Julesz, B. (1965)Scientific American v. 212, no. 2: 38

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Kaufman, L. (1964) Am. J. Psych. 77: 393.

CHAPTER FIVE

BINOCULAR VISION IN REAL LIFE

The visual world in real life is so complicated that no useful psychophysical experiments have been done using real images. The experiments and data reviewed on the previous chapters on depth perception should not leave the impression that retinal disparity must be an integral part of depth perception under all circumstances. To put things into perspective (among other factors), it is useful to review briefly some of the evidence for visual information and learning which at times makes disparity insignificant.

Familiarity cues (also called secondary and psychological cues) such as clarity, overlapping of objects, shading, geometric perspective, etc., complicate the physiological cues most of the time. Accomodation and convergence can be shown to be of little importance in real life: accommodation alone cannot distinguish the depths of objects more than a meter from the eye (Peter, 1915). Convergence is of little use distinguishing depths of objects more than three meters away (Gogel, 1961). Retinal disparity is by far the most important physiological cue, and is operative to about 600 meters, assuming minimum detectible disparity of 20 sec arc and interpupillary distance of 65 mm (in some special circumstances, detectable disparity may be as little as 2-3 sec arc).

(Head movements are sometimes regarded as another physiological cue, allowing the observer to move and see which objects in turn obscure other objects. Given enough movement, this would operate over any range. Head motion is controlled in every visual experiment to some degree; most psychophysical experiments used fixed head position.)

Even at close range, where physiological cues, particularly retinal disparity are clearly operative, the familiarity cues are probably sufficient most of the time. Persons blind in one eye rarely encounter depth situations which give them trouble; most visual recreations, such as photographs and motion pictures have only flat images, yet with care there is little difficulty in producing what most would describe as a "realistic" image. (The technical difficulties in producing true three dimensional images, almost always using disparity as the cue, usually result in these displays being less satisfactory than two dimensional ones.)

For persons with normal binocular vision, ambiguous interpretations of depth can occur even when viewing objects with all three physiological cues operating. For example, a wire outline of a cube, held close can still be made to invert perceptually (i.e., the apparent spatial distances to the near and far portions of the cube are the reverse of reality). This can give rise to a most extraordinary percept. If the cube is rotated clockwise, it is seen to move counter-clockwise; the visual and tactile senses do not agree.

There is a complex interaction between physiological and familiarity cues. In the experiment just described, reversing the accurate percept of the wire outline cube is more difficult to achieve than when looking at a Necker cube, which is simply a two dimensional drawing of an outline cube, and physiological cues are inoperative.

The familiarity of an object can prevent accurate utilization of physiological cues-- for example a stereo view of a person's face should, when the left and right images are interchanged, yield a face with the nose seen as a depression. This is never perceived; the knowledge of how a face should look is overwhelming, disparity and other cues notwithstanding.

The importance of retinal disparity as a physiological cue to depth perception is because it is the most significant unambiguous interpreter of novel stimuli.

Depth perception uses many cues, which are interactive. At the present state of understanding of the visual system, disparity is the most important cue accessible to systematic study. The Julesz patterns have special importance because they have no familiarity cues, and accomodation and convergence are fixed.

References

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CHAPTER SIX

METHODS

The following terminology is used in describing the experiments (refer to figure 6-1): Four patterns are used, two on each side (left and right). For each side, the patterns are complements of each other-- in photographic terms, one is a positive (pattern one) and the other a negative (pattern two). Superimposed in white light, each side produces a uniform white field when projected with the same light source. The individual patterns will be called left 1, left 2, right 1 and right 2 (L1, L2, R1, R2). Figure 6-1 is a simplified diagram which shows how the patterns are viewed; the complete optical system is described below. L1 and R1 are the same except for the center section shift, as are L2 and R2.

From the perceptual standpoint, there is no discernible difference between patterns one and two since each is a 100 x 100 element pattern of squares. Thus if pattern one is viewed binocularly (pattern two not illuminated) the center is seen in depth, and the same is true for pattern two viewed in the absence of pattern one.

The complete optical system is shown in figure 6-2. In a typical experiment, L1 and L2 are lined up using the same light for a field uniform in appearance. The same is done for R1 and R2. The left and right sides are then adjusted

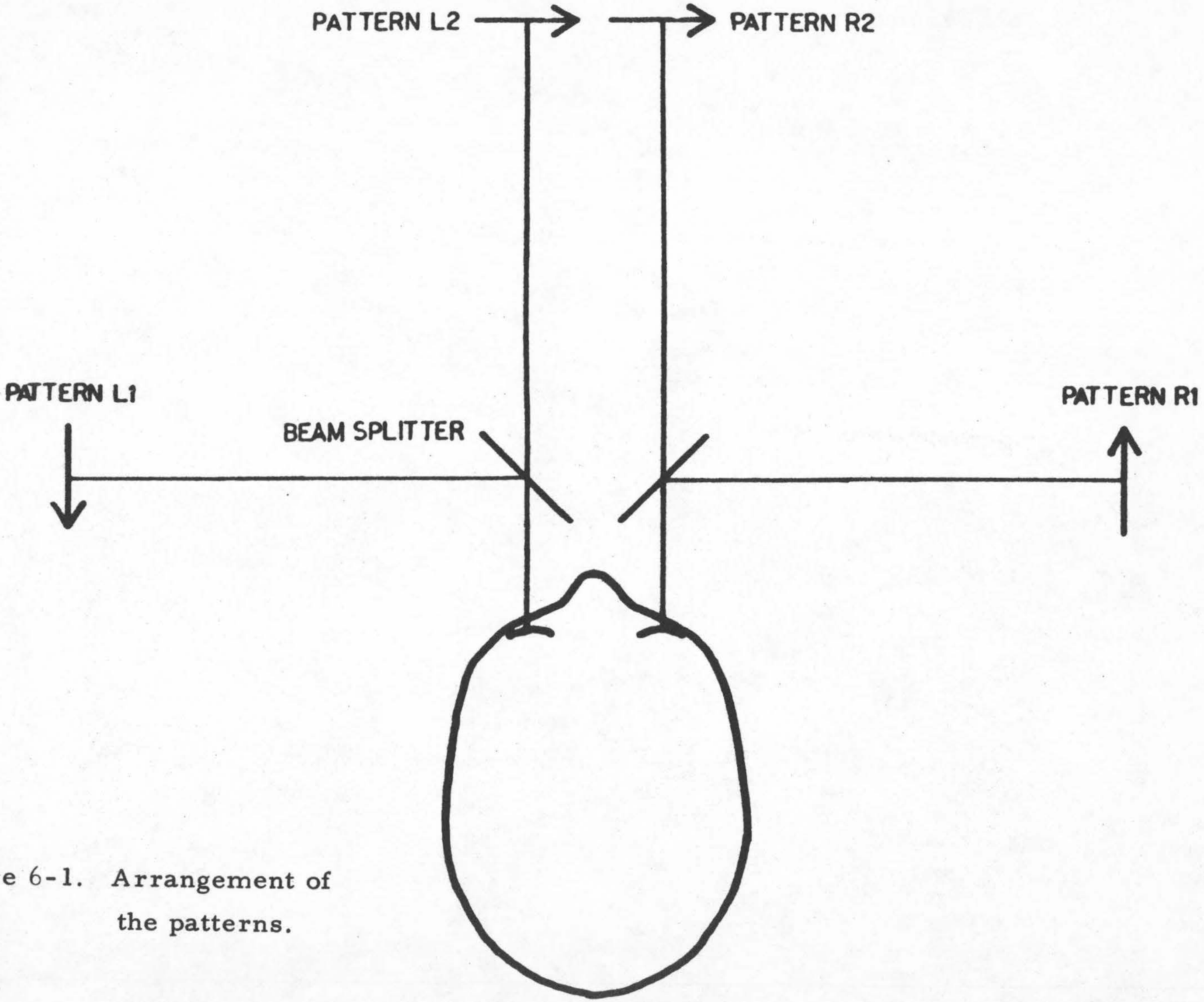


Figure 6-1. Arrangement of the patterns.

Captions

Figure 6-2. Diagram of complete optical system used in the experiments. See text.

Figure 6-3A. Overlay for figure 6-3.

Figure 6-3. (Following figure 6-3A). Photograph of experimental apparatus in operation. Some of the components are indicated on the overlay (figure 6-3A).

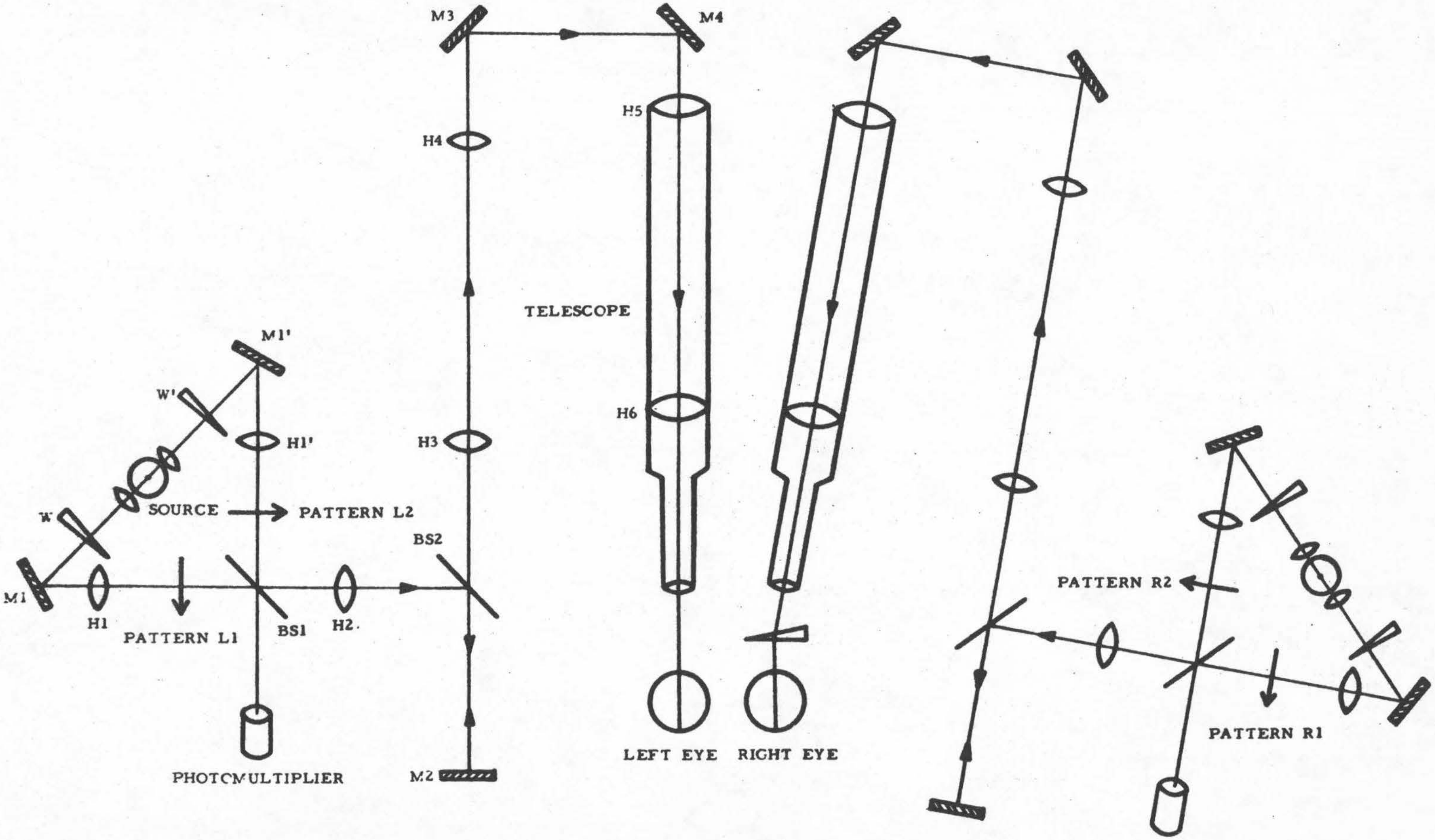


Figure 6-2. A complete diagram of the optical system.

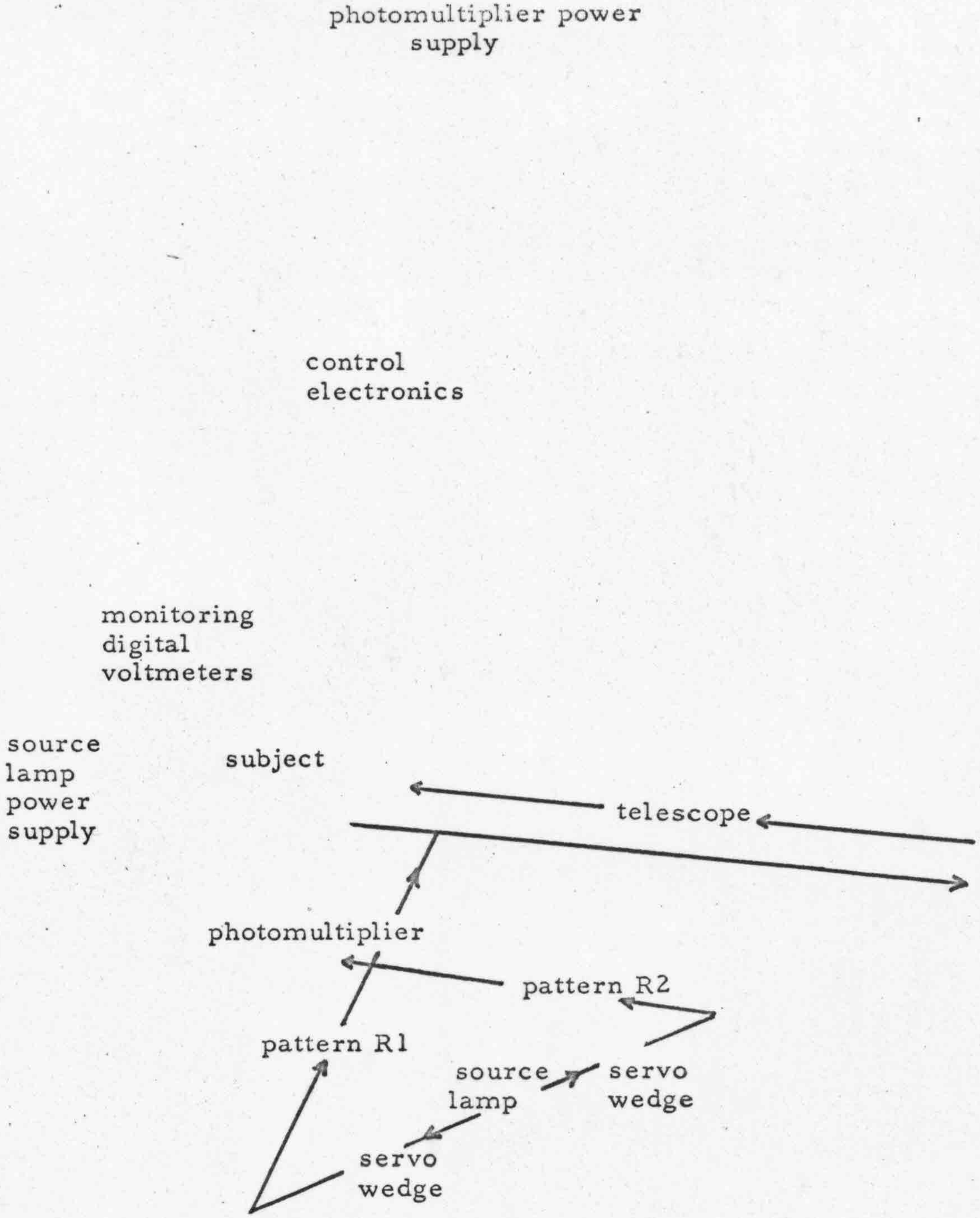
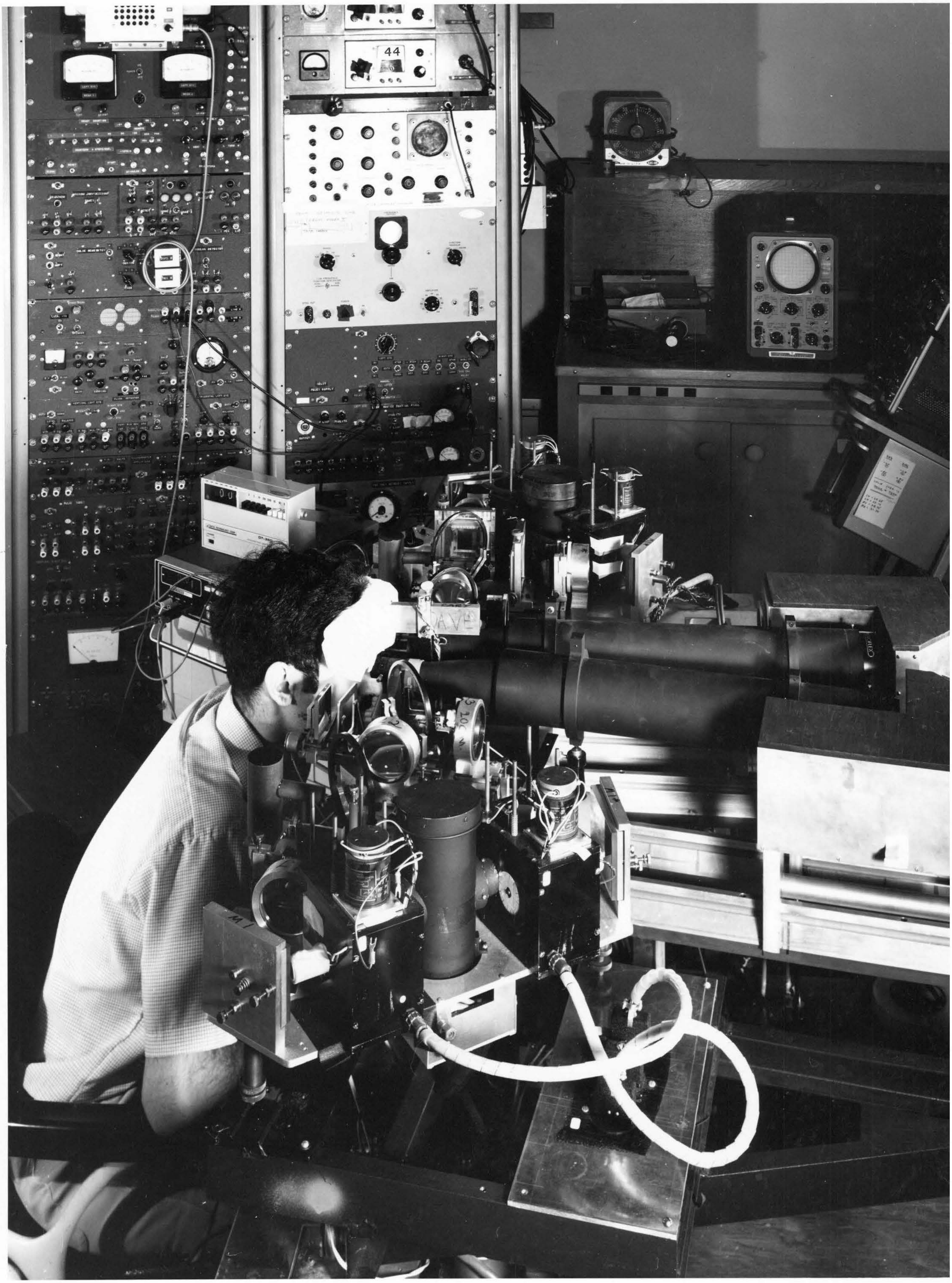


Figure 6-3A. Overlay for figure 6-3, following page.


44
DAVE
M1

so they converge at infinity optically. Filters for control of color and luminance are inserted between M1 and H1 (and between M1' and H1' and on the right side) for the specific experiment at hand. Holding the luminance of L1 and R1 constant, the subject adjusts the luminance of L2 and R2, by servo driven neutral density wedges (at W' and similarly on the right side; the two servoes are driven in step by electrical interlock). In general, the subject will observe that as the luminance is adjusted, depth is easily perceived when pattern two is dimmer than pattern one; as the luminance of pattern two is increased, a point is reached at which the depth can no longer be perceived, and only when pattern two is at a higher luminance than pattern one is the percept of depth regained.

The criterion for seeing depth is subjective; however there is a simple method of providing a direct comparison between the test stimulus and a stimulus which does have easily perceived depth. This involves simply turning off either pattern one or two, so the images are then seen as some color and luminance against black. This always results in easy depth perception. When the blanked pattern is turned on again, the subject judges if the depth remains. In practice, it is found that subjects are fairly consistent in their criterion for determining the threshold for depth perception.

The system uses a ribbon filament lamp on each side (marked "source"). The center of the filament is used for the light source and the system is telecentrically illuminated and the final image of the filament is formed in the entrance pupil of the eye (Maxwellian view). Patterns are aligned with micrometer screws. Luminance and color are controled by filters introduced between M1 and H1 (and similarly for the other channels); neutral density wedges, marked W and W' are servo driven and normally controlled by the subject. These wedges provided about 1.7 log units of luminance control. Larger changes in luminance or matching of luminances in the various channels are achieved with neutral density filters (Kodak Wratten filter number 96, various densities). Color is controlled by the use of interference filters (Balzers type B-40).

For all experiments, the field of view of the patterns was 10 degrees. The optical distance of the patterns was one meter (i.e., the image is accomodated one diopter in from infinity, which all subjects found comfortable). The field outside the Julesz patterns is not illuminated (aside from minor scattered light).

The luminance of the patterns is measured by photomultipliers (RCA 931A) illuminated by the unused light from beam splitter BS 1. Solenoid driven shutters permitted light from only one pattern at a time to reach the photomultiplier tubes. The voltage drop across the anode and the last dynode was measured by a digital voltmeter and automatically printed.

Calibration of the readings from the photomultipliers was done with a Gamma Scientific model 2000 telephotometer, which measures in absolute foot-lamberts. The photometer was placed at the eyepiece of the system, after each experiment, before any changes had been made and readings of the photometer and the photomultipliers on the apparatus compared. The telephotometer measured the central 3 degrees of the field. After correction for the specific response of the photometer (using the data supplied with the instrument) and applying a correction factor for the difference between the exit pupil of the apparatus and the entrance pupil of the photometer, the comparison measurements are made for each channel, for each color. A computer program converts the photomultiplier readings to absolute foot lamberts. At each step of the process, a error detection system is used, and tests of the conversion technique assure accuracy for all the measurements reported to about 5%, which is acceptable for this type of experiment.

Filters were introduced into the system for the particular experiment at hand. Pattern one was set to the highest luminance possible, and then the subject adjusted pattern two until depth could be perceived. This adjustment was made so pattern two was lower in luminance than pattern one and a point was found at which depth could be seen, but if pattern two was increased in luminance, depth would be lost. Pattern two was always adjusted from low luminance upwards. Depending on the transmission of the various filters, the luminance of pattern two could not at times be increased sufficiently with respect to the highest possible luminance of pattern one to prevent depth perception. These cases required the luminance of pattern one to be reduced so that depth could not be perceived with the available luminances of pattern two; again pattern two was adjusted from low luminance upwards.

There were two possible threshold criteria: the point where depth could just be seen, and the point where depth could just not be seen. In all the data reported here, the measurements are for the case where depth could be seen.

The luminances of each channel were used to calculate the contrast ratio, which is always given as higher luminance/lower luminance (luminance pattern one/luminance pattern two).

Experiments began with high luminance in pattern one, and after an adjustment of pattern two and measurement of luminances, pattern one was reduced in luminance and pattern two readjusted, always from a very low luminance setting. This process was normally repeated until the patterns were too dim to permit the patterns to be easily seen (monocularly and binocularly). Typically, the luminance of pattern one would begin at about 250 ft.-lamberts and end at about 10 ft.-lamberts. About fifteen minutes was required for a series of these measurements with a given set of colors.

Table 6-1 displays the results of a typical experiment. The numbers under the column headings L1, L2, R1, R2 are the absolute luminances in foot-lamberts measured from the four channels respectively.

These results are for an experiment where red (634 nm) and green (512 nm) were used. The first set of numbers are for the case of the red at higher luminance, and the second for the case of green at higher luminance.

The contrast ratio calculated from the luminances of the channels is shown in the right hand column. These contrast ratios are plotted against the log luminance of the brighter pattern in figure 6-4 for the red-at-higher-luminance data, figure 6-5 for the green-at-higher-luminance data. On the graphs, "x" corresponds to the contrast ratio to the left eye, "+" for the right eye, and "o" for the average.

The average contrast ratios for each graph are themselves averaged, to obtain a single number which is then transferred to the graphs which will be discussed in the next chapter. Thus each of these two experiments is reduced to a single point, one for the case of red higher luminance, one for the case of green higher luminance.

The reduction to a single point is made for several reasons. There is no observable relationship between

Table 6-1.

Measured values of the luminances of patterns one and two at the threshold for depth perception, with calculated contrast ratio. Pattern one was red (634 nm) and pattern two green (512 nm); red set brighter than green. Subject CL.

Luminance		
Pattern one (red)	Pattern two (green)	Contrast ratio (pattern one/ pattern two)
256.47	26.40	9.78
167.25	13.00	12.90
104.25	8.95	11.68
54.40	4.62	11.75
34.21	3.86	8.80
22.12	2.42	9.47
13.08	1.42	9.17
	mean contrast ratio	10.51

Table 6-1, continued

This second set of data is for the reverse case of the data above. These are the measured values of luminance for the case green brighter than red.

Luminance, foot lamberts

Pattern one (green)	Pattern two (red)	Contrast ratio (pattern one/ pattern two)
199.44	151.16	1.32
97.36	45.38	2.17
69.00	45.08	1.53
45.03	31.33	1.45
30.20	22.15	1.37
19.30	15.03	1.27
11.91	7.89	1.48
	mean contrast ratio	1.51

Figure 6-4

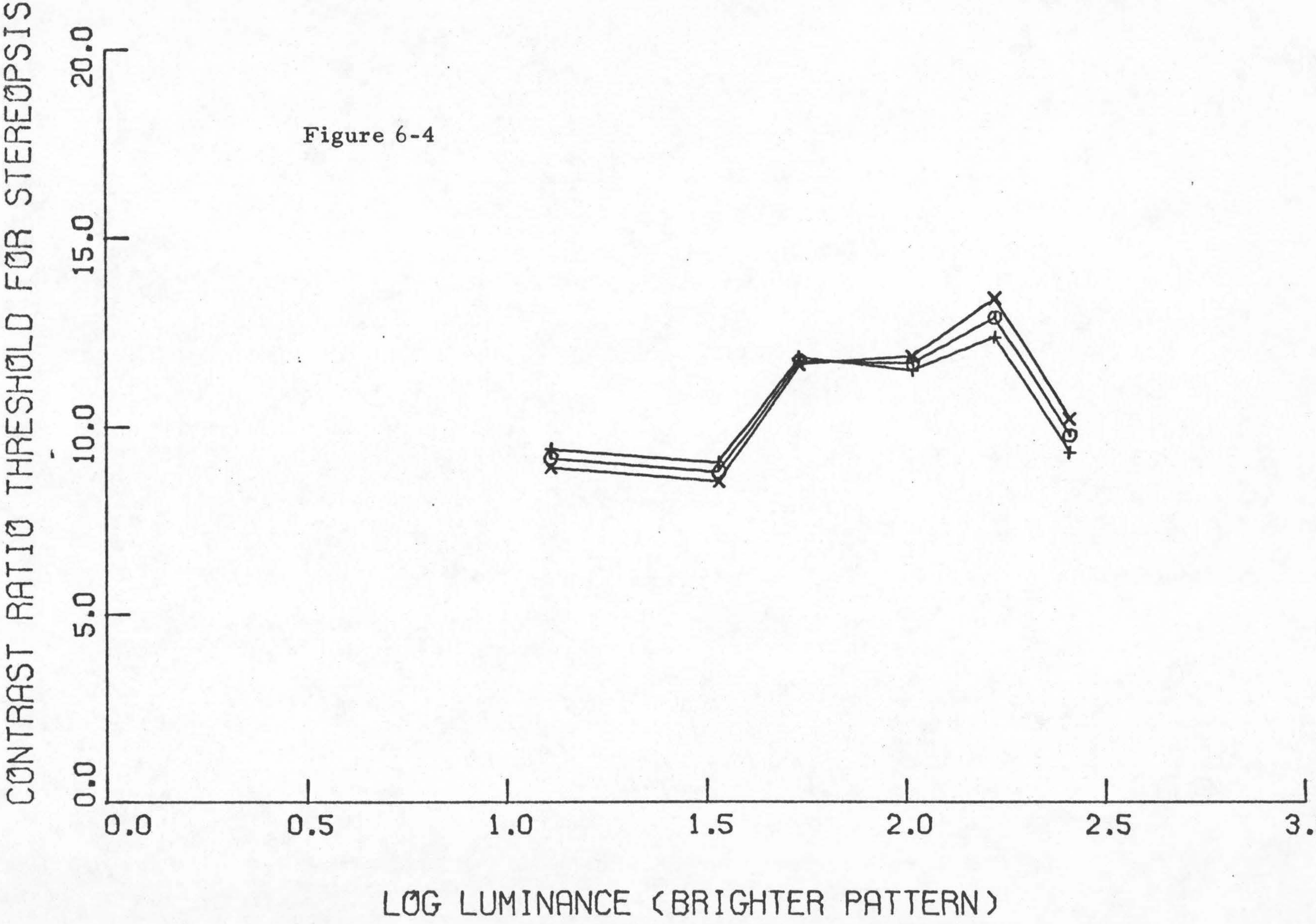
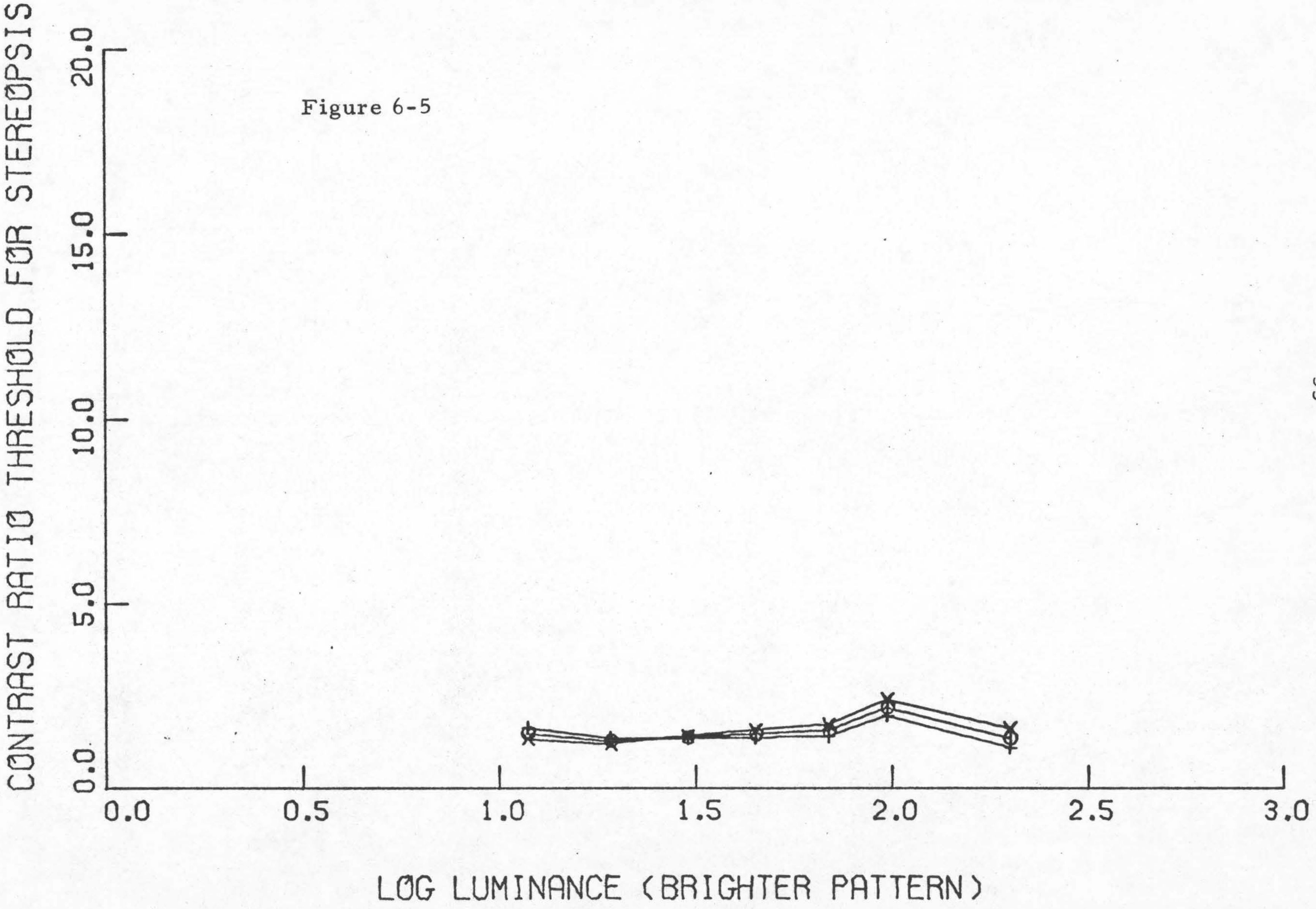

CONTRAST RATIO THRESHOLD FOR STEREOPSIS
0.0
5.0
10.0
15.0
20.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
LOG LUMINANCE (BRIGHTER PATTERN)

Figure 6-5


CONTRAST RATIO THRESHOLD FOR STEREOPSIS
0.0
5.0
10.0
15.0
20.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
LOG LUMINANCE (BRIGHTER PATTERN)

luminance and the required contrast ratio for stereopsis. Figure 6-4 seems to show a tendency toward lower contrast ratios at low luminances, but when compared to other graphs of other experiments, it appears to be only a chance variation, and many graphs have tendencies toward a slight positive or negative slope. Experiments with the same conditions on the same subject at different times have yielded two curves, one with a slight positive slope, the other with a slight negative slope. Because of the subjective criteria employed in these experiments, this kind of variation is to be expected. In the following chapters, the data of many subjects will be compared, and the significance of data is shown not in the specific point to point numbers, which varies widely between subjects, but in the general phenomena shown by all subjects.

Image Quality

The monocular alignment (L1 with L2, R1 with R2) was done by the subject visually aligning the patterns. There were several minor problems in alignment: the final size of the image varied with the color used because of the secondary color aberrations of the achromatic lenses. This reached about 1½% for differences between red (634 nm) and deep blue (421 nm). This corresponds to about 3/4 of a square error around the edges of the patterns (the subjects aligned the center of the patterns) which is readily visible. Over the part of the pattern with the center square shift, the error thus varied between zero and about $\frac{1}{4}$ square error, not enough to obscure the visibility of the small component squares which make up the Julesz patterns.

Pincushion distortion was visible, but was the same for all patterns and thus did not affect alignment.

Light scattering occurred due to the complexity of the optical system; as a result, the portions of the patterns which were nominally not illuminated did have a small luminance, in all cases less than 2% of the illuminated portions of the patterns.

Alignment of the exit pupils was achieved by viewing the exit pupils on axis, and adjusting beam splitter BS 1 until they coincided. Small errors were of little consequence since the exit pupil of the system was smaller than the entrance pupil of the eye under the dim light-adapted conditions of the experiment. Subjects were instructed to keep their heads in a position such that the apparent brightness of all parts of the image was as high as possible.

Subjects

All subjects were experienced observers familiar with the operation of the experimental apparatus but not the purpose of the experiment initially. All subjects had no difficulty or ambiguity in identifying depth seen in black and white Julesz patterns, and were trained to use the various optical adjustments of the apparatus for alignment and experiments while maintaining the correct head position for Maxwellian view exit pupils. Quantitative data were recorded from five subjects, and qualitative data from an additional six subjects were used to confirm the basic effect found, that is the disappearance of depth perception with patterns having no luminance differences, only color differences. All persons who passed the initial screening confirmed the qualitative effect.

CHAPTER SEVEN

RESULTS

The most important result has already been mentioned, and was shown for one particular case in chapter 6. This is the inability of the visual system to see depth when contours are presented in color differences only; that luminance differences are required for stereopsis.

The luminance difference required is dependent on which of the stimulating colors is at a higher luminance. In the case of red and green (634 and 512 nanometers) discussed in chapter 6 for example, depth is perceived when the green is brighter than the red by a factor (contrast ratio) of about 1.51, or when red is brighter than green by a factor of about 10.5 (subject CL). Between these two points, there is a range of contrast ratios where depth is not perceived. (For subject CL, this range of contrast ratios is larger than for the other subjects and was used in chapter 6 for clarity; see below.)

Thus the curves on figure 6-4 and 6-5 divide a plane of points corresponding to varying contrast ratios at varying luminances into two sectors; regions where depth can be perceived, above the line, and where depth cannot be perceived, below the line. As described in chapter 6, the graphs are reduced to a single point, and the data which remains are two numbers, one from each graph: a contrast ratio for red brighter than green, and for green brighter than red. These numbers can be regarded as points on a continuous scale of contrast ratios; see figure 7-1. In the middle of the scale, the contrast ratio is one, where the red and green are of equal luminance. There are three regions on the scale; one in the center corresponding to contrast ratios where depth is not perceived, and two regions on either side where depth is perceived.

The scale can be transferred to a continuous graph shown in figure 7-2, where the scale is plotted vertically passing through the x axis at 512 nm. Here there is a range of colors across the spectrum, let us call these colors C1. Red appears in all the data plotted here, call this fixed color C2, and a series of scales of the type shown in figure 7-1 are plotted, with the points connected by the lines. Above the x axis, the contrast ratios are plotted for patterns with the red (C2) brighter than the color C1 on the x axis; below the axis, the color on the axis C1 is brighter than red (C2). The regions of the scale in figure 7-1 are now areas in the graph; between the plotted lines, depth is not perceived, above and below the lines depth is perceived.

Similar plots are shown in figures 7-2 to 7-10, for two other values of the color C2, green (512 nm) and blue (477 nm), are for different subjects. The exact colors

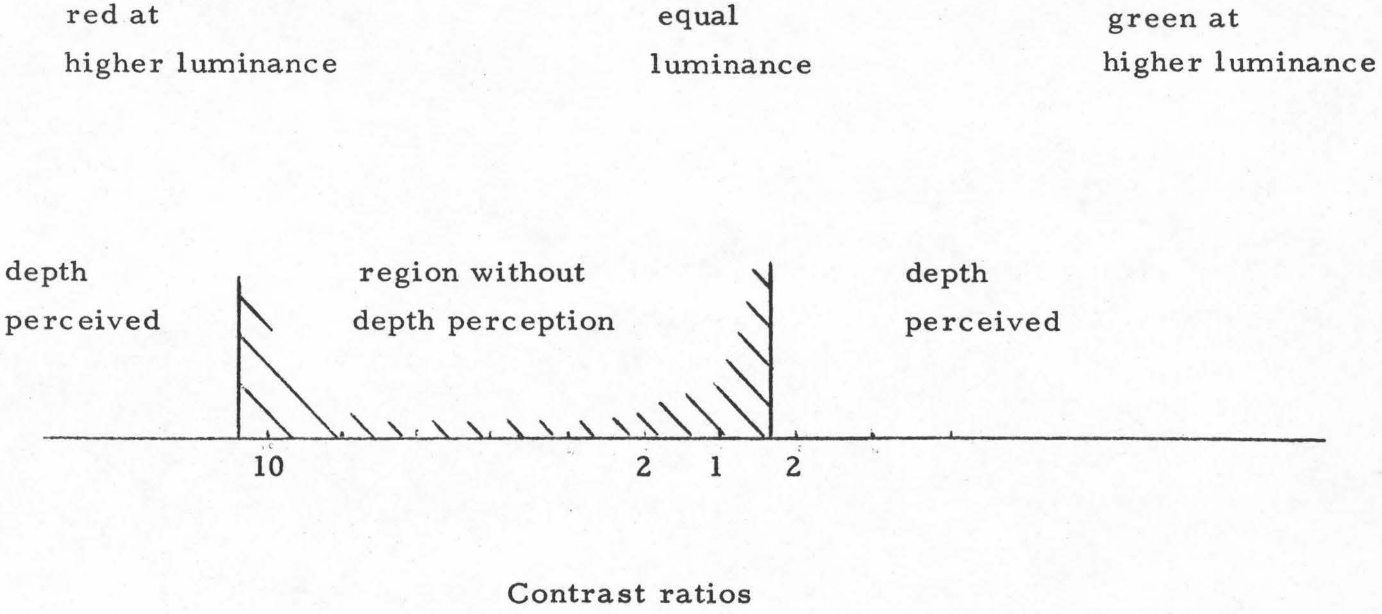


Figure 7-1. Ranges of depth perception for varying contrast ratios using red (634 nm) and green (512 nm). Subject CL.

Captions for figures 7-2 to 7-11:

Subject CL:

figure 7-2 The primary color is red (634 nm)

7-3 The primary is green (512 nm)

7-4 The primary is blue (477 nm)

Subject JRC:

figure 7-5 The primary is red

7-6 The primary is green

7-7 The primary is blue

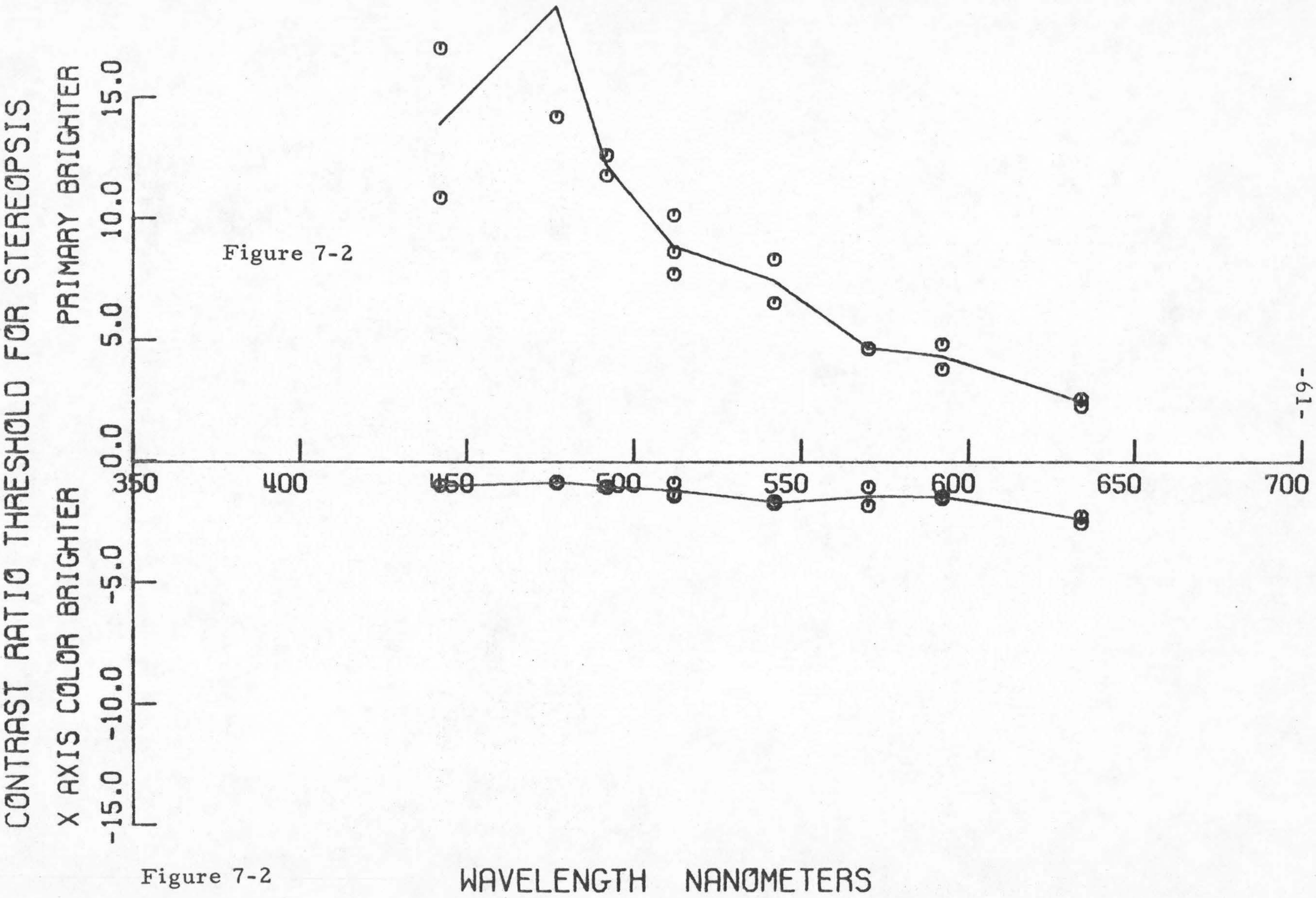
Grouped graphs, for several subjects:

figure 7-8 The primary is red

7-9 The primary is green

7-10 The primary is blue

7-11: A three dimensional surface of contrast ratios, for subject CL. See text.


CONTRAST RATIO THRESHOLD FOR STEREOPSIS
PRIMARY BRIGHTER
X AXIS COLOR BRIGHTER
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
350
400
450
500
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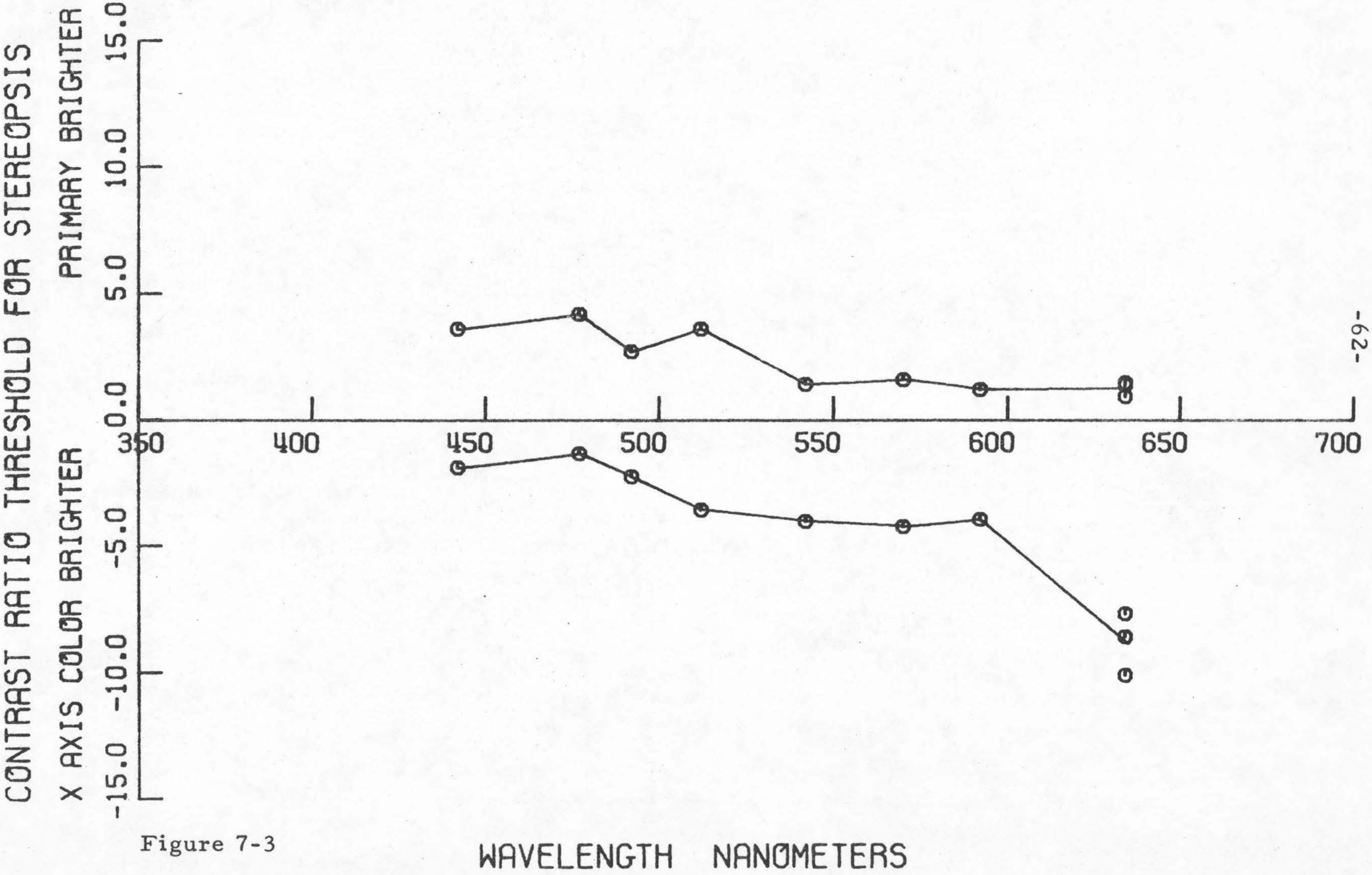
600
650
700
Figure 7-2
WAVELENGTH NANOMETERS

Figure 7-2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X AXIS COLOR BRIGHTER
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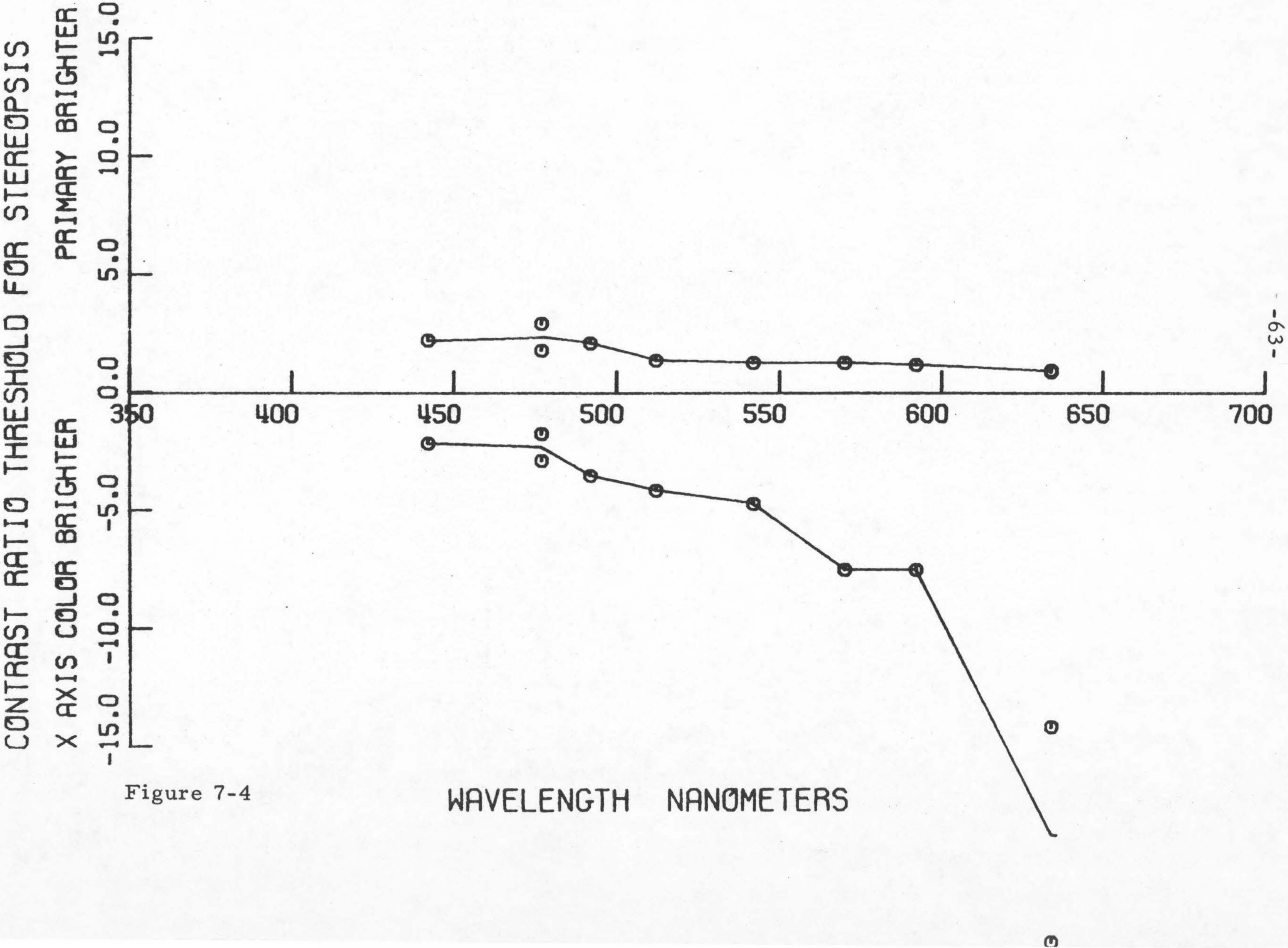
WAVELENGTH NANOMETERS

Figure 7-3


CONTRAST RATIO THRESHOLD FOR STEREOPSIS
PRIMARY BRIGHTER
X AXIS COLOR BRIGHTER
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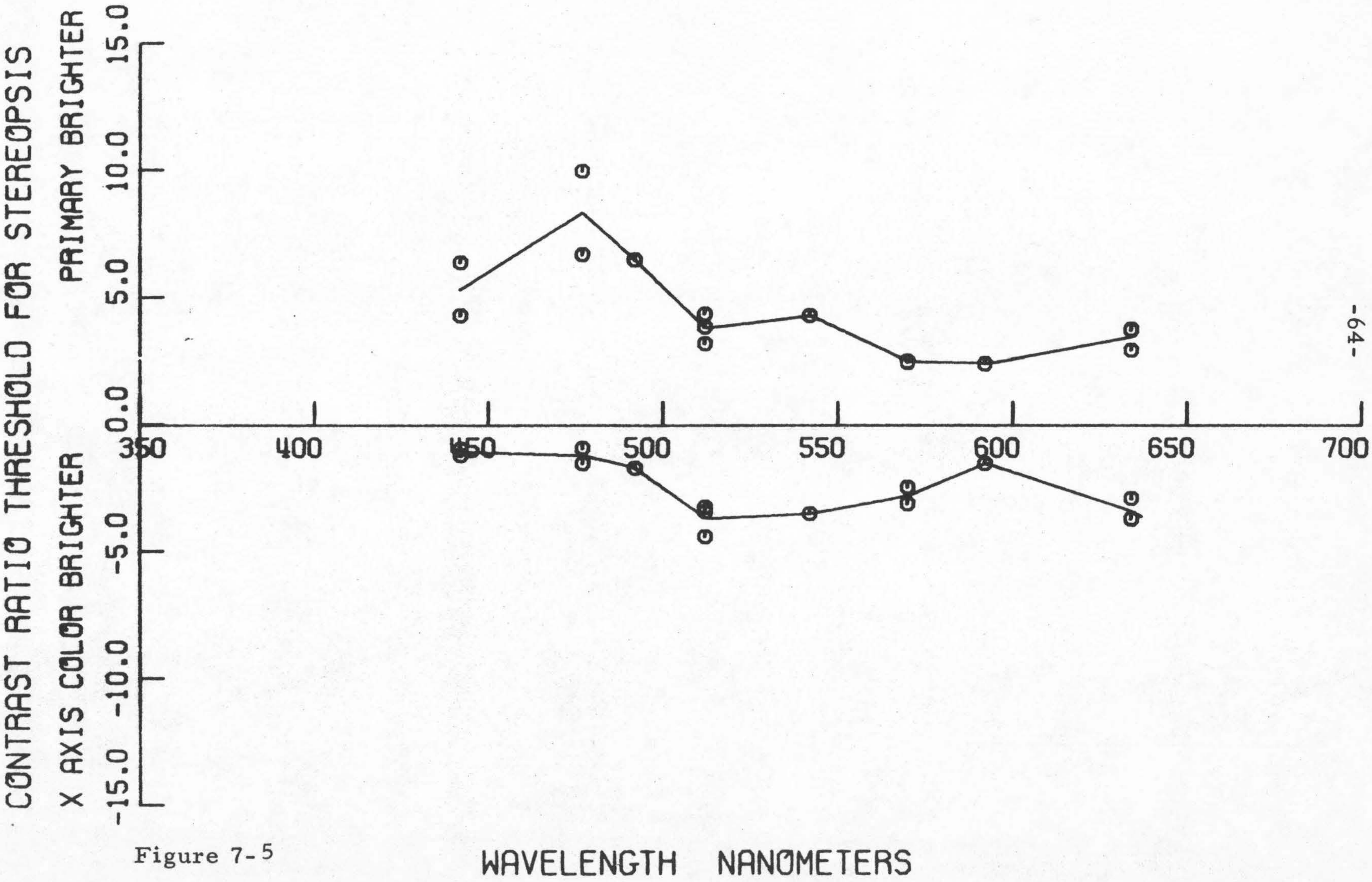
WAVELENGTH NANOMETERS

Figure 7-4


CONTRAST RATIO THRESHOLD FOR STEREOPSIS
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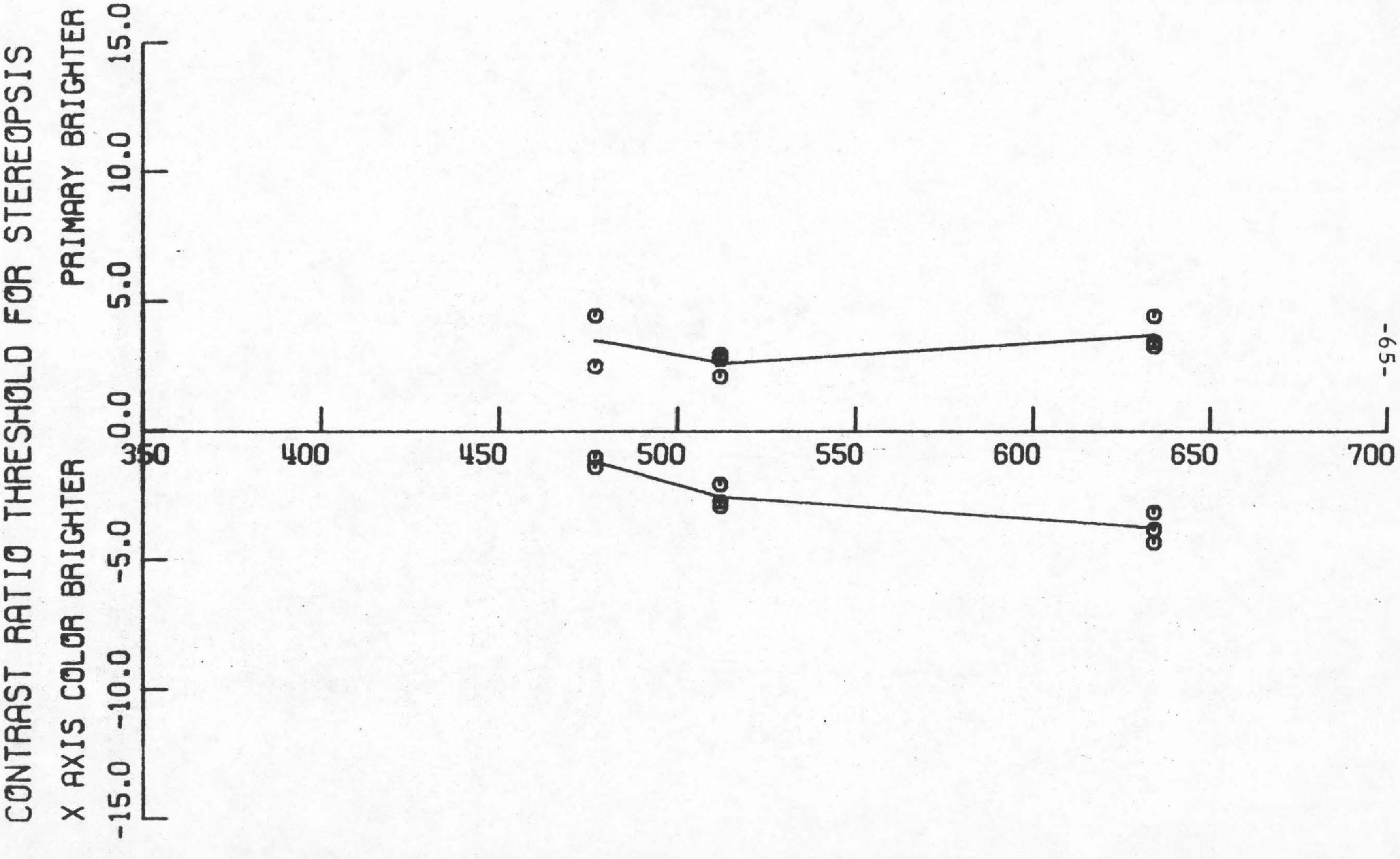
WAVELENGTH NANOMETERS

Figure 7-5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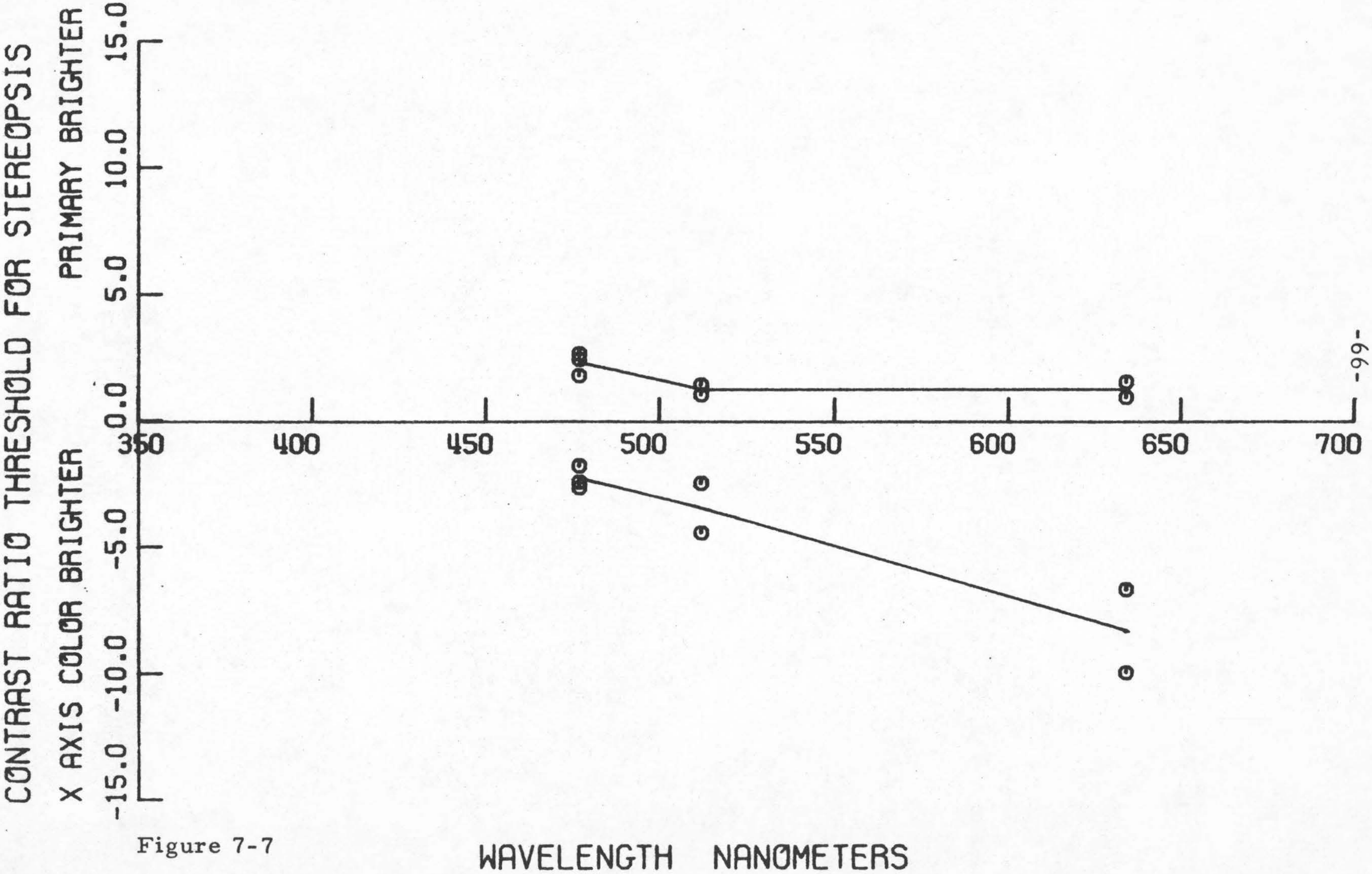
WAVELENGTH NANOMETERS

Figure 7-6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WAVELENGTH NANOMETERS

Figure 7-7

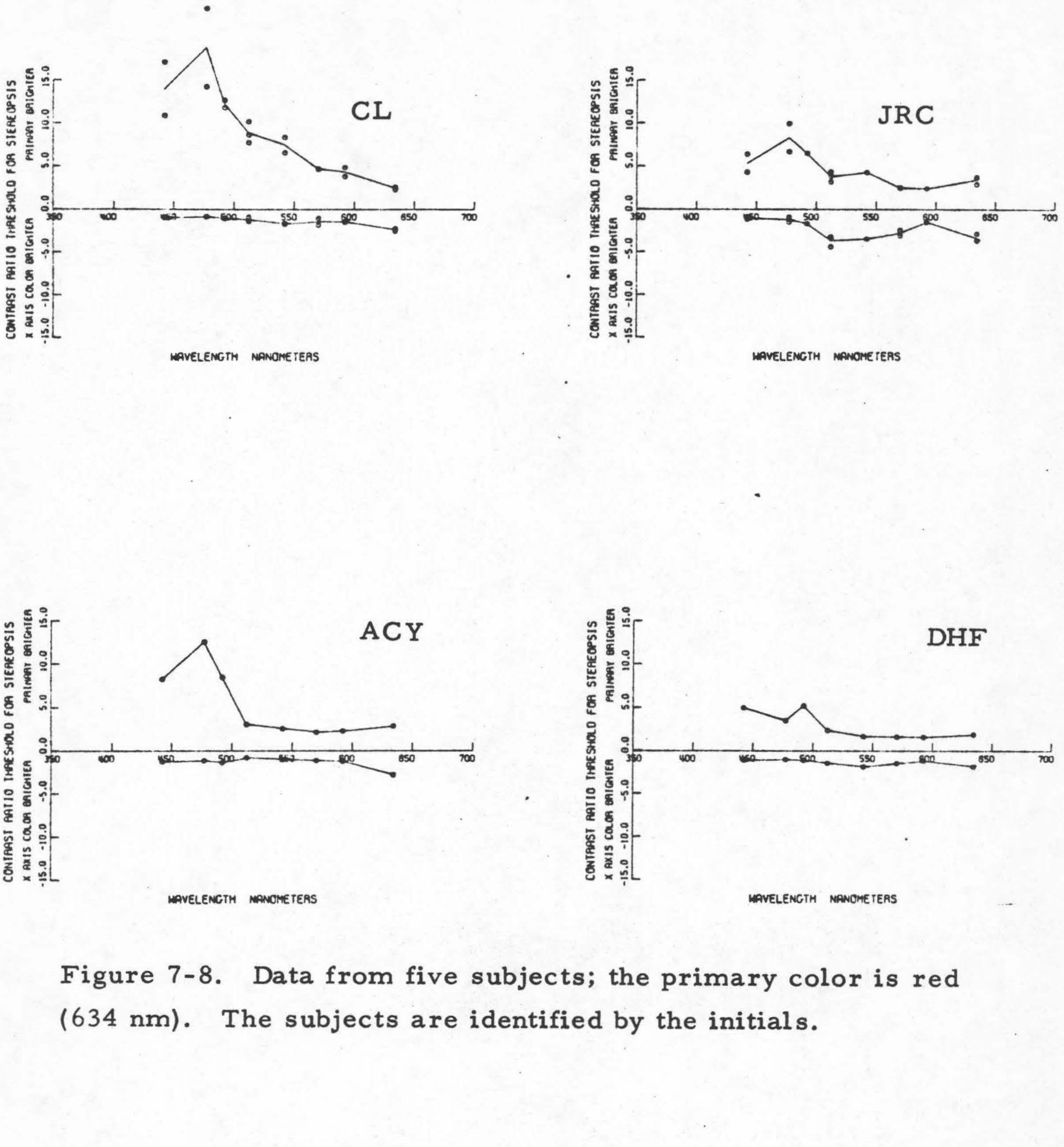
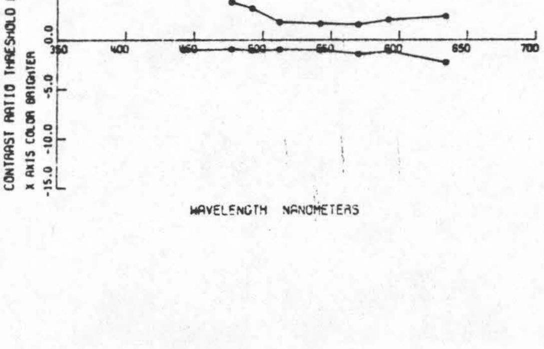
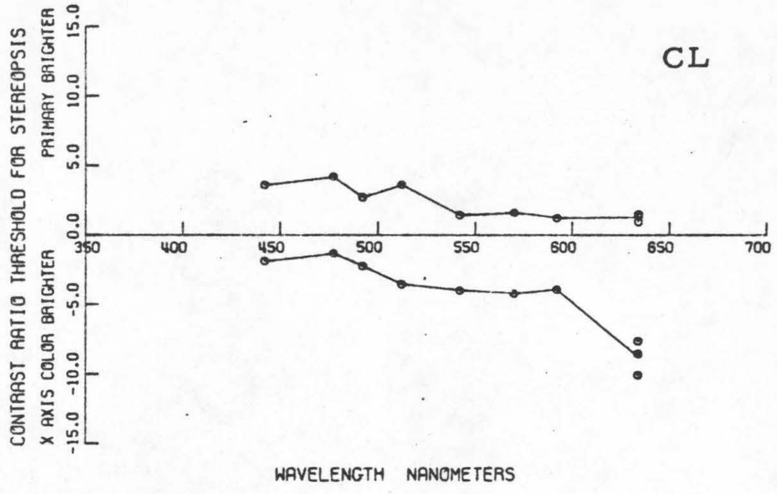


Figure 7-8. Data from five subjects; the primary color is red (634 nm). The subjects are identified by the initials.





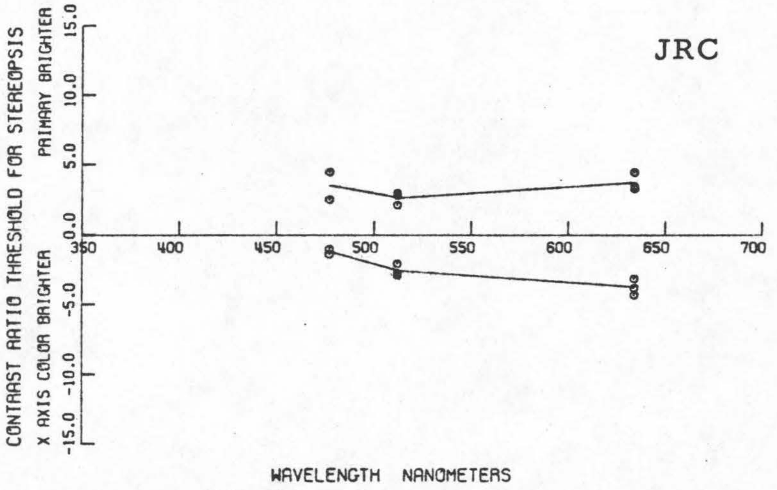
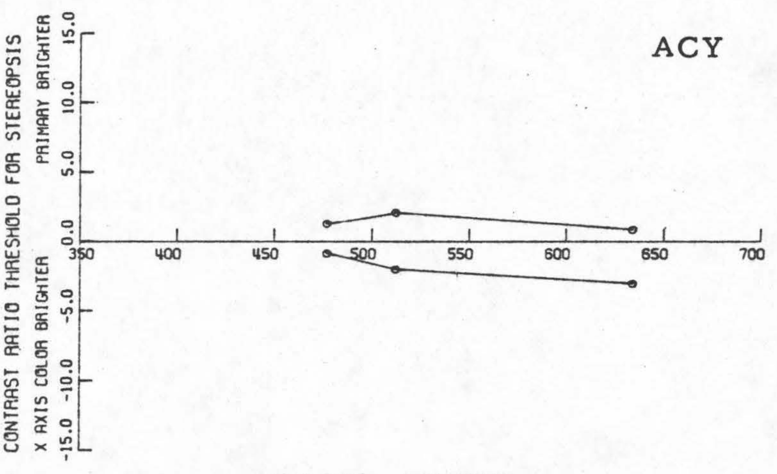


Figure 7-9. Data from three subjects; the primary is green (512 nm).



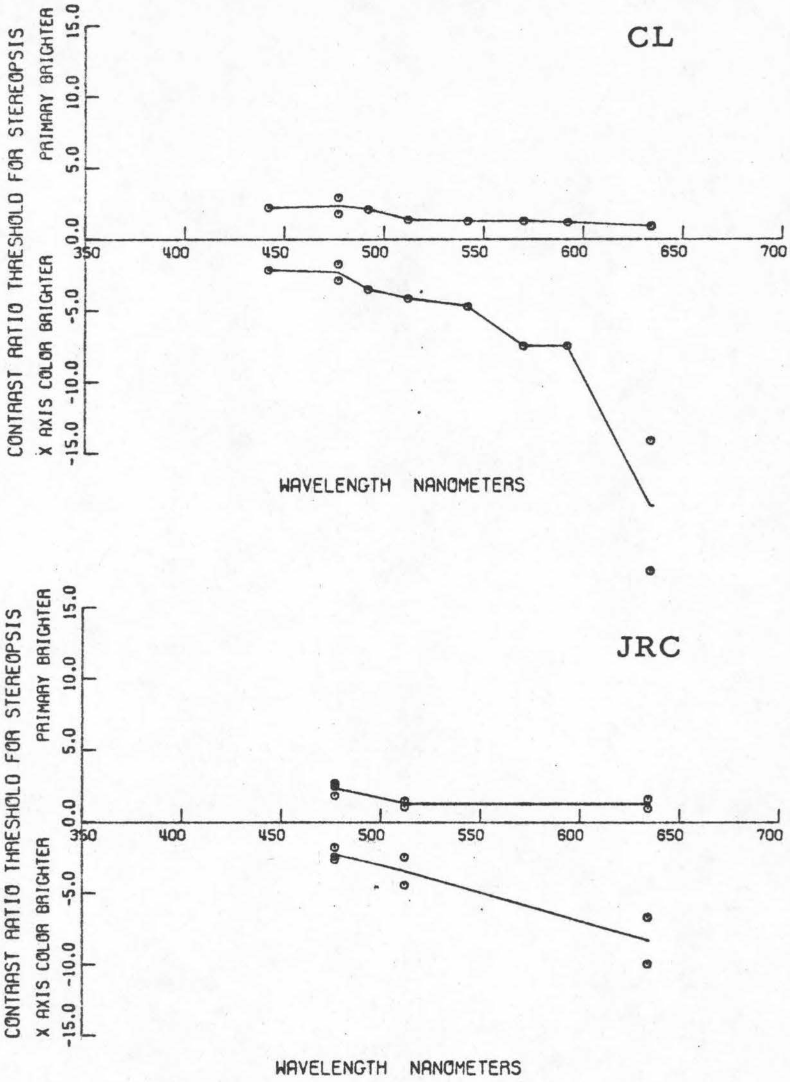
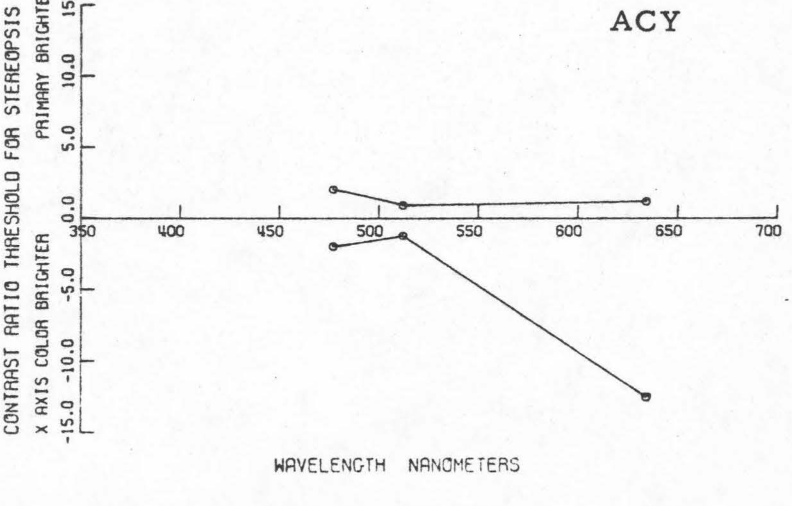


Figure 7-10. Data from three subjects; the primary is blue (477 nm).



and subjects involved are noted on the captions.

If, for one subject, the three graphs corresponding to C2 equals red, green, and blue are put together, a three dimensional plot can be obtained in the following way: The x axis of the graphs such as figure 7-2 is wavelength of C1. Figure 7-3, 7-4 are similar but for different wavelengths of C2; a third axis can be constructed using this parameter C2, where figure 7-4 (for blue, 477 nm) is assigned 477 nm on the y axis, figure 7-3 assigned 512 nm and so on. The result is figure 7-11, based on figures 7-3, 7-4, and 7-5, which shows two wavelength axes C1 and C2 on the horizontal plane, and the contrast ratios are plotted vertically above the x-y plane for the case of y axis color C2 brighter than the x axis color C1.

If both values of contrast ratios, above and below the x axis of figures 7-2, 7-3, 7-4 were used in figure 7-11, another surface below the x-y plane would be constructed. This is not plotted in figure 7-11 since this second surface is mirror anti-symmetric to the surface above the x-y plane about the line C1 equals C2. This lower curve plots the case of x axis color C1 brighter than the y axis color C2. Therefore the position of X = 634, y = 477 nm below the x-y plane is equivalent to the condition y = 634, x = 477 nm above the plane.

By the elimination of the lower surface, the single surface plotted in figure 7-11 separates the condition of depth perceivable (above the surface) and depth not perceivable (below the surface, to the x-y plane).

The most significant feature is that for all subjects, the surface is bent upward (i.e., higher contrast ratios required) when the red is brighter, particularly when red is brighter than blue. The amount of this increased contrast ratio varies with the subject, but the visual criteria used by the various subjects probably varied. They were only instructed to find the minimum contrast ratio for stereopsis, and given no further instructions about subjective standards. A tabulation of this increase is shown in table 7-1.

A section through the surface where the x axis color equals the y axis color (C1 equals C2) is shown for two subjects in figures 7-12 and 7-13. Along this section, all the colors used in the channels are the same, and hence only luminance differences are involved. The contrast ratios are about the same as found when using white light for all channels (white light of a tungsten filament, about 2800 degrees Kelvin correlated color temperature). The variation of contrast ratios shown in these plots is small compared to the variations shown in the surface in figure 7-11.

Table 7-1

Contrast ratios for cases involving
red (634 nm) and blue (477 nm).

subject	red brighter than blue	blue brighter than red
CL	19.7	1.32
JRC	8.4	2.0
ACY	15.5	1.36
DHF	4.53	1.35
LMO	3.83	1.18

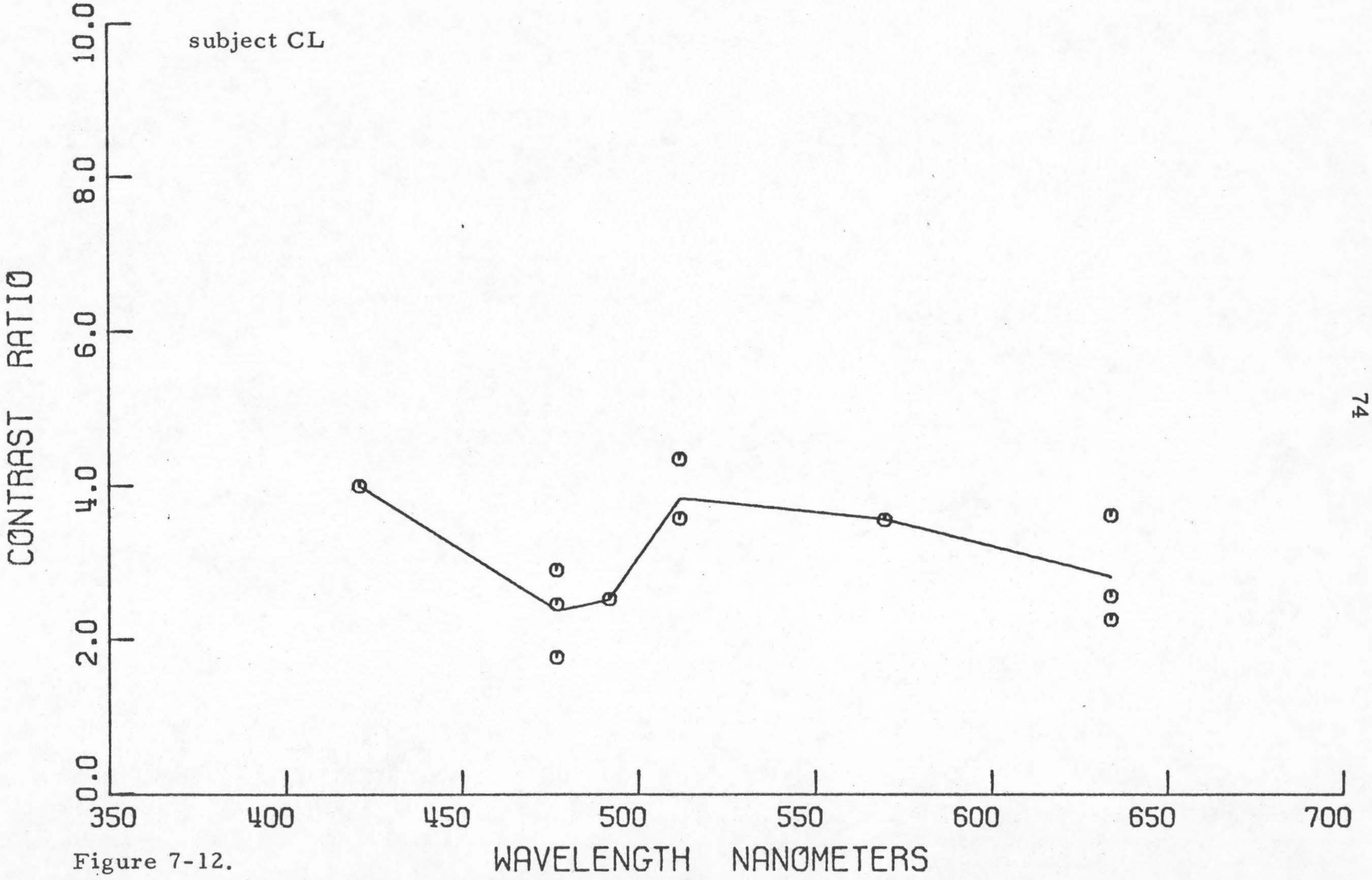

subject CL
CONTRAST RATIO
10.0
8.0
6.0
4.0
2.0
0.0
350
400
450
500
550
600
650
700
WAVELENGTH NANOMETERS

Figure 7-12.

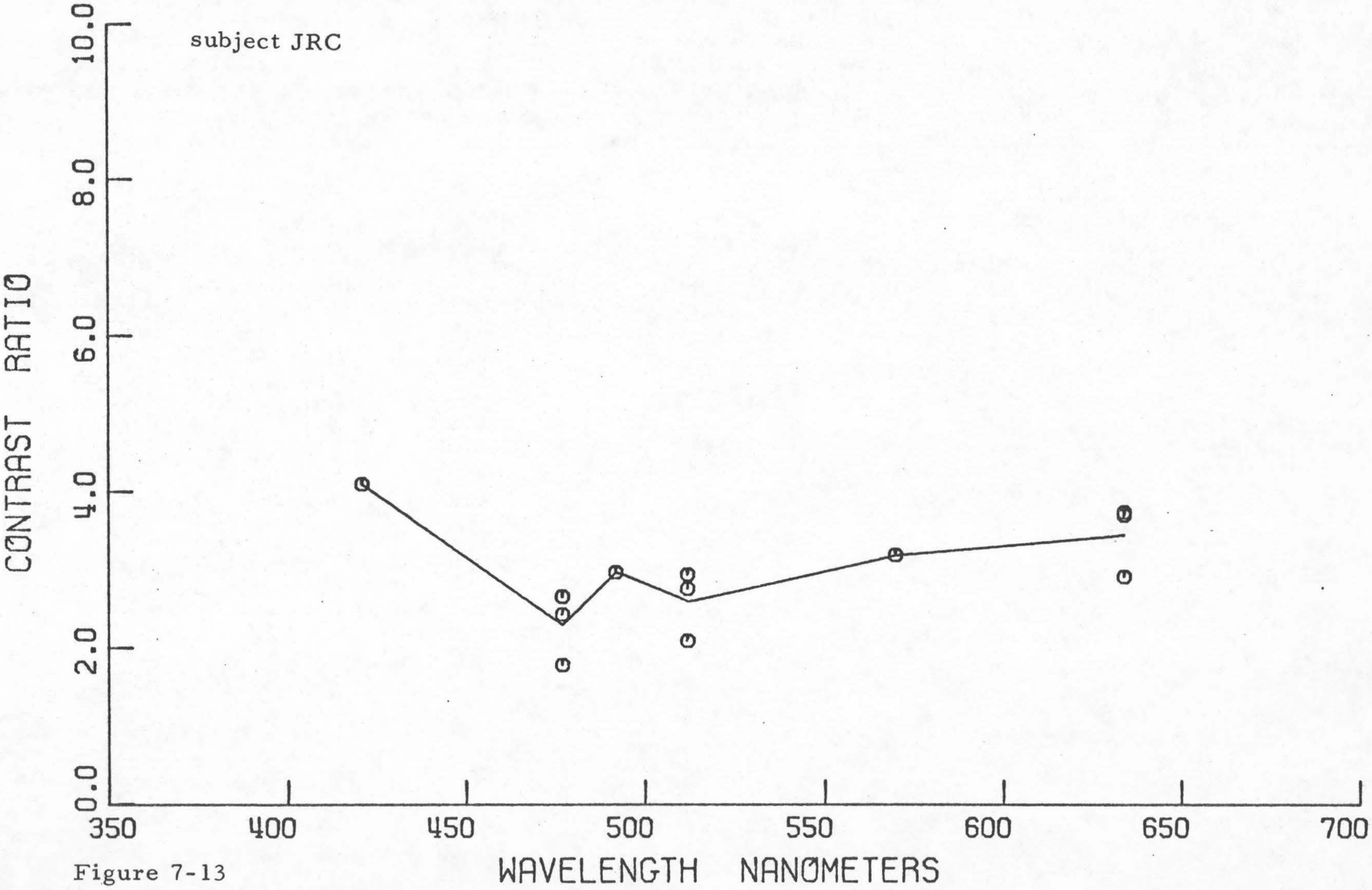

subject JRC
CONTRAST RATIO
0.0
2.0
4.0
6.0
8.0
10.0
350
400
450
500
550
600
650
700
WAVELENGTH NANOMETERS

Figure 7-13

Binocular Rivalry

Binocular rivalry occurs when the images to the two eyes do not match, and the mismatch is severe enough to be perceptible. (Binocular rivalry does occur when there are large retinal disparities, as described in chapter two, but this does not apply here.) The rivalry which can occur with the Julesz stereo pairs in the configurations used in these experiments are generated by mismatches in luminance and color, and not by changing the spatial arrangement of the patterns. For the purposes of this discussion, binocular rivalry will be separated into several types. Rivalry or mismatch in luminance means a perceptible difference in luminance between the left and right patterns, rivalry in color means different color filters were used in L1 and L2 or R1 and R2 or for both pattern one and two.

Type 1. Rivalry in luminance only, colors match, and contours match--that is the direction of increasing or decreasing luminance across a monocular contour (the small squares) is the same across corresponding borders in the fields of the two eyes. For these experiments this means that L1 and R1, for example, are both brighter than respective L2 and R2, but the luminance of L1 and R1 (or L2 and R2) do not match

Type 2. Rivalry in luminance, colors match, contours do not match. Directions of increasing or decreasing luminance across a monocular contour are not the same. In this case, L1 is brighter than L2, and R2 is brighter than R1. This means that the pattern which is brighter on the left side is darker on the right side.

Type 3. Rivalry in colors only, luminances match. Here the luminance of L1 and R1, and L2 and R2 match, but the colors of L1 and R1 are not the same.

Type 4. Rivalry in both luminance and color.

An experiment involving type one rivalry is shown in figure 7-8. The set up begins with the normal type of configuration, using red and green with colors and luminances matched. Then a neutral density filter is introduced into the light path of R1. Since the experiment is to test for stereopsis with pattern one dimmer, the presence of the filter makes pattern R1 very dim and produces very large differences in luminance on the right side.

Figure 7-14 displays the results of several trials, and is plotted in the manner of figure 6-4. The very large

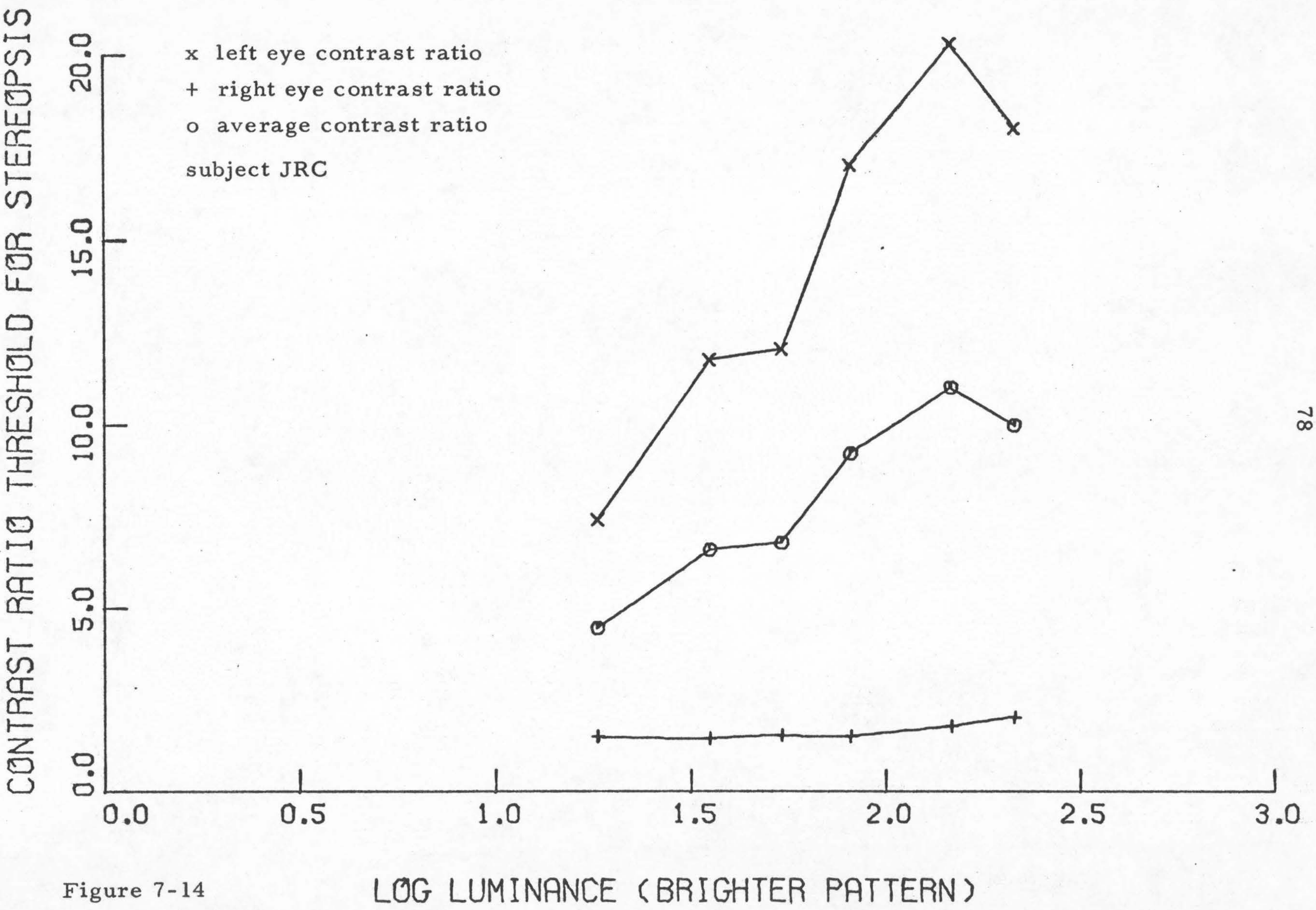

x left eye contrast ratio
+ right eye contrast ratio
o average contrast ratio
subject JRC
CONTRAST RATIO THRESHOLD FOR STEREOPSIS
0.0
5.0
10.0
15.0
20.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
LOG LUMINANCE (BRIGHTER PATTERN)

Figure 7-14

contrast ratio to the right eye due to the interposed neutral density filter does not offset the requirement for a threshold contrast in the left eye; to put it another way, a large contrast ratio to one eye cannot offset a smaller than threshold contrast ratio to the other eye. The reverse case is shown in figure 7-15, where the filter is placed in the light beam of R2. This reduces the luminance difference between R1 and R2 (again the visual task is to find the threshold for stereopsis with pattern one dimmer).

In type two rivalry, no depth perception is possible, regardless of the color involved. (For this type of visual task, see chapter 8.)

In type three rivalry, depth perception is always possible, provided that the contrast ratio is sufficiently large. The conditions of type two rivalry explained above do not normally result in a alternation of visibility between the two eye images which is the classic description of rivalry. The alternation of visibility of eye fields is at least partly a function of the size of the rivalrous regions. If the size of the region (which must be a continuous integral region, without breaks) is large, then alternation clearly occurs. At the other extreme, looking at metallic surfaces, for example, each eye essentially sees many rivalrous points of light and color, there is no apparent alternation, but rather an impression of

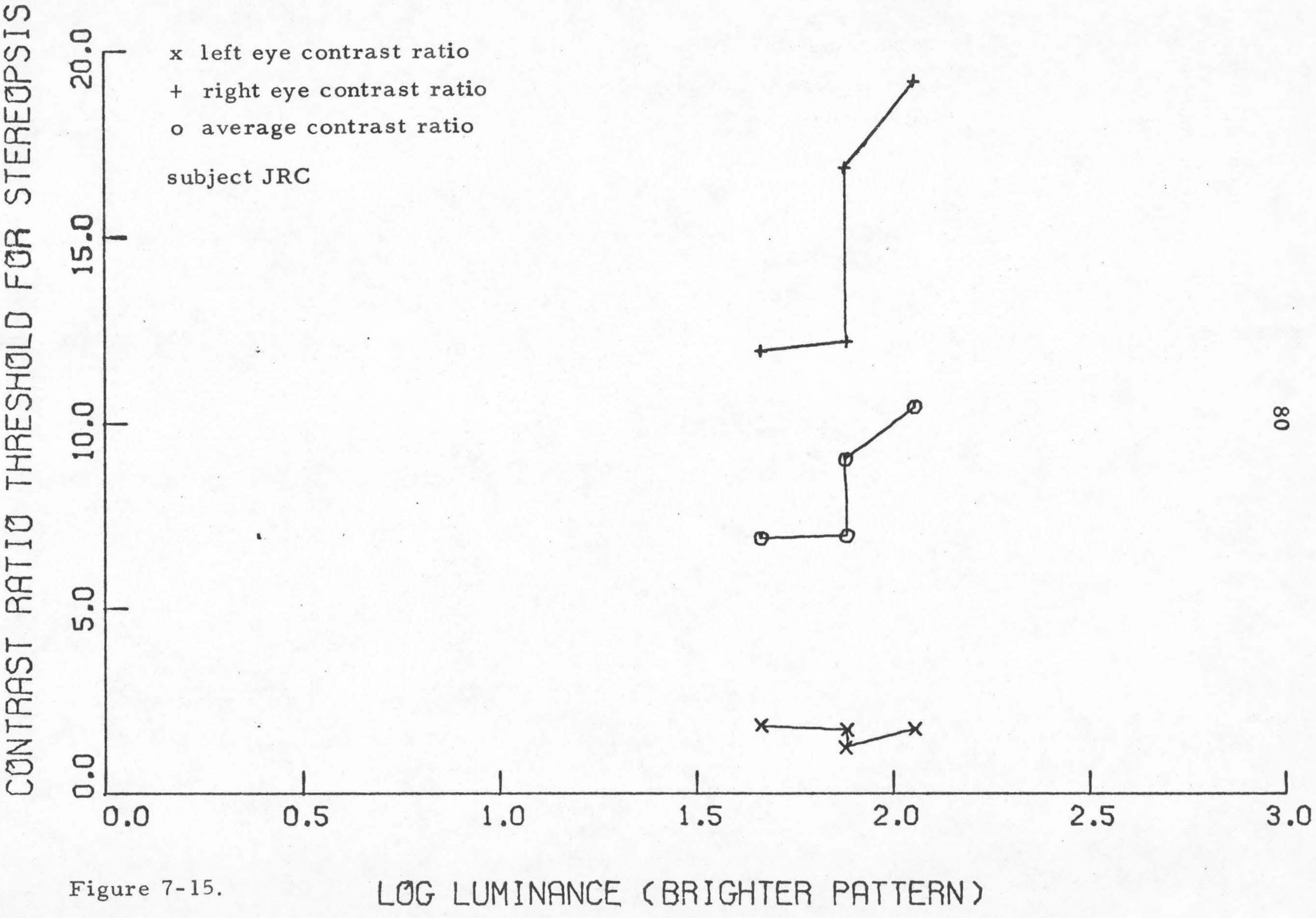

x left eye contrast ratio
+ right eye contrast ratio
o average contrast ratio
subject JRC
CONTRAST RATIO THRESHOLD FOR STEREOPSIS
0.0
5.0
10.0
15.0
20.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
LOG LUMINANCE (BRIGHTER PATTERN)

Figure 7-15.

luster (see chapter 1). The Julesz patterns used here in type two rivalry is closer to the luster appearance rather than alternation of images.

An experiment with type three rivalry is shown in figure 7-16. Here the channels were set up L1 and R2 red (634 nm) and L2 and R1 green (512 nm).

For type four rivalry, depth perception is not possible (the reservation noted above for type two rivalry applies here also).

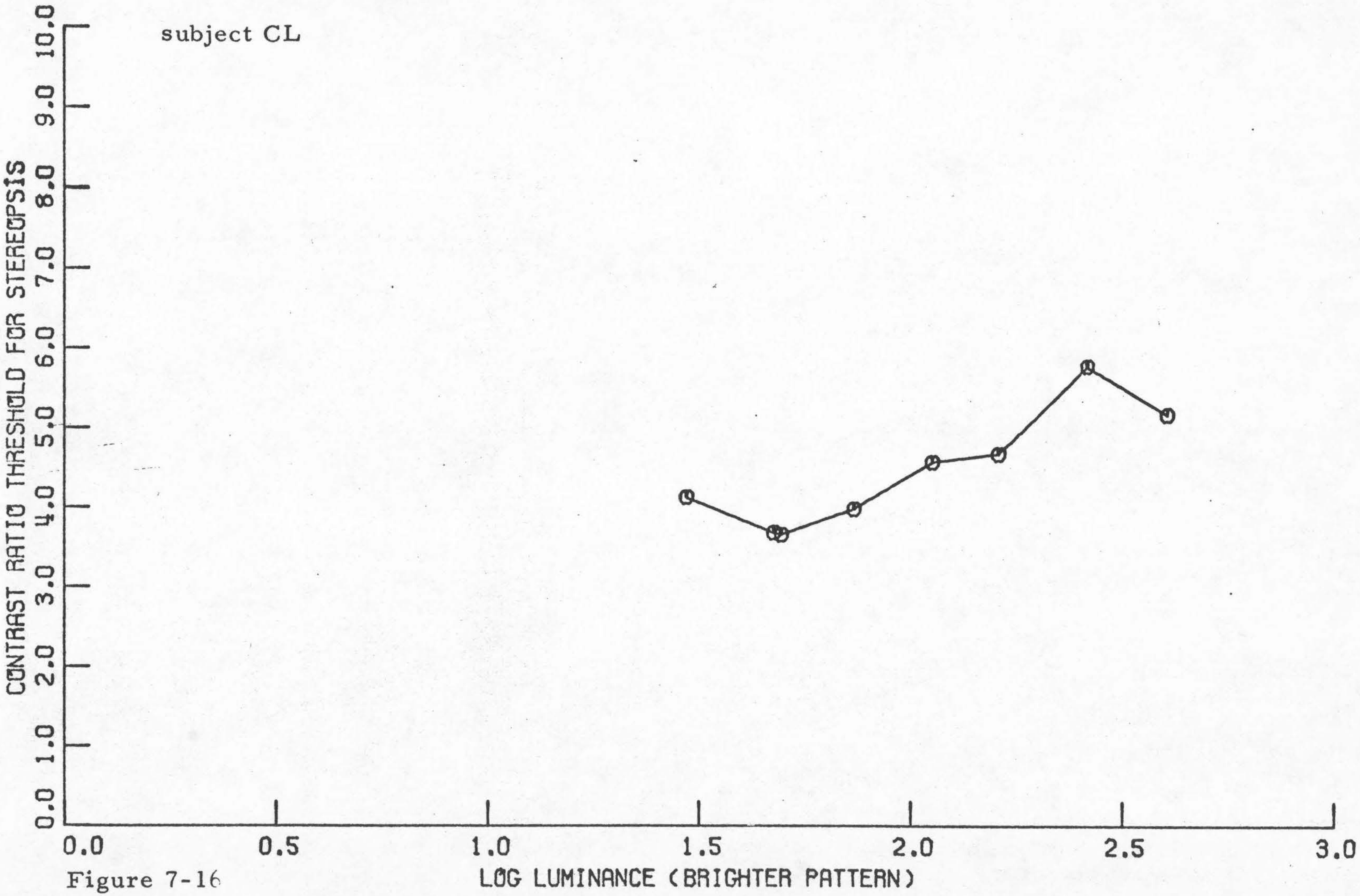

subject CL
CONTRAST RATIO THRESHOLD FOR STEREOPSIS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
LOG LUMINANCE (BRIGHTER PATTERN)

Figure 7-16

CHAPTER EIGHT

DISCUSSION

The result that depth perception is possible only with a luminance contrast, and not from contours created by color differences alone is not expected from the psychophysical literature.

Experiments have been done previously with binocular color only for fixed luminances, and without the ability to systematically vary the stimulus parameters. It has always been tacitly assumed, that the detection of contours (the basis of the CIE color system, for example) is just a matter of varying the colors and luminances for detectable borders. While this is valid for monocular contours, stereo contour detection is now shown to be quite a different matter.

The evidence here suggests a separate mechanism for the color and luminance channels in the visual system, that binocular vision uses the luminance channel principally with secondary effects based on the particular colors involved.

The neurophysiological literature suggest the explanation of the phenomena. At the level of the retina of several animals, including the frog, snake, and guinea pig, Granit (1947) found that electrophysiological recordings supported the hypothesis of two types of fibers, the dominators, which had broad sensitivity through out the spectrum, corresponding to luminosity curves, and modulators, which have narrower responses, to restricted portions of the spectrum. In the lateral geniculate, DeValois and his associates (1972) find two general types of cells, opponent color cells, with differential responses to varying spectral stimulation, and non-opponent cells, with the same responses irrespectively of the spectral stimulation.

Hubel and Wiesel (1968) found that most of the cells in the primary visual cortex (area 17) of the macaque and spider monkey responded to spatially appropriate stimuli without regard to the color of the stimulus, and the cells which respond to color are in the minority (7%). About half of these color responsive cells had responses to a specific color (but not others) similar to their response to white light, the other half responded more specifically, such as only responding to moving bars of a particular color, and not to white light.

The neurophysiological data suggest and the present experiments confirm that simple contour detection and binocular contour detection use different criteria for finding objects (contours) and the color information about the location of simple contours is discarded before binocular contour information is processed.

This conclusion applies, of course, to the particular stimulus configuration used in these experiments, and might not apply to all possible binocular stimuli. DeValois has found that in general, opponent color cells respond to stimuli over a greater spatial angle than achromatic cells. The implication of this is that opponent color cells have lower acuity than achromatic cells, but this cannot be drawn absolutely because acuity is dependent on the interaction between different cells. But if the implication is correct, and the data from monkeys can be applied to humans, then it is possible that the Julesz patterns if presented over a larger visual field would allow depth perception with squares generated in color alone. The present experiment's ten degree patterns produce small squares 6 min arc on a side, only a few times larger than the absolute resolution of the eye (about one min arc). A large field stereoscope is feasible, although there are formidable technical problems in generating a controllable four channel display in Maxwellian view.

There is an additional reservation to the absolute conclusion that color information is not used at all, but may be used in a minor way. The plots shown in figures 7-12 and 7-13 are similar to plots of the luminance difference or contrast ratio required to see monocular borders in a bipartite field of uniform spectral color. The difference is that the contrast ratios obtained in these experiments are larger than the contrast ratios for monocular experiments. Since binocular contours are usually based on monocular contours, the higher threshold is not surprising. The threshold is also somewhat larger than for some of the combinations of different colors. This raises the possibility that some color difference information is used in depth perception, enough to lower the threshold contrast ratio under certain conditions.

Although the existing psychophysical literature does not provide information about the interactive effects of color and luminance in binocular vision, there is some information about the possibility of independent processing of color and luminance information in other visual tasks.

Tyler (1971) has summarised this material. The original psychophysical opponent color theory, by Hering, and developed by Hurvich and Jameson (1955) is based on the independence of color and luminance channels, but does not specify the extent of such independence. Several studies of chromatic adaption have suggested independence of color and luminance systems (Brindley, 1953; Scheibner, 1966). Cone monochromats have unimpaired chromatic aberration reflexes for accomodation without color vision, implying that chromatic information is available at the stage needed for accomodation, but absent at later stages (Fincham, 1951).

Spatial interactions of regions of different color and regions of different luminance are not the same. Mach bands are readily observable at luminance difference borders, but only at certain types of color difference borders (Daw, 1964). Hilz and Cavonius (1970) studied the ability to discriminate square wave gratings which consisted of alternating bars of two spectral colors. They found that the ability to see the grating as a grating instead of a uniform field depended on the spectral distance between the two colors, and when the bars were set to the same luminance, then a much larger spectral distance was required.

The Liebman effect (1927) is the blurring and loss of definition of colored objects against a colored or neutral background when the luminances of the object and background are made the same.

All of this psychophysical data lend support to the hypothesis of independent color and luminance channels in the visual system, although none touch on the question of binocular perception when all monocular portions of the image are perceived intact.

There is at present no satisfactory explanation for why the contrast ratio required for depth perception should be higher when red is brighter than blue compared with most other color combinations.

There are several factors which may contribute to differing contrast ratios over the various colors. They are discussed below, but it should be at once mentioned that these factors mostly affect blue light, and would be more likely to intrude into results had those results shown that higher contrast ratio was required when blue was brighter (instead of red brighter, which is the experimental result).

The acuity of the eye is generally the same for monochromatic light as it is for white light as measured by most conventional techniques. This does not apply to the case of sinusoidal gratings, where in blue monochromatic light, acuity is only about 7'30", as opposed to about 1' for red and green (Brindley, 1954).

The 7.5 min arc acuity to sinusoidal gratings in blue light can be compared to 6 min arc small squares. This is not a completely realistic comparison since Landolt C patterns or two line discrimination tests in blue light yield about 1-2 min arc acuity, about the same as other spectral colors.

If there is lowered acuity to the blue light in the patterns, this is difficult to reconcile to the fact that when blue is brighter than red, then only about a 1.5 contrast ratio is required for depth perception, since poor acuity in the blue would imply more problems if blue were brighter.

The color stereo effect is an example of differential visual appearance of red and blue objects. This effect is simply seen by viewing strongly colored patches of red and blue. For most observers, the blue will appear slightly behind the red. This is a binocular effect. Fender (1955) explains the effect as being caused by the difference in chromatic magnification for different colors, which results in slightly different fixation and therefore different convergence for the colors.

It is difficult to see how this can influence these experiments. Regardless of the perceived depth of the small squares in red and blue, (and no subject reported on apparent depth of this kind) the color stereo effect does not interfere with perception of the monocular contours of the pattern.

The question, then is one of differential acuity between channels which handle red and blue color information, and only when working in conjunction. The answer must lie in the neural coding of information, but at present the neurophysiological data are too slim to permit any useful speculations.

The inability of the visual system to perceive depth with rivalry in luminance should be regarded in light of past experiments with rivalry.

There is a classic demonstration of Helmholtz that a stereo picture pair of an outline pyramid, one image black lines on white, the other white lines on black, yields strong stereopsis (Helmholtz, 1909). This type of binocular stimulus does have monocular cues.

A Julesz pattern presented with retinal rivalry (a stereo pair with the normal center square shift, but the left and right eye images are complements; in the present experiments, this would be pattern L1 and R2 on, pattern L2 and R1 off) cannot be seen in stereo (Julesz, 1963). Julesz found that increasing spatial complexity resulted in increasing difficulty in perceiving depth. Spatial complexity here refers to the density of contours of an image in the visual field, and his patterns are much more complex than the simple stereograms of the type Helmholtz used.

For real images, rivalry of this type, using black and white images only, rarely occurs. Real life situations with rivalry most commonly occur when there is a reflection which is seen by one eye and not the other. For familiar objects this does not cause any problems; for unfamiliar objects, one must move to eliminate the rivalry. From the standpoint of novel stimuli, then, the results indicate that binocular vision is not prepared to handle rivalry in luminance.

Rivalry in luminance does not result for most observers in a stable visual percept, but rivalry in color may sometimes produce a unified percept in color, corresponding to simple color addition of the left and right eye stimulus colors. This point has been long argued in the vision literature, with about half of the reports claiming that binocular colors never add, and the other half saying that it does, sometimes. It appears that the luminances of the colors must be fairly carefully set, and that the effect is more easily seen with large uniform fields.

Binocular color addition was not reported by any of the subjects in these experiments, perhaps partly because of the spatial complexity of the patterns, but the apparent desaturation of the colors was seen, and almost everyone agrees that this occurs.

Binocular color addition, if it occurs, and the desaturation of colors seen in rivalry are examples of interaction of color information between the eyes which does not involve depth perception. The visual effect of color rivalry is less disturbing than luminance rivalry, which is probably evidence for the most fundamental nature of luminance information in vision.

From the evolutionary standpoint, the perception of luminance is more fundamental than color, and in the evolution of mammalian visual systems, binocular vision apparently occurs lower than color; these results suggest that color was not added to stereo contour detection, but was to simple or monocular contour detection.

Another way to study the relative importance of luminance and color information is to consider photographs which have no color content (ordinary black and white photographs) and those with no luminance content and only differences in color in a scene (these can be produced by manipulation of color television images or by a tedious photographic process). There is little question that the loss of color content rarely interferes with the recognition of objects, while loss of luminance content requires much more careful scrutiny to identify objects (this is another statement of the Liebman effect noted above).

Given the information handling capacity of the visual system, there is an argument of economy that color information be disregarded in depth perception. Depth perception requires very fine analyses of retinal disparity to localize an object. If color information is used, there must be at least two additional channels of input, regarding color as a two dimensional variable, with the third color or primary contrained, as in the CIE color system. There may be more channels if color information is handled by opponent color processes of the four variable types discussed in chapter three. This implies at least a three fold increase in the complexity of the neural wiring, with little useful information to be gained, since the color of an object is already identified by simple contour detection. Hence the much simpler neural wiring can be used for nearly all real life situations with virtually no impairment of vision. The results here indicate that color and relative luminance are used to identify objects, luminance alone is used to determine their depth.

end

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