AN INVESTIGATION OF CHROMATIC BRIGHTNESS ENHANCEMENT TENDENCIES

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
Richard James Ball
1963

This is to certify that the

thesis entitled

AN INVESTIGATION OF CHROMATIC BRIGHTNESS ENHANCEMENT TENDENCIES

presented by

Richard James Ball

has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Psychology

S. Howard Bartley
Major professor

Date June 3, 1963

O-169

ABSTRACT

AN INVESTIGATION OF CHROMATIC BRIGHTNESS ENHANCEMENT TENDENCIES

by Richard James Ball

A modified Fry type prism monochromator with episcotister and surround field attachments was utilized to quantitatively investigate chromatic brightness enhancement tendencies. Thirteen narrow band targets were used ranging from 460mμ to 680 mμ. For most of the investigation a constant target luminance of 50 foot lamberts was maintained. Rates of intermittency from 6.5 to 20.0 cycles per second were used and pulse to cycle fractions of 1/16 to 3/4. Target sizes of $1\frac{1}{4}$ and 4 degrees were used. Most of the investigation was done with dark target surround but target surrounds of varying intensity and dominant wavelengths of 540mμ and 600 mμ were also utilized. In one portion of the study target luminance was also systematically varied. Three color normal subjects were used.

A bipartite target was used with one-half steady and one-half intermittent. The two halves were separated by a narrow black band. Data were collected on the brightness, hue, and saturation of the intermittent target in relation to the steady target.

The following results were obtained. Only pulse to cycle fractions of around 1/4 gave marked brightness enhancement tendencies. Only rates of intermittency of 12 cycles per second or less gave marked brightness enhancement tendencies. Only wavelengths close to 500mμ gave marked brightness enhancement tendencies. Increased target size

or decreased target luminance tended to decrease brightness enhancement tendencies. Illuminating the target surround tended to decrease the brightness enhancement tendencies except for the condition where target and surround were matched on both luminance and hue.

Desaturation or "washout" of the intermittent target was obtained only in the regions of 500mμ and 620mμ. At 500mμ with the proper target rate of intermittency, pulse to cycle fraction, and luminance level the intermittent target became almost achromatic as well as enhanced in brightness. At 620mμ the intermittent target became moderately desaturated but brightness remained at about the Talbot level.

Hue shifts in the intermittent target were often obtained and when they occurred they always followed a specific pattern. For wavebands below 500mμ the hue of the intermittent target appeared to shift to that of a lower wavelength; that is it became purplish. For wavebands from 500mμ to 560mμ the hue appeared to shift to that of a higher wavelength; that is it became yellowish. For wavebands from 580mμ to 680mμ the hue appeared to shift to that of a lower wavelength; that is it became orangish. Thus, neutral points in hue shift were obtained at 570mμ where the intermittent target did not shift in hue and at 500mμ where the intermittent target became almost achromatic.

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By

Richard James Ball

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Psychology

1963

ACKNOWLEDGMENTS

It is doubtful that many truly original pieces of work occur. Most of what we consider original research is the result of digestion, assimilation, alteration, and regurgitation of various facets of what is already known. This makes it very difficult to give proper recognition for assistance on this project. Acknowledgment must be given to the entire human race, past and present, for providing the necessary foundation of knowledge which we call civilization.

Special acknowledgment must also be given to certain individuals who have been particularly instrumental in my work. First of all my parents whose sacrifices and encouragement made possible my primary, secondary, and undergraduate education as well as providing me a wholesome and stimulating environment in which to grow. I owe an especially great debt to my mother whose demonstration of complete lack of selfishness in dealing with others deeply imbued me with the realization that the only worth-while things in life are obtained by working with others and not against them.

To Dr. Glenn A. Fry I owe the inspiration which has guided me through my graduate work. Dr. Fry has for over ten years provided me a living symbol of the highest scientific endeavor and attainment toward which I can only strive. Also, without Dr. Fry's generous loan of equipment I could never even have commenced this investigation.

Dr. S. Howard Bartley is owed a great debt of thanks for his inspiring and generous guidance as my graduate advisor. Without his untiring assitance this project could not have been completed. Certainly great credit is due the other members of my guidance committee, Dr. Paul Bakan, Dr. Charles Hanley, and Dr. Byron VanRoekel for their contributions of time and assistance in my graduate work. Also, a debt of thanks is owed Dr. Charles Bourassa who served as subject and to Dr. Thomas M. Nelson who not only served as subject but made many other valuable suggestions and contributions. An extremely valuable service was also rendered by Dominic J. Zerbolio who drew the final copies of the figures and to Richard Clark who photographed and reproduced the figures.

Of invaluable assistance in all phases of my graduate program has been my wife. Without her abundance of help and understanding throughout the trials and rigors of the doctoral program I most certainly would never have made it. Also, it was her initial idea that started me on the train of thought which led to this research. Finally, and above all, I give thanks to the transcending Power from above that has made possible my work and all of the foregoing assistance.

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INTRODUCTION

This study is an investigation of chromatic brightness enhancement. The brightness enhancement phenomenon or the "Bartley effect" has been extensively investigated by Bartley and others (6, 8, 10, 11, 12, 14, 20, 21, 37, 38, 65). All of this research, however, has utilized essentially achromatic or white sources. The influences of rate of intermittency (17, 19), pulse to cycle fraction (PCF) (12, 16, 18, 20), and stimulus intensity (4, 6) have been studied but not the possible effects of varying the wavelength composition of the source. Recent work by Bartley and Nelson (15, 51, 53) has shown the existence of strange color effects when rate of intermittency, PCF, and intensity are properly manipulated. Color appearance in an achromatic source has been demonstrated and strong "washout" effects in certain chromatic stimuli. The present study has been designed to quantitatively investigate the effects of intermittent stimulation on brightness, hue, and saturation.

No claim is made that this is more than an introductory investigation into what has turned out to be a potentially fruitful area. However, there is an attempt to cover a good deal of territory in this area and also to make the investigation as systematic as possible. Since a number of variables are influential in their effect on brightness enhancement, a rather complex and extensive investigative procedure is necessary. The effects of the following variables have been investigated in this present study.

1. Wavelength of the photic stimulation.
2. Pulse-to-cycle fraction of intermittency (PCF). This is defined as the fraction of the total cycle during which photic energy is transmitted through the episcotister.

3. Size of the retinal area stimulated.
4. Rate of intermittency.
5. Intensity of photic source.
6. Effect of dark target surround.
7. Effect of intensity of target surround.
8. Effect of chromaticity of target surround.

All of these variables except the one under investigation during a particular phase of the study were held constant while this one was systematically varied. Relative brightness was quantitatively measured by manipulating a rotary polaroid arrangement over the steady half of the field to match it to the intermittent half. Saturation was determined by relating the appearance of the intermittent target to a predetermined five-step scale of desaturation. Hue was determined by recording the apparent hue of the intermittent target in relation to the known hue of the steady target.

Historical Review

A review of the literature in chromatic brightness enhancement can be extremely short because almost no investigations exist in this area. No systematic quantitative study with controlled conditions has been reported. However, a literature review for this study should encompass mention of work in a number of very closely related facets of the problem.

Many mentions have been made of unusual color changes initiated by proper intermittent stimulation. Some of these concern the creation of hue in an intermittent achromatic stimulus and others in the "washout" of a chromatic stimulus. Recently, Bartley and Nelson (15, 51, 53) have investigated these phenomena but not in a highly quantitative manner.

Many persons in the past have made note of color phenomena in flicker. Nelson (50) has compiled a bibliography containing seventy-eight studies where mention is made of a color effect in flicker.

All of these studies could be discussed but mention will be made of just a few in order to show the progression of thinking and methodology. Smith (61) in 1881 used a bicycle wheel as an episcotister and the sun as a source in trying to show that light might be broken up by interruptions proportional to the wavelength of a particular ray in a composite beam. In 1918 Baumann (22) discussed the factors involved in the production of Fechner-Benham colors. DuBois (26) in 1922 formulated a modulation theory very similar to Troland's (64) based on research with mollusks. During this same period Pieron (55, 56, 57, 58) studied Fechner-Benham phenomena under monochromatic illumination and also concerned himself with temporal differences between Fechner-Benham colors and after images. Pauli and Wenze (54) postulated that receptors have natural temporal periods and response occurs when the frequency of the pulse is the natural period of the receptor. Marked color changes were obtained by LeGrand (43) in 1937 during peripheral intermittent stimulation. In 1940 Segal (60) also put forth a modulation type theory. Gebhard (35) in 1943 discussed Fechner-Benham colors in relation to color vision theory including modulation theory. Another explanation of Fechner-Benham colors on the basis of modulation theory was made by Roelofs and Zeeman (59) in 1958. An excellent review of the literature in this area was made by Cohen and Gordon (25).

The first to report a brightness effect of considerable magnitude in flicker was Brücke (23) in 1884. This work was done with black and white Disks and Bartley (14) has succinctly differentiated this Brücke effect from the Bartley effect of brightness enhancement obtained with episcotisters.

Fry (30, 31, 32, 33, 34) conducted a series of experiments using chromatic flicker phenomena as a basis for prediction on color vision theory. He expanded Troland's modulation theory into the Fry modulation theory as the best theory to explain these chromatic flicker phenomena.

Bartley has formulated his Alternation of Response theory to explain the brightness enhancement phenomenon and other sensory phenomena. This theory has been presented in a number of publications (3, 5, 10, 11, 12, 14, etc.), but is most comprehensively covered in Bartley's Freiburg Symposium presentation (14).

Recently a number of animal studies have been done concerning electrical discharge in the visual system. These studies have the advantage of allowing direct recording of electrical activity at any level of the visual system. However, they have the disadvantage of all animal studies in that there is no assurance that the results are applicable to human organism behavior. Lennox and co-workers (44, 45, 46, 47, 48, 49) have conducted studies at the levels of retina, optic tract, lateral geniculate, and occipital cortex. They found among other things that cortical responses were of differing amplitude dependent on spectral differences in stimulation and spectral differentiation in On and Off fiber responses. Ingvar (40) in measuring spectral sensitivity in the cerebrum of cats made the speculation that "in a general way these results support the hypothesis that differences in conduction velocity may also be a possible mechanism by which visual centers are informed about color."

Granit and Wirth (36) in 1953 in an animal study made the observation that under light adaptation there is a "blue shift" in the sensitivity curve. This is an interesting finding when compared to the results of the present investigation.

Halstead and co-workers (37, 38) in working with monkeys found that they could produce cortical driving at rates of intermittency very close to Bartley's enhancement rates. A finding that is of particular interest for this present study is that driving was greatest for wavelengths around 500mμ.

DeValois and co-workers (27, 28, 29) have isolated layers in the monkey lateral geniculate which have a selective spectral sensitivity. Hartridge (39) and Clark (24) have also studied electrical responses in the lateral geniculate.

Mention must also be made of Landis (41, 42). His annotated bibliography is a monumental piece of work in the general area of flicker.

Expectations

The results do not lend themselves well to statistical evaluation. Therefore, no attempt has been made to set up null hypotheses and test them. However, on the basis of previous research I attempted to make predictions concerning the effects of the individual variables. These predictions follow as a list of "expectations."

1. A pulse-to-cycle fraction (PCF) of approximately 1/4 will give maximal enhancement effect.
2. A rate of intermittency of approximately 10 cycles per second will give maximal enhancement effect.
3. Greater intensity of stimulation will give maximal enhancement effect.

This next group of "expectations" are on much less firm footing because the literature provides no concrete basis for prediction. These are my "expectations" based solely upon what seems reasonable in the light of existing knowledge and were made before I began to collect data.

4. Varying wavelength of source, as long as luminosity is kept constant, should have no significant effect on brightness enhancement. Concurrent research by Bartley and Nelson has

shown this to be an erroneous "expectation" but when I started my research it seemed like a reasonable guess.

5. Dark target surround should give greater brightness enhancement effect than illuminated surround.
6. As intensity of surround is increased, enhancement effect should be decreased.
7. Chromaticity of surround, as long as luminosity is kept constant, should not give any significant effects with respect to brightness enhancement.
8. Larger target size should give increased brightness enhancement effect up to a certain point. This would be expected on the basis of activating a larger grouping of visual channels. However, this might be negated by Bartley's finding (7, 14, 21) that in a bipartite viewing field greater target size causes greater stray light during the supposed dark phase of intermittency.

METHOD

Apparatus

The apparatus utilized is a modified Fry type prism monochromator with episcotister and field surround attachments. This is schematically shown in Figure 1A. A ribbon filament bulb source (1) is powered through a constant voltage battery eliminator. A collimating lens (2) causes two parallel beams of light to pass through the double slit (3). The width of these slits is 1 mm. The bottom beam of this pair can be controlled in intensity by a rotary polaroid arrangement (5). This is composed of a fixed polaroid over the bottom slit with a rotating polaroid in front of this. This rotating polaroid is connected to a shaft with a knob and calibration dial which allows recording of the percentage transmission through the polaroid system. A neutral density 0.2 filter (4) is placed over the upper slit of pair (3) to reduce intensity of this beam. Thus, when the brightness of the upper and lower beams are equated by turning polaroid (5) the scale reading is kept below 100 per cent.

An episcotister (6) chops only the upper beam. Thus, the upper beam is intermittent and the lower beam steady. Rate of intermittency and PCF are varied respectively by changing the disk at (6) and the rate of rotation of the disk. A direct gear drive through a synchronous motor is used to drive the episcotister.

A lens (7) focuses the two parallel beams onto the face of the prism (9). A filter holder (8) allows for introduction of filters to vary the two target beams without changing the surround illumination. The spectrum formed by the prism (9) is reflected off the first surface mirror (10) and through the biprism lens (11). This lens separates the two original beams from (5) and collimates them. The field stop (12) is a first surface mirror. The bipartite aperature in this mirror can be varied in size to provide different sized targets. The mirrored surface allows for surround illumination to be introduced into the system. A filter holder (13) allows the entire target and surround field to be varied together. A lens (14) focuses the spectrum onto the slit (15) which is 1 mm. in width. The observer places his eye just behind slit (15).

The prism (9) is mounted on a spring loaded stage which can be accurately rotated to provide any desired narrow portion of the spectrum as the target. The settings of the stage for providing various wavelengths were calibrated with a spectrometer.

The surround illumination is provided by a ribbon filament source (18) and collimated by lens (17). Filter holder (16) allows the surround to be varied in chromaticity and intensity. The parallel beam of the surround illumination is reflected off first surface mirror (12) while the bipartite target field passes through the aperature in mirror (12).

The field seen by the subject is illustrated in Figure 1B. The bipartite target is composed of a steady top half (1) and an intermittent lower half (2). The fixation point (4) is at the center of a narrow black band (3) which separates the halves of the field. The surround (5) can be dark or illuminated to any desired intensity and chromaticity.

In summary the variables used in this study are controlled in the following manner. Reference should be made to Figure 1A.

1. Wavelength is controlled by turning a calibrated knob which rotates the mounting stage for prism (9). This causes a different portion of the spectrum formed by prism (9) to pass through the eyepiece slit (15). The width of the wavelength band varies in increasing magnitude from 5.3mμ at 420mμ to 33.5mμ at 700mμ.

2. The size of the target is controlled by changing the size of the aperature in mirror (12).
3. Pulse-to-cycle fraction is controlled by the episcotister disk (6).
4. Rate of intermittency is controlled by the gear ratio in the direct drive between a synchronous motor and the shaft of disk (6).
5. Intensity of source is controlled by neutral density filters at (8).
6. Surround is kept dark by eliminating power to bulb (18).
7. Surround intensity is controlled by a variac on the power supply to bulb (18) or by neutral density filters at (16).
8. Chromaticity of the surround is controlled by Corning glass filters at (16).

Procedure

The first portion of the investigation was done with a dark surround, maximum target intensity, and a foveal target size (1.25°). Thus, the variables manipulated were wavelength of source, PCF, and rate of intermittency.

It was desirable in this part of the study to maintain equal luminosity for all wavelengths, have the highest possible stimulus intensity, and still utilize a wide portion of the visible spectrum. A necessary compromise of these last two requirements was made by utilizing wavelengths from 480mμ to 680mμ. These two were a match in luminosity while the necessary neutral density filters were introduced into the system for all wavelengths between 480mμ and 680mμ to maintain equal luminosity. The amount of neutral density filter necessary was de-determined by matching a blue-green surround illumination in brightness to the 480mμ target and then stepwise matching the higher wavelength targets to the surround. The chromaticity of the surround was varied several times to reduce the problems of heterochromatic photometry but each time the surround was changed it was matched in brightness to a target which matched the previous surround. This procedure was repeated starting at 680mμ and working downward. Thus, the neutral density filters necessary to maintain equal luminosity were determined. The results of this procedure correlated well with an additional procedure done where the neutral density filter necessary to reach CFF at rate 36 cps for each waveband was determined. Thus, agreement was obtained by two completely different methods that the desired condition of equal luminosity was a reality in this experiment. The equal luminosity condition for the 460mμ waveband was obtained by using 2 mm. rather than lmm. slits in front of the ribbon filament source and making the necessary prism dial setting corrections.

An example may illustrate best how the data were collected. Suppose that PCF was set at 1/4, rate of intermittency at 9.8 cycles per second, and wavelength at 480mμ. The observer viewed the bipartite target for one minute prior to making any evaluations. This one minute adaptation period each time the subject commenced viewing was found to be sufficient. The observer then noted the state of desaturation of the intermittent target in relation to the steady target. A response was made on the basis of a five-step scale of "no washout," "slight washout," "moderate washout," "extreme washout," and "total washout." Then the observer made an evaluation of the hue of the intermittent target in relation to the known hue of the steady target. This was recorded as to whether the intermittent target appeared to be the same hue as the steady, the hue of a longer wavelength, or the hue of a shorter wavelength.

Then the observer turned the dial controlling the brightness of the steady target until the steady and intermittent halves of the bipartite field appeared the same brightness. Three ascending and three descending readings were taken. Then the waveband was changed to 500mμ, proper neutral density filters put into the system to maintain equal luminosity, and the same procedure repeated. This was done for each waveband step up through 680mμ. Then the rate of intermittency was changed and the whole procedure repeated. When all the desired rates had been tested then PCF was varied and the entire procedure of twelve waveband steps at each rate repeated. Data were also collected for steps going downward from 680mμ to 480mμ but this was found to give no different results than going in steps from 480 mμ upward to 680mμ.

After extensive investigation had been made utilizing the variables of wavelength, PCF, and rate, the other variables were introduced one at a time and the whole procedure repeated. Thus, each time a new variable was introduced, an increasing number of stimulus situations had to be tested.

An additional procedure was done utilizing 13 mm. slits rather than 1 mm. slits in front of the ribbon filament source. This allowed a relatively wide spectral band rather than the previously used narrow bands. Three bands were used in this portion of the investigation. They were 437-490 mμ, 472-576mμ, and 528-688mμ.

RESULTS

The author's photopic luminosity curve has been previously determined and is available in the literature (1). It closely approximates the standard I.C.I. photopic luminosity curve. The transmission curve of a similar instrument is also available in the literature (1). The instrument transmits better in the longer wavelengths than in the shorter wavelengths. Thus, as would be expected, the peak of the luminance distribution curve derived from CFF data will be shifted to a higher wavelength (575-580mμ).

Figure 2 illustrates the effect on brightness at five points of the spectrum when PCF is varied. It is readily seen that only a PCF of 1/8 or 1/4 gives brightness substantially above the Talbot level (62) and even here only for the wavelength of 500mμ.

A statement should be made here concerning the ordinate values. The values 0 through 70 are percentage transmission through the rotary polaroid arrangement over the steady half of the bipartite field. Each point recorded on the graph is a mean value of six experimental brightness matches (three ascending and three descending). When the two halves of the bipartite field are both steady (episcotister not running) they are matched in brightness for all wavelengths at a rotary polaroid setting of 62.5 per cent transmission. Thus, any brightness value of over 62.5 is an enhanced value and the Talbot level value is found by multiplying 62.5 by the PCF. Luminance of the test stimulus throughout the experiment is maintained at 50 foot lamberts except where specifically noted otherwise.

The question has arisen as to the best method of presenting the data of this investigation. In most previous work luminance of the matching stimulus has been the ordinate and rate of intermittency the abscissa. This investigation, however, is greatly concerned with the brightness effect pattern as it relates to wavelength so that the author has decided to present much of the data with wavelength rather than rate of intermittency as the abscissa. However, in Figure 3 data are presented in the usual way to facilitate comparison with results of previous studies. Here rate of intermittency is the abscissa and a separate curve is plotted for each wavelength. The substantially increased effectivity of wavelength 500mμ over all longer wavelengths is quickly seen. These data are for a PCF of 1/4 and target size of 1.25°.

Each figure from Figures 4 to 8 represents data for a given combination of stimulus size and PCF. The various curves on each graph represent data for specific rates of intermittency. The lower portion "A" of each figure shows for each waveband the luminance of the matching stimulus plotted as a function of wavelength. The upper portion "B" of each figure shows the effect of wavelength on saturation or "washout." A multiple point symbol is used when points from two or more lines fall at the same place on the "washout" graph. In each case all of the coincident points are drawn directly above the multiple point symbol.

Figure 4A shows there is not much increase in brightness over the Talbot level with a PCF of 1/16 although there is a hint of greater brightness for wavebands around 500mμ and lower rates of intermittency. Figure 4B shows very little "washout" at PCF 1/16 but it is greatest at 500mμ and 6.5 cps rate.

Figure 5 presents data for PCF 1/4, target 1.25°, and seven different rates of intermittency between 6.5 and 20.0 cycles per second. Figure 5A shows the increased brightness effect of PCF 1/4, the great increase in apparent brightness of wavebands 500mμ and 510 mμ over longer or shorter wavebands, and the increased brightness effect for rates of 10 cps or less over the faster rates.

Figure 5B follows by showing a strong "washout" effect at 500mμ which is greater for rates of 10 cps or less. Because a marked increase of the enhancement effect also occurs at 500mμ, it might be supposed that there is some interdependence between "washout" and brightness enhancement. However, the occurrence of the second "washout" hump at 600-620mμ as shown in Figure 5B illustrates that the brightness enhancement tendency and the "washout" phenomenon do not possess a simple invariant relationship. This increase in "washout" in the red-orange and red regions has also been described by Bartley and Nelson (51).

Figure 6 presents the same kind of data as Figure 5 but for a target size of 4°. This is no longer as strictly a foveal target as is the 1.25°. Essentially all of the same tendencies are present here as with the smaller target but of a decreased magnitude. Of significant difference is the increased brightness effectiveness of the 12.0 cps rate and the decreased effectiveness of the 7.8 cps rate. In "washout" the rates of 10 cps to 13 cps are most effective rather than the rates of 10 cps and less for the smaller target.

Figure 7 shows the decreased brightness and "washout" effectiveness when a PCF of 1/2 is used. Also, the greatest brightness occurs at 480mμ rather than 500mμ.

Figure 8 shows the extreme ineffectiveness of PCF 3/4 in elliciting either the brightness enhancement or the "washout" phenomena.

Figures 9 through 16 display the effects for five wavebands between 500mμ and 680mμ when luminance level, PCF, and target size are systematically varied. In all cases, the rate of intermittency was maintained at 9.8 cps. Results for four levels of intensity are shown in each graph. The highest level (100%) is the level used in all previous figures (50 foot lamberts). For the other levels neutral density filters of 0.5, 1.0, and 2.0 were added. In terms of the filter free level, the filters provide levels of 32%, 10%, and 1% or 16, 5, and .5 foot lamberts. By observation it appears that the 2.0 N.D. filter reduces luminosity to not far above the photopic threshold.

Figure 9A shows that for the 100% and 32% levels of luminance of the intermittent stimulus the luminance of the matching stimulus is above the Talbot level with PCF 1/8 but that the 100% level at 500mμ gives the greatest apparent brightness. The 32% level gives somewhat less apparent brightness at 500mμ and the 10% and 1% levels give essentially no difference in apparent brightness for the five wavelength bands and essentially no difference from the Talbot level. Figure 9B shows that "washout" is strong only at 500mμ at the 100% level.

Figures 10 and 11 show the results for PCF 1/4 and target sizes of 1.25° and 4°. Here it can be noted that the 1.25° target gives more apparent brightness than the 4° target for the 100% level 500mμ waveband. This is the same situation that was noted in comparing Figures 5A and 6A. As in the previous figures, the 500mμ waveband is much more effective in producing apparent brightness and this tendency decreases as the intensity level of the stimulus is decreased. Here the 32%, 10%, and 1% levels give essentially no brightness difference for the five wavebands.

Figures 10B and 11B show the strong "washout" at 500mμ full intensity and also the existence of the previously mentioned second "washout" hump at 620mμ. "Washout" decreases as intensity decreases.

Figure 12 shows the loss of the apparent brightness hump at 500mμ when PCF is 1/2 but that the full intensity "washout" remains strong at 500mμ. This again illustrates that brightness enhancement tendency and "washout" do not always go hand in hand.

Figures 13 through 16 utilize the same experimental conditions as Figures 10 and 11 but for two different observers. This is probably an appropriate place to interject a statement on what will certainly be considered a weak point in this investigation; the small number of observers involved in the data collection. Only three observers were used and two of these in only limited phases of the study. Thus, the great majority of all the data discussed were obtained from one observer; the author. It is difficult to find or produce trained observers who can participate in this kind of experiment.

For this study, the word "trained observer" should be italicised and in double quotes. In the majority of the experimental conditions in this investigation apparent brightness, hue, and saturation are all varying simultaneously. The problem for the observer is to view a bipartite field where the flickering half is different in brightness, hue, and saturation from the steady half. Then the observer must separately make a qualitative hue difference judgment, a semi-quantitative "washout" judgment on a five-point scale, and a quantitative brightness match judgment while never allowing the other two attributes of color to influence his judgment on the one being measured. It requires a fantastic amount of practice to make valid repeatable judgments.

The author collected data by countless observations during a period of over one year. Previously, this author had spent a year in color vision research under the direct supervision of Dr. Glenn A. Fry where the research on lines of constant hue (2) required a similar type of observational task of making judgments on one variable in a complex brightness, saturation, hue stimulus situation. Even with this total of two years of intensive training in making these judgments, all of the data presented in this study were collected during the last four months of this period. The earlier data showed exactly the same trends but with much greater variance in individual readings. The author is now able to make a set of three ascending and three descending brightness matches and rarely have a spread of over 5 per cent in the six readings. Thus, differences between wavelength bands illustrated by the graphs certainly cannot be attributed to chance variance in individual judgments.

The two other subjects used, Dr. Thomas Nelson and Dr. Charles Bourassa, have had extensive experience as observers in visual perceptual experiments but not in this particular type of experiment. As expected, the variance in their individual judgments is much greater but still only in the area of 10 to 15 per cent spread for groups of six readings.

In general, the data collected from these two subjects confirm very well the data collected with the author as observer. Some of the data are depicted in Figures 13 through 16. The same hump on the graph at 500mμ for both brightness and "washout" is apparent. Also, the second "washout" hump at 620mμ can be noted and the same effects of decreasing intensity. The greatest difference is in the effect of target size. Bourassa concurred with the author in finding the 1.25° target more effective in producing apparent brightness but Nelson found the 4° target more effective.

In Figures 17 and 18 a new variable has been added with very interesting results. Here the surround field is not dark as it has been in all previous figures. The experimental condition where the greatest differential wavelength brightness effect has been obtained is utilized to study the effect of adding surround luminance. This is the condition of PCF 1/4, target 1.25°, and rate 9.8 cps.

Figure 17 depicts the results for a surround luminance with a dominant wavelength of 540mμ. The surround is quite desaturated since it is obtained with Corning filters rather than with a monochromator. Four curves are shown; the first a repetition of the dark surround condition; the second with the surround illuminated but with the luminance definitely less than that of the target; the third with the luminance of the surround equal to that of the target when the target is not intermittent; and the fourth with surround luminance definitely greater than that of the target.

Several interesting things should be noted on Figure 17A. Increasing the surround luminance decreases the brightness hump at 500mμ and increases the apparent brightness of the longer wavelength bands. Of extreme interest is the appearance of a large apparent brightness hump at the dominant wavelength of the surround when the target and surround are of equal luminosity. This is of almost an enhancement level and occurs at a wavelength that with dark surround consistently gives low apparent brightness.

Figure 17B shows that the "washout" hump at 500mμ is decreased as surround illumination increases and that the second "washout" hump is shifted from 620mμ downward to 580-600mμ.

Figure 18A illustrates the same conditions as Figure 17A but with a surround of dominant wavelenth 600mμ. Very similar trends are seen in the results except that the interesting second hump in apparent brightness shifts to the surround dominant wavelength of 600mμ. In Figure 18B the second "washout" hump occurs at the surround dominant wavelength of 600mμ rather than at 620mμ as in the dark surround condition or 580-600mμ as in the 540mμ surround condition.

Figure 19 is presented to illustrate that the results can be replicated. The condition which yielded the greatest differential brightness effect is graphed as it gives the greatest variance in replication. This is the PFC 1/4, rate 9.8 cps, and target 1.25°. All other conditions can be replicated much more closely. These four curves are from data collected at different times for different sequence conditions. The four curves in Figure 19A can be noted as the appropriate curves appearing in Figures 5A, 18A, 17A, and 10A. The curves in Figure 19B can be noted as appearing in Figures 5B, 18B, 17B, and 10B.

Figure 20 shows the results when a wider spectral band is utilized as a target. Three wavelength bands of 437-490mμ, 472-576mμ, and 528-688mμ were used. The graphs are plotted as luminance against rate of rotation. It can be readily noted from Figure 20A that only the 472-576mμ waveland gives brightness even approaching an enhancement level and then only for rates of 10 cps or less. These findings on effectivity of rate of rotation agree very well with the previous figures which utilized narrow wavebands throughout the visible spectrum (compare Figures 3 and 20A). By taking into account the overlap of the three bands used the enhancement tendency appears to be caused by wavelengths somewhere between 490mμ and 528mμ. This agrees extremely well with the previous figures which show the 500mμ and 510mμ wavebands as being the primary contributors to brightness enhancement tendencies (compare Figures 3, 5A, and 20A).

Figure 20B shows the correspondence with previous figures in comparing "washout" with rate and wavelength. A comparison of Figures 5B and 20B shows that "washout" is moderate to total for rates of 15 cps or less if the waveband contains the 500mμ wavelength. Rates over 15 cps or wavebands not including the 500mμ wavelength give very little "washout."

Data were collected on all the three variables of brightness, "washout," and hue. Up to this point only the results of the quantitative brightness judgments and the semi-quantitative five-point scale "washout" judgments have been presented. Figures 21 and 22 present the qualitative hue shift judgments for all of the experimental conditions. Figure 21 shows experimental conditions where thirteen wavebands are utilized and Figure 22 for those conditions where five wavebands were used.

A number of interesting and extremely consistent things can be noted from these figures. For wavebands 500mμ, 510mμ, 520mμ, and 540mμ a hue shift occurs for a great many of the experimental conditions and it always shifts the apparent hue of the intermittent target to a longer wavelength. For wavebands 600mμ, 620mμ, 640mμ, and 680mμ there is usually a hue shift and it always causes the apparent hue of the intermittent target to shift towards a shorter wavelength.

Only rarely is there a hue shift for wavebands 560mμ and 580mμ but when it occurs it is always upward at 560mμ and downward at 580mμ. This places the invariant hue point at about 750mμ. A very different situation appears for wavebands 480mμ and 460mμ. When they do shift in hue they become purplish and shift downward away from the 570mμ point. Also, it can be noted that total "washout" never occurs except at the 500mμ waveband.

In all of the results it is noted that while there are great differences in brightness obtained there is very little true brightness enhancement where brightness of the intermittent stimulus is actually higher than the steady state stimulus. Most of the values obtained are of an intermediate brightness where they fall between the enhancement and Talbot levels. Bartley and others have, on occasion with achromatic stimulation, reported much greater magnitudes of brightness enhancement. Some explanation needs to be made as to why large degrees of enhancement are not found in this present investigation. While narrow waveband stimulation is certainly a very different situation from achromatic stimulation one would expect more enhancement. Part of this lack of enhancement may be due to a problem with the apparatus. Bartley's findings indicate this to be a definite possibility. Bartley (14) notes that "In using intermittent stimulation in the comparison target and steady illumination in the standard target, the retinal area supposedly at rest during the 'dark' periods of the intermittency cycle will be stimulated by the stray illumination of the steady target." Bartley (21) further found that "By putting more light into the intervals between intermittent pulses, we pre-empted the usilization of a portion of the total number of otherwise available parallel circuits by the light pulses themselves."

The biprism arrangement, unfortunately, does not yield a completely on-off stimulus situation. There is some light leakage between the halves of the field in addition to the expected stray light effects.

This means that the intermittent half of the target does not go completely dark. If a total cessation of stimulation rather than an almost total cessation had been possible greater enhancement levels might have been obtained.

Summary of Results

This section will attempt to assess the "expectations" originally made in the light of the results of this investigation. We will take these expectations in the same order in which they were made.

1. A PCF of approximately 1/4 will give maximal enhancement effect. This has been definitely shown. Ability to cause brightness enhancement falls off quite rapidly as PCF is either increased or decreased from 1/4. Figure 2 illustrates this.

2. A rate of intermittency of approximately 10 cps will give maximal enhancement effect. The data show this to be substantially true although it does not seem to be as critical a variable as some of the others investigated. Rates much over 10 cps and especially over 12 cps decrease apparent brightness tendency but rates of 6.5 cps and 7.8 cps appear almost as effective as 9.8 cps. Thus a range of rates from 12.0 cps down to 6.5 cps or possibly lower seem to give an increased apparent brightness tendency.

3. Greater intensity of stimulus will give maximal enhancement effects. This has essentially been substantiated by the data.

4. Varying wavelength of source as long as luminosity is kept constant should have no significant effect on brightness enhancement. The results show this "expectation" to be completely wrong thus forming one of the interesting and, I hope, significant contributions made by this study. Apparent brightness tendency has been shown to be extremely dependent upon wavelength of stimulation. A narrow and very specific

range of wavelengths around 500mμ have been shown to be extremely subject to increased apparent brightness when intensity and temporal variables are properly manipulated.

5. Dark target surround should give greater brightness enhancement effect than illuminated surround. This is found to be true.

6. As intensity of surround is increased brightness enhancement effect should be decreased. The results show this to be essentially the case.

7. Chromaticity of surround, as long as luminosity is kept constant, should not give any significant effects on brightness enhancement. Here again the "expectation" is incorrect and, thus, provides another very interesting result. The data show the existence of a great increase in apparent brightness of the intermittent target when the surround and target are of the same wavelength and intensity.

8. Larger target size should give greater brightness enhancement effect. This is supported by the results of one subject but opposed by the results of two subjects.

CONCLUSIONS

I know of no better introduction to this section on conclusions than a quotation from Troland (64) written in 1921 in the first concrete formulation of a modulation type color vision theory. Though written over forty years ago, this quotation is just as poignant for color vision theory today as it was then. "The actual task which we have before us in constructing a rationale of the data of physiological optics is a tremendous one, making more rigorous demands upon the intellect, I fear, than the formulation of certain far more cosmic theories, and one upon which our present, neat little academic explanations form only a burlesque."

It appears that this investigation may have revealed a new ramification of a visual function or possibly even a complete new function concerning brightness transmission. A brightness phenomenon is indicated which for intermittent stimulation is extremely dependent on wavelength of stimulus, quite highly dependent on PCF, and moderately dependent on rate and intensity of stimulation. Bartley (6) prophesied this in part when he stated "we should expect monochromatic light to be somewhat more effective than white, and expect wavelengths toward the blue end of the spectrum to be most effective."

One of the most striking features about this function is the highly restricted wavelength region in which it operates with an enhancement tendency. When one looks at the curve in Figure 5A one must note that its peak wavelength falls near to that of the standard scotopic luminosity curve. But this is obtained with a 1.25° target which is strictly foveal. Thus, we have cones with an enhanced response at 510mμ when the proper form of the intermittent stimulation is used. Can it be that these specific temporal-spatial stimulus patterns have isolated a cone brightness response? Is this hump due to lack of inhibition or favorable summation for these specific wavelengths?

This would agree well with Bartley's Alternation of Response theory. That is, brightness is dependent on the total number of separate channels in the visual system which are being activated at a given instant. The number of channels can be increased and thus brightness increased either by increasing the stimulus intensity or by proper timing of the stimulus input. The interesting new feature is that photopic brightness function is dependent not just on the intensity level and the timing of the stimulus but also is highly dependent on the spectral composition of the stimulation. This is a new piece in the puzzle which ultimately must find a place to fit. There are those intensity-timing-wavelength combinations which produce an optimum stimulus pattern to the visual system and thus give brightness enhancement.

When the area of stimulation is increased so that a strictly foveal target is not used (4° rather than 1.25°), two of the three observers found that the 500mμ brightness hump is markedly decreased. See Figures 10A, 13A, and 15A. A dangerous simplification of these results might be, that under proper patterns of stimulation, cones will give a brightness response curve much like that of rods but that when target size is increased to include rods the rod response inhibits the ability of cones to act like rods.

An important aspect of these data concerns the effects of surround. The finding that the surround illumination decreases the brightness hump at 500mμ is not too surprising. See Figures 17A and 18A. Steady stimulation of adjacent channels surrounding a small intermittent area (1.25°) might well be expected to disrupt the intensity-timing-wavelength interrelationship necessary for enhancing brightness. Also, the decreased effectiveness of increasing area of retinal stimulation as shown in Figures 10A, 11A, 13A, 14A, 15A, 16A by two of the three observers might come into play here. With the same reasoning one should expect the depressive situations to also be disrupted. See 600mμ on Figure 18A. The striking feature is the emergence of the brightness hump at the dominant wavelength of the surround when surround and target are equal in luminosity. This means that a surround illumination where intensity and wavelength are matched to the pulse of the intermittent target acts as an enhancer of brightness rather than a depressor. Furthermore, intensity alone in the surround illumination acts to decrease both the functions of brightness enhancement and brightness depression but if the proper surround intensity-wavelength interrelationship is used then a condition of strong brightness enhancement tendency is created at a previously depressed waveband.

One would hope to be able to relate the results of this investigation to color vision theory. In this respect, the most striking feature of the result is the strong effect of temporal stimulus variables. This would tend to support some sort of modulation type color vision theory. I do not believe that the known facts concerning photochemistry can alone be used to explain these results.

The results of this investigation would tend to support a modulation color vision theory where brightness is dependent on total number of visual channels activated and color is dependent on some subtle modulation of impulse transmission among a group of adjacent channels or a superimposed modulation on the impulse in a single channel. Here one could speculate that maximum brightness would be achieved when all channels within the area of stimulation are activated maximally at the same instant. This, however, would leave no chance for a temporal or amplitude variation among the channels or a modulation effect within a channel impulse that could transmit a modulated color response. The results of this investigation support this possibility. As brightness increases substantially (at wavelengths around 500mμ) there is also a strong "washout" or desaturation effect. See Figures 5A and 5B. This could mean that as brightness increases more channels are being maximally activated at a given instant and at the same time the possibilities of interchannel modulation are decreased so that hue progressively washes out. At peak brightness the results show total "washout." This might be approaching the condition where all channels within the area of stimulation are being maximally activated simultaneously with no interchannel modulation possibilities remaining. Thus, a very bright achromatic target results.

This, of course, creates a situation where brightness and color sensation are highly related but not totally interdependent. Brightness sensation would of necessity be present when color sensation occurs because any modulated interaction of channel activation would necessitate some channels being activated at a given instant. However, brightness sensation would not necessitate color sensation for two possible reasons. The first which could hold true for cones and the fovea is that maximum channel activation leaves no room for modulation and an achromatic sensation results. The second possibility is if there were not a fine enough mosaic of visual channels in a given retinal area to allow for proper interchannel timing and/or amplitude of activation that would give the necessary modulation. This might be the reason that rods, with many being connected to a single ganglion cell, give essentially no color response.

Something should be said concerning the possible site of a modulating mechanism. Here the author is apt to wander into that fascinating world of "pure speculation." If a modulating mode of stimulus transmission is the actual means of color vision it must exist in some form at all levels of the visual system. Too many investigators in their fervor for a particular concept have seemingly forgotten this. You cannot have unmodulated impulse trains from the retina to the cortex and then suddenly modulate them in the cortex. Equally impossible would be a situation where the retinal elements produce a modulation stimulus pattern and the cortex has no mechanism capable of utilizing a modulated input. The third impossibility is that one could have a modulation mechanism at the retinal and cortical levels but no means of transmitting a modulated message along the optic nerve. This means that if stimulus modulation on a temporal and/or amplitude basis is the means of color vision then the visual system must have the mechanism capable of modulating, transmitting, and decoding this message at every step of the visual pathway.

In this paper, speculation has primarily been concerned with how a modulated input might be transmitted from the retina to the lateral geniculate and/or occipital cortex. This has utilized a combination of the Bartley Alternation of Response theory and a modulation type color vision theory. Recent work by DeValois and others (24, 27, 28, 29, 39) on the lateral geniculate in monkeys has shown layers of cells which can be differentiated on a spectral input basis. If the gap can be lumped and the inference made that a human lateral geniculate operates in the same manner then the lateral geniculate could be thought of as a way station in the visual system. It could be that the modulation of the optic nerve transmission is decoded here and then impulses sent to other brain centers for various visual reflex and associative functions while a recoded message is sent to the visual centers in the occipital region. Or it might be that the lateral geniculate in man only skims off a portion of the input for transmission to other centers while the major portion of the modulated impulse train continues on to the occipital cortex where it is decoded by a cortical mechanism which yields the sensation of color. In either case both the input and the output of the lateral geniculate must be coded.

A large remaining speculation concerns how a modulated message might be initiated at the retinal level. That this coding of some sort takes place is essential for any color vision theory. This author does not feel that a photochemical basis or a three-component basis best describe the results of this investigation. But if modulation occurs how is it initiated? One could speculate variance in cone diameter or nerve fiber diameter as being selectively effective for different wavelengths. Cones of relatively small differences in diameter could be randomly distributed and thus different wavelengths of stimulation could set up different interchannel or intrachannel temporal and/or amplitude modulations.

The author would consider a better possibility to be the effects created by the cells in the bipolar retinal layer. In this layer are cells such as the amacrine and horizontal cells whose function has never been adequately explained. They must have a definite function as nature does not operate otherwise. Is it possible that these cells form the basis for a modulated visual message? Can they provide the facilitation, inhibition, and modulation between channels in the visual system at the bipolar cell level by being selectively responsive to intensity and wavelength photic stimulation?

The foregoing is not intended to intimate a formalized color vision theory in any way. The author possesses neither the information nor the insight necessary for such a cosmic undertaking at this time. The author merely feels that this investigative procedure opens fruitful new avenues for color vision research. The speculations are presented only as an attempt to stimulate thought and comment both pro and con. Only by diligent, continuing, and exhaustive efforts can the complexity of color vision finally be unraveled.

FUTURE PLANS

As was stated at the outset I hope that this is not a finished topic but merely a beginning. The results of this investigation seem to indicate that future work in this area is warranted and could prove extremely fruitful. Investigation can well be expanded and more exhaustive on all of the variables already dealt with. Surround illumination in particular has only been touched. Also, target size has not been systematically varied.

In addition, several new variables might well be added. For example single pulses or limited trains of pulses can be utilized as stimuli. Stimulus input can be modulated in various ways other than the on-off situation of the sectored disk. For instance a rotating polaroid disk would give a sine wave input.

Many of these present studies might well be replicated on individuals with various types of color vision deficiencies. These are just a few of the possible avenues of future investigation in this area.
The author can only hope that he has been fortunate enough to stumble onto a means by which significant additions can be made to man's knowledge concerning his sense of vision.

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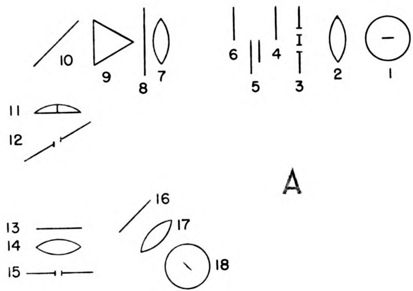
APPENDIX



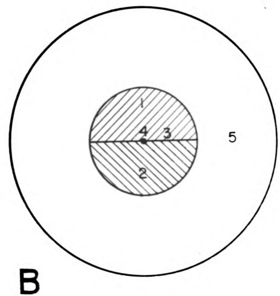


FIGURE 1

TARGET $1\frac{1}{4}^{\circ}$

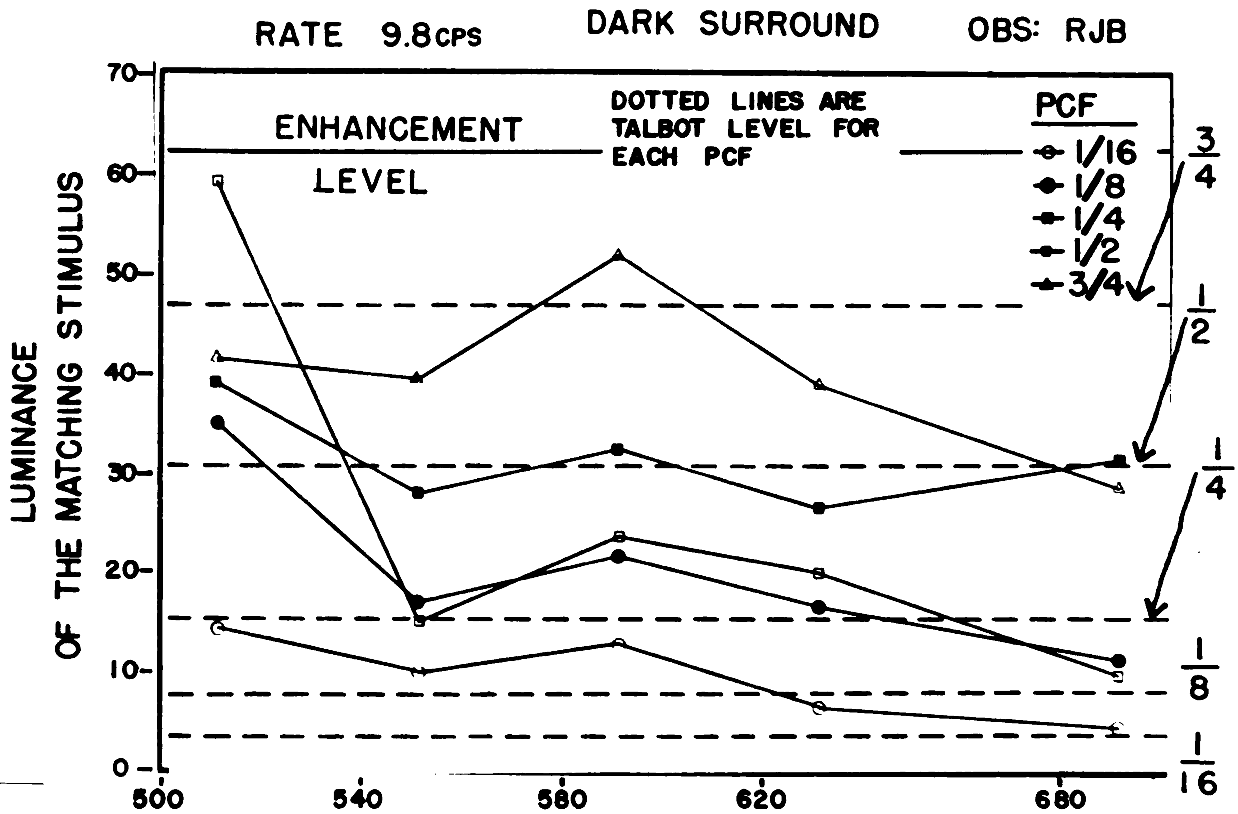
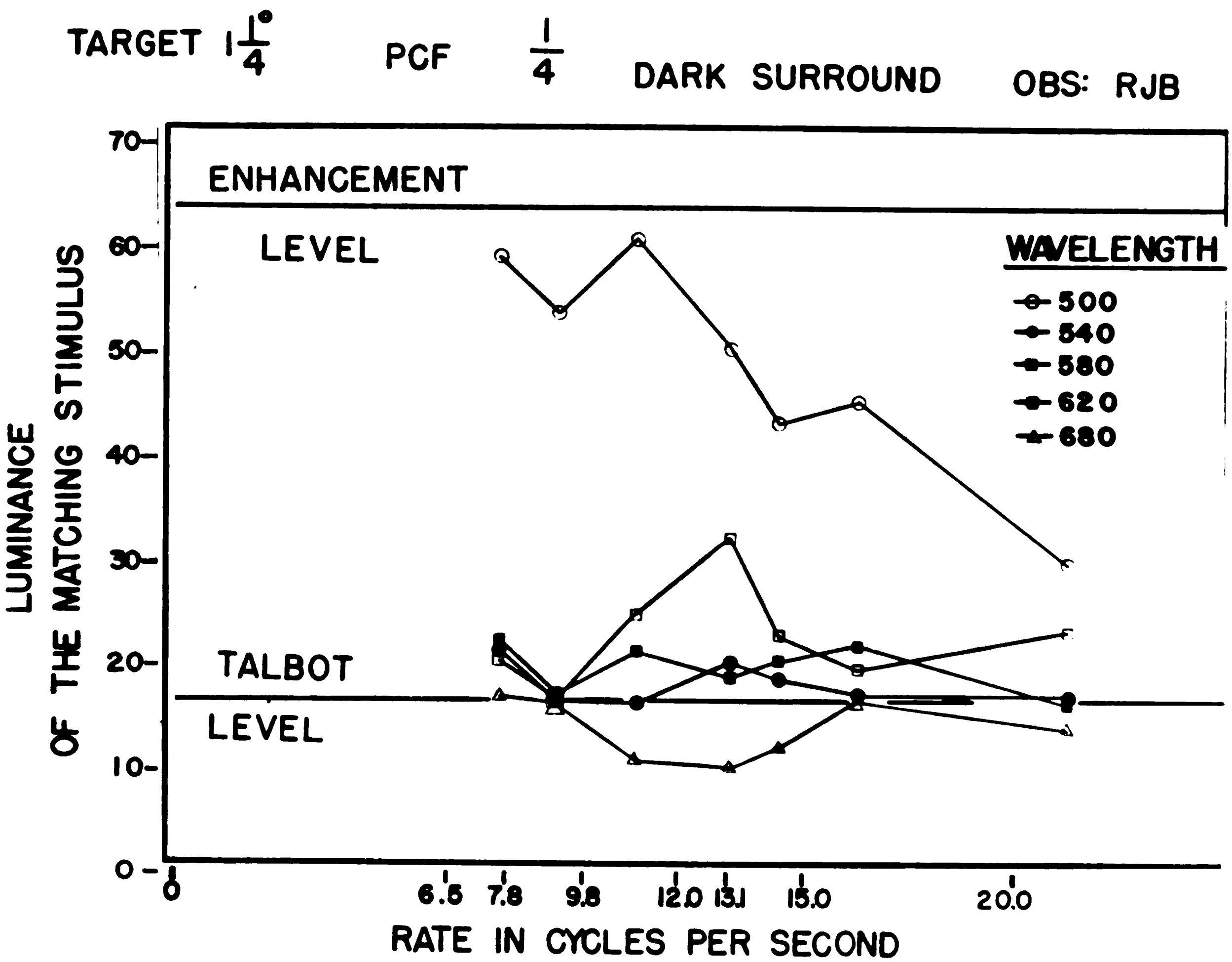


FIGURE 2


TARGET $1\frac{1}{4}°$
PCF $\frac{1}{4}$
DARK SURROUND
OBS: RJB
ENHANCEMENT
LEVEL
WAVELENGTH
500
540
580
620
680
TALBOT
LEVEL
LUMINANCE OF THE MATCHING STIMULUS
0
10
20
30
40
50
60
70
0
6.5
7.8
9.8
12.0
13.1
15.0
20.0
RATE IN CYCLES PER SECOND

FIGURE

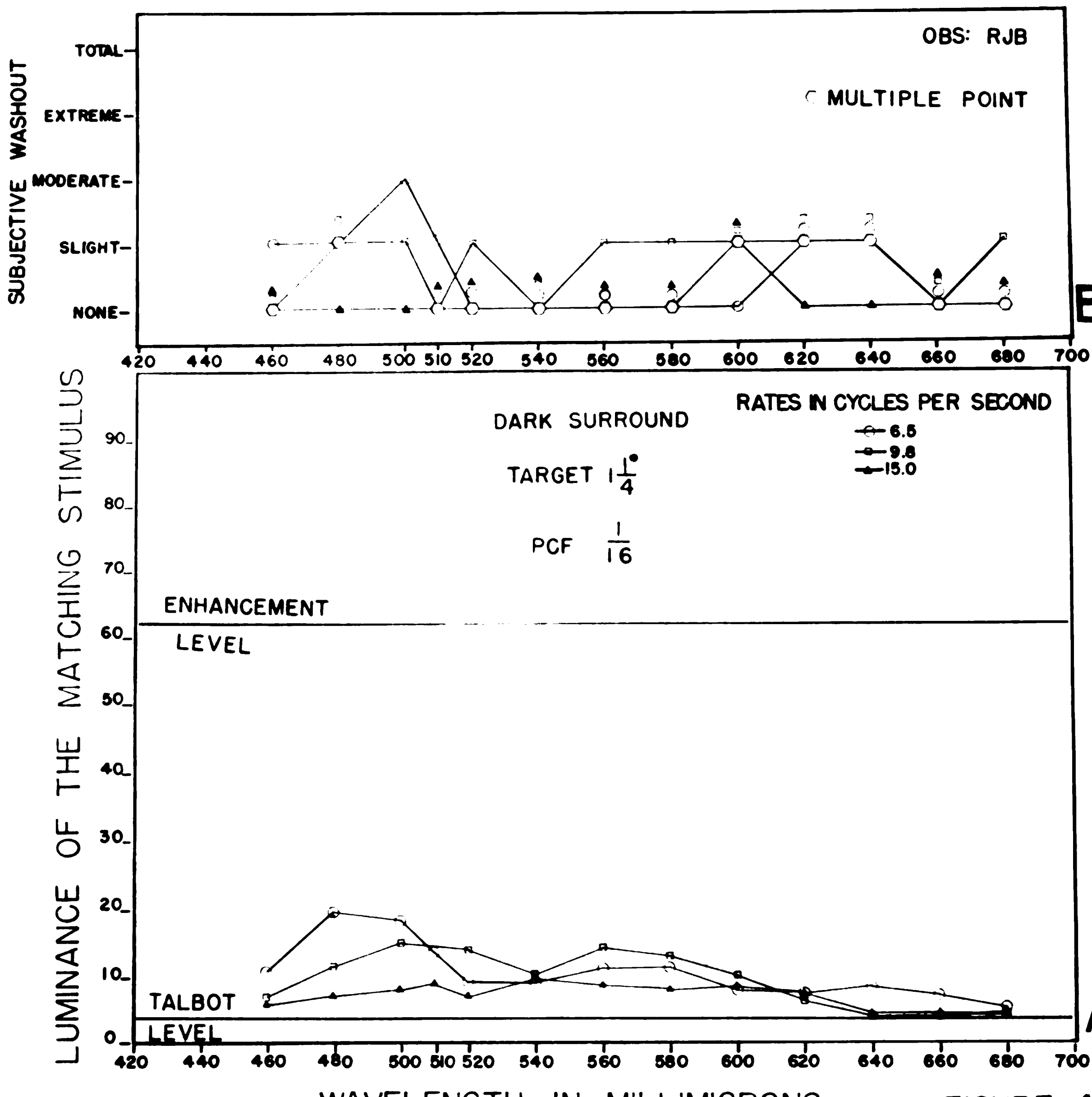

OBS: RJB
MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
LUMINANCE OF THE MATCHING STIMULUS
DARK SURROUND
TARGET 1 1/4°
PCF 1/16
RATES IN CYCLES PER SECOND
6.5
9.8
15.0
ENHANCEMENT LEVEL
TALBOT LEVEL
0 10 20 30 40 50 60 70 80 90
A
WAVELENGTH IN MILLIMICRONS

FIGURE 4

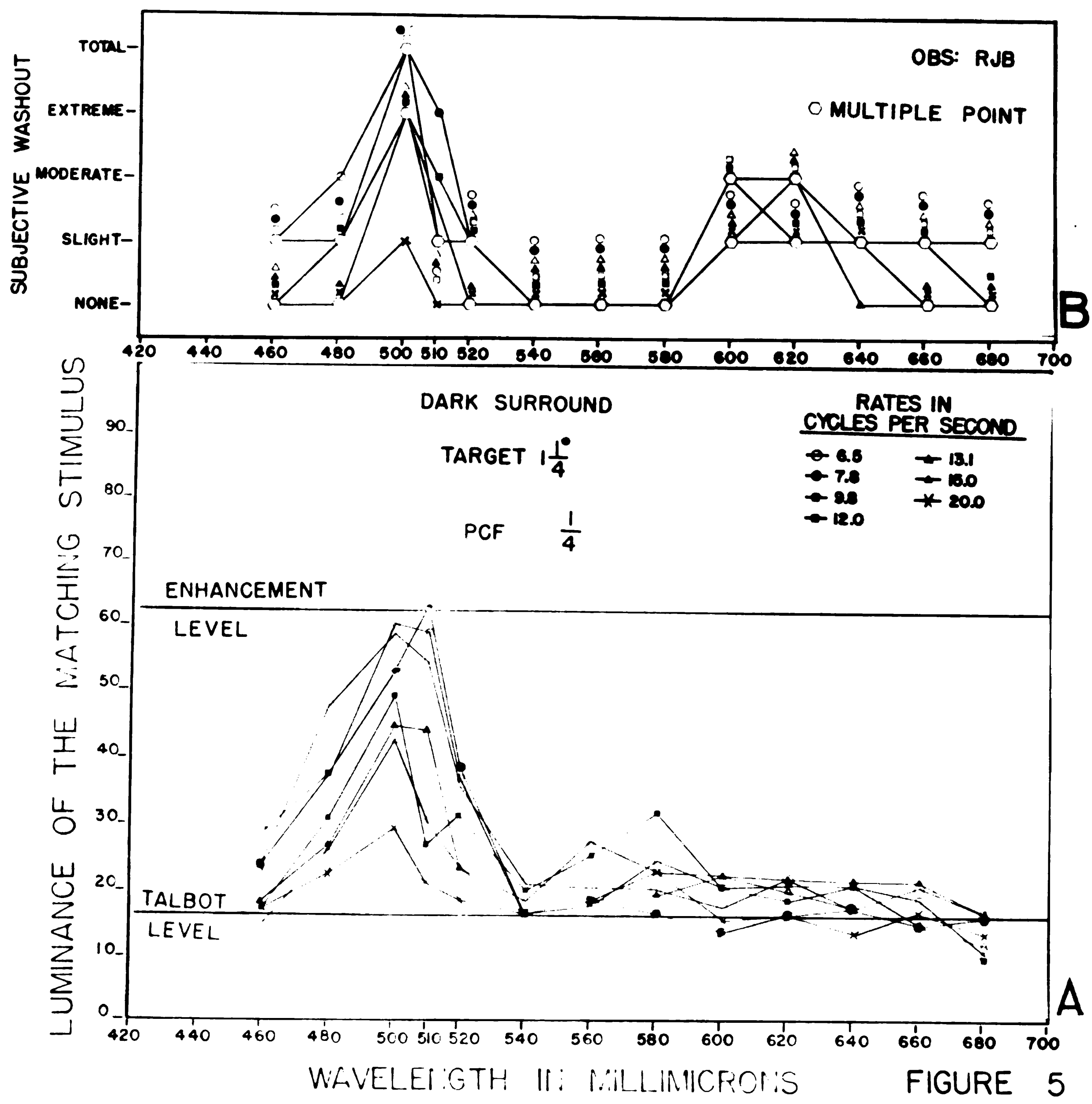

SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
OBS: RJB
○ MULTIPLE POINT
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
LUMINANCE OF THE MATCHING STIMULUS
DARK SURROUND
TARGET 1 1/4°
PCF 1/4
RATES IN CYCLES PER SECOND
6.5
7.8
9.8
12.0
13.1
16.0
20.0
ENHANCEMENT LEVEL
TALBOT LEVEL
0 10 20 30 40 50 60 70 80 90
A
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
WAVELENGTH IN MILLIMICRONS

FIGURE 5

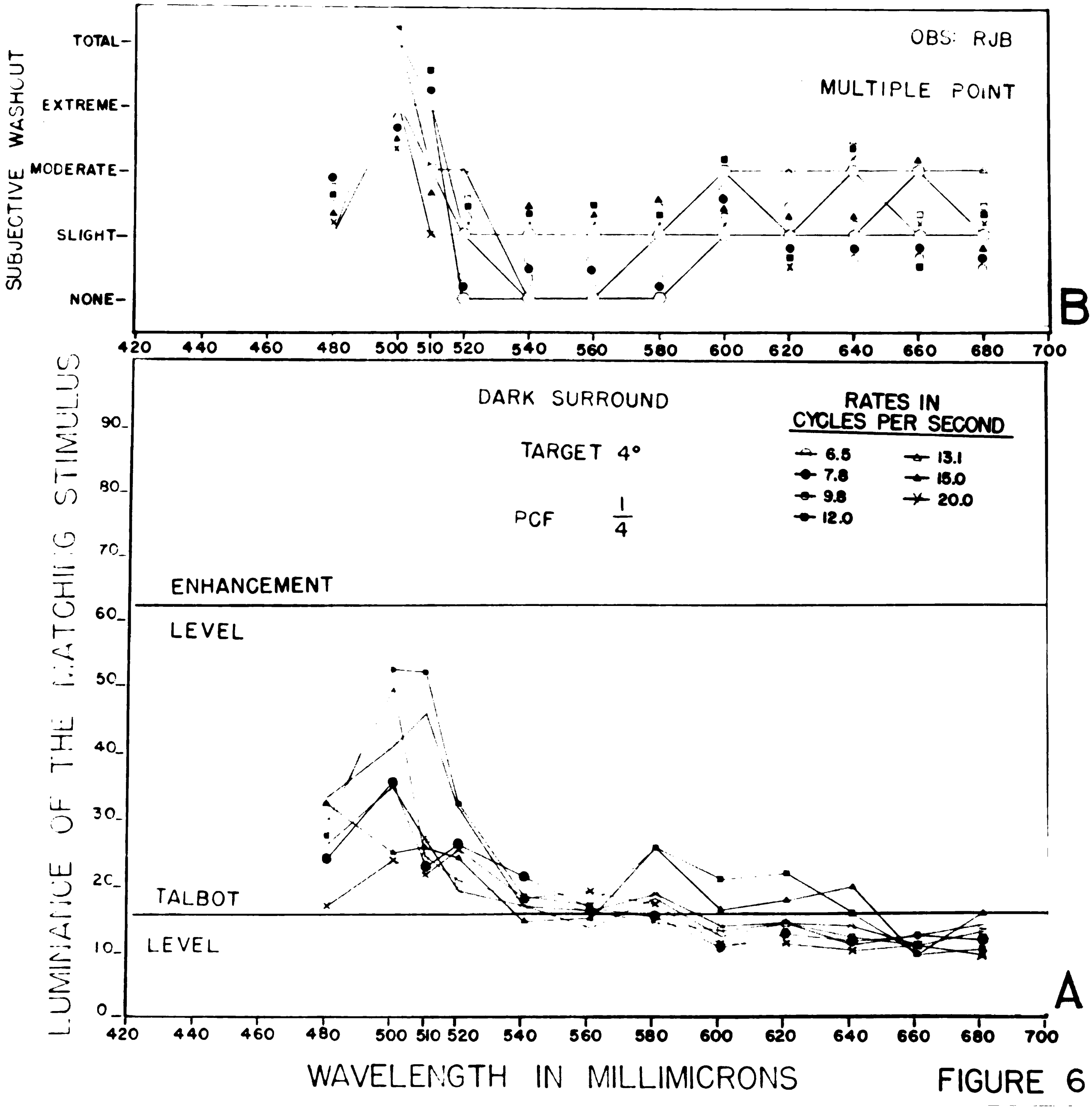
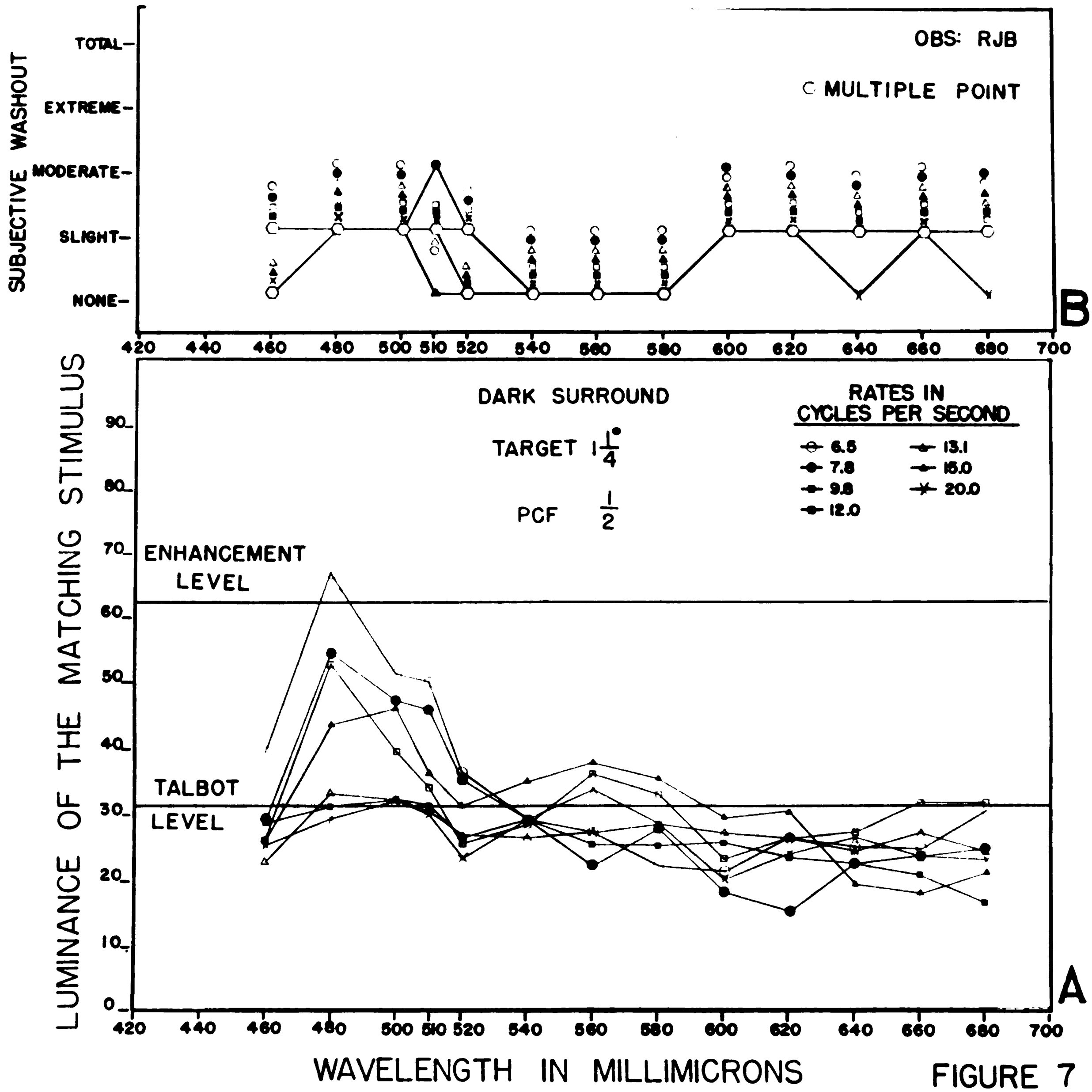

TOTAL
EXTREME
MODERATE
SLIGHT
NONE
SUBJECTIVE WASHOUT
OBS: RJB
MULTIPLE POINT
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
DARK SURROUND
TARGET 4°
PCF 1/4
RATES IN CYCLES PER SECOND
6.5
7.8
9.8
12.0
13.1
15.0
20.0
ENHANCEMENT
LEVEL
TALBOT
LEVEL
LUMINANCE OF THE MATCHING STIMULUS
0 10 20 30 40 50 60 70 80 90
A
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
WAVELENGTH IN MILLIMICRONS

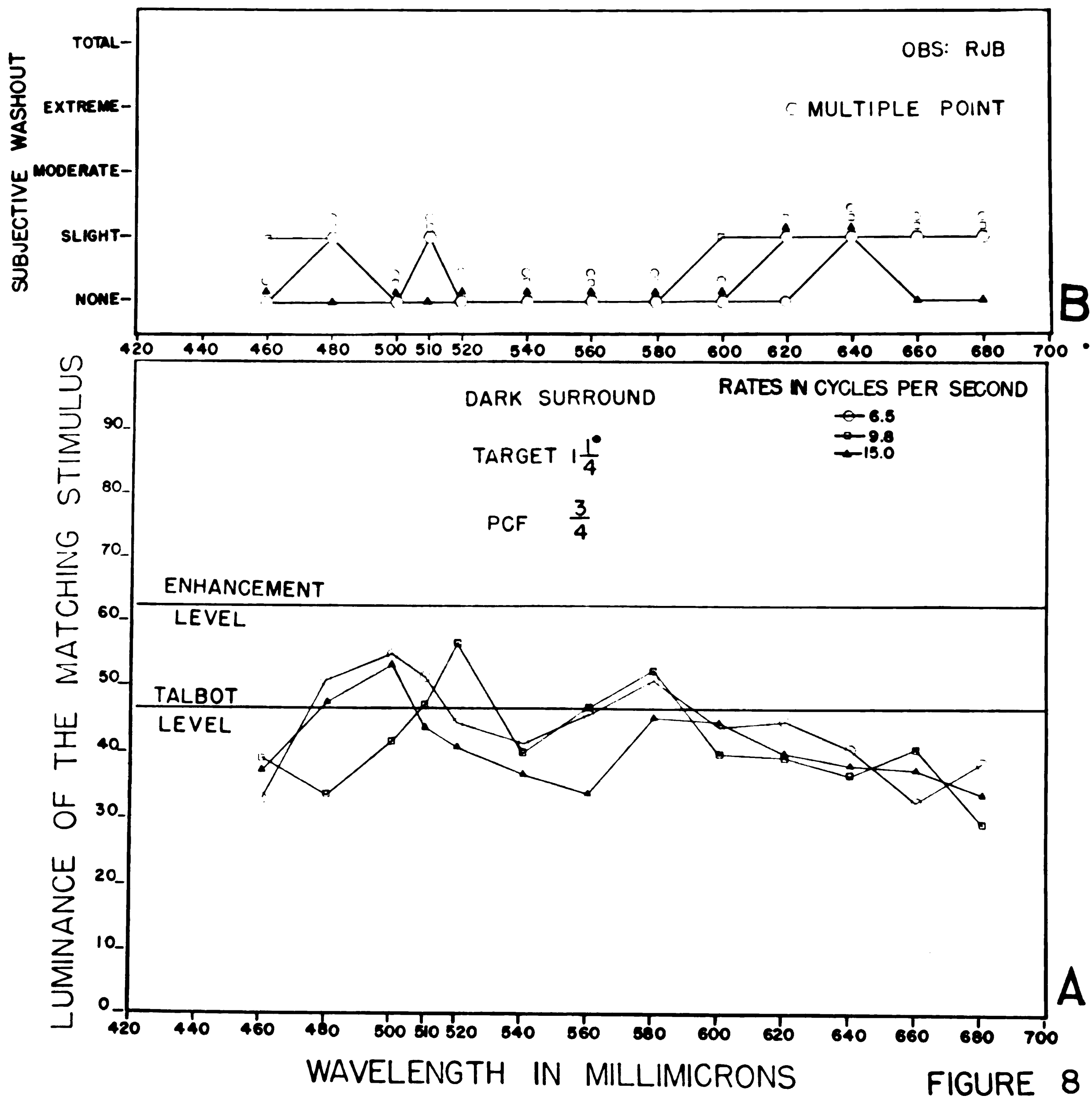
FIGURE 6

SUBJECTIVE WASHOUT



TOTAL-
EXTREME-
MODERATE-
SLIGHT-
NONE-
SUBJECTIVE WASHOUT
OBS: RJB
MULTIPLE POINT
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
DARK SURROUND
TARGET $1\frac{1}{4}°$
PCF $\frac{1}{2}$
RATES IN CYCLES PER SECOND
6.5
7.8
9.8
12.0
13.1
15.0
20.0
ENHANCEMENT LEVEL
TALBOT LEVEL
0 10 20 30 40 50 60 70 80 90
LUMINANCE OF THE MATCHING STIMULUS
A
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
WAVELENGTH IN MILLIMICRONS

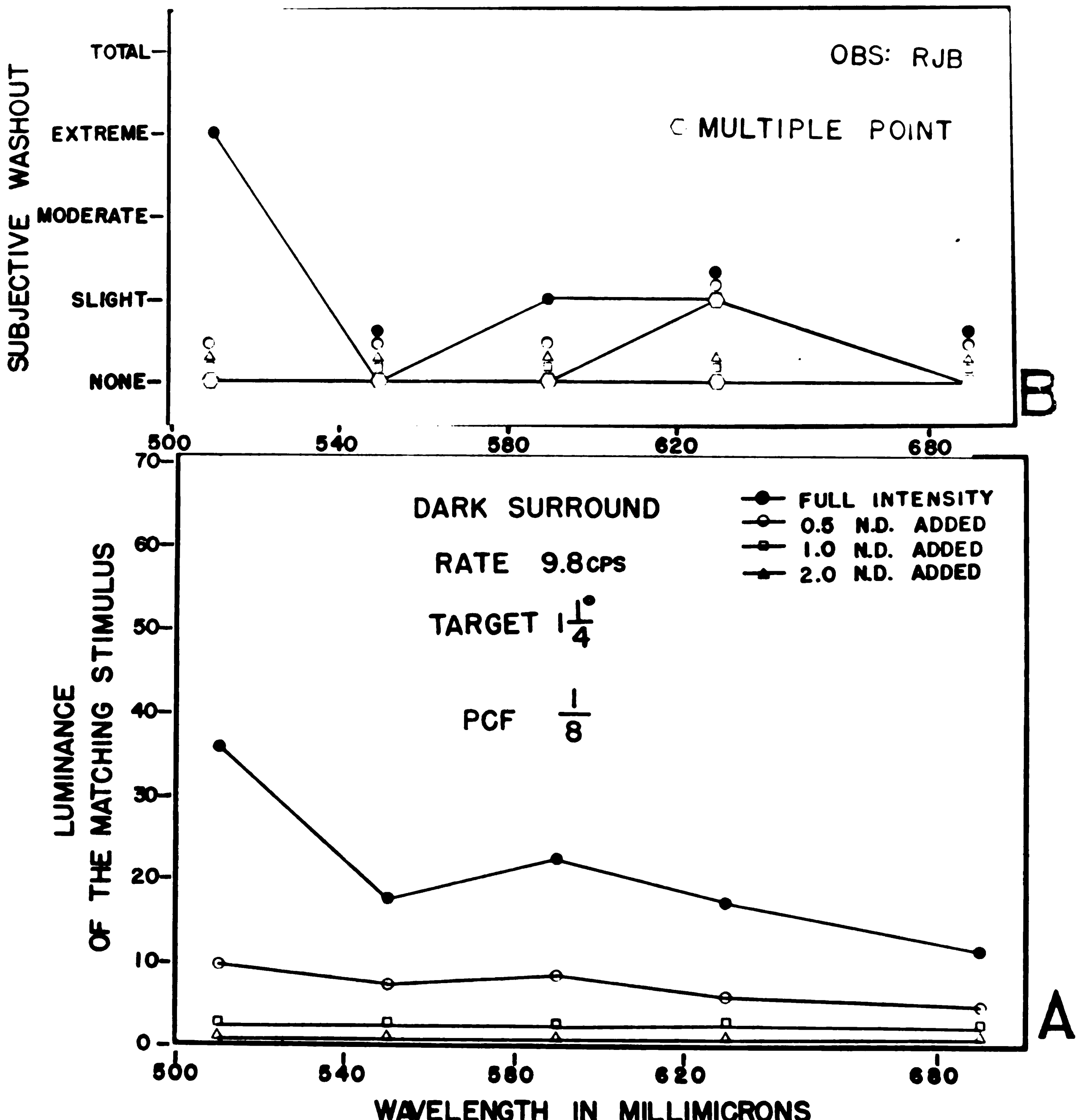
FIGURE 7



SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
OBS: RJB
MULTIPLE POINT
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
LUMINANCE OF THE MATCHING STIMULUS
90 80 70 60 50 40 30 20 10 0
DARK SURROUND
TARGET 1 1/4°
PCF 3/4
RATES IN CYCLES PER SECOND
6.5
9.8
15.0
ENHANCEMENT LEVEL
TALBOT LEVEL
A
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
WAVELENGTH IN MILLIMICRONS

FIGURE 8


LUMINANCE
SUBJECTIVE WASHOUT



SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
OBS: RJB
MULTIPLE POINT
B
LUMINANCE OF THE MATCHING STIMULUS
0
10
20
30
40
50
60
70
500
540
580
620
680
DARK SURROUND
RATE 9.8 CPS
TARGET 1 1/4°
PCF 1/8
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
A
WAVELENGTH IN MILLIMICRONS

FIGURE 9


LUMINANCE
SUBJECTIVE WASHOUT

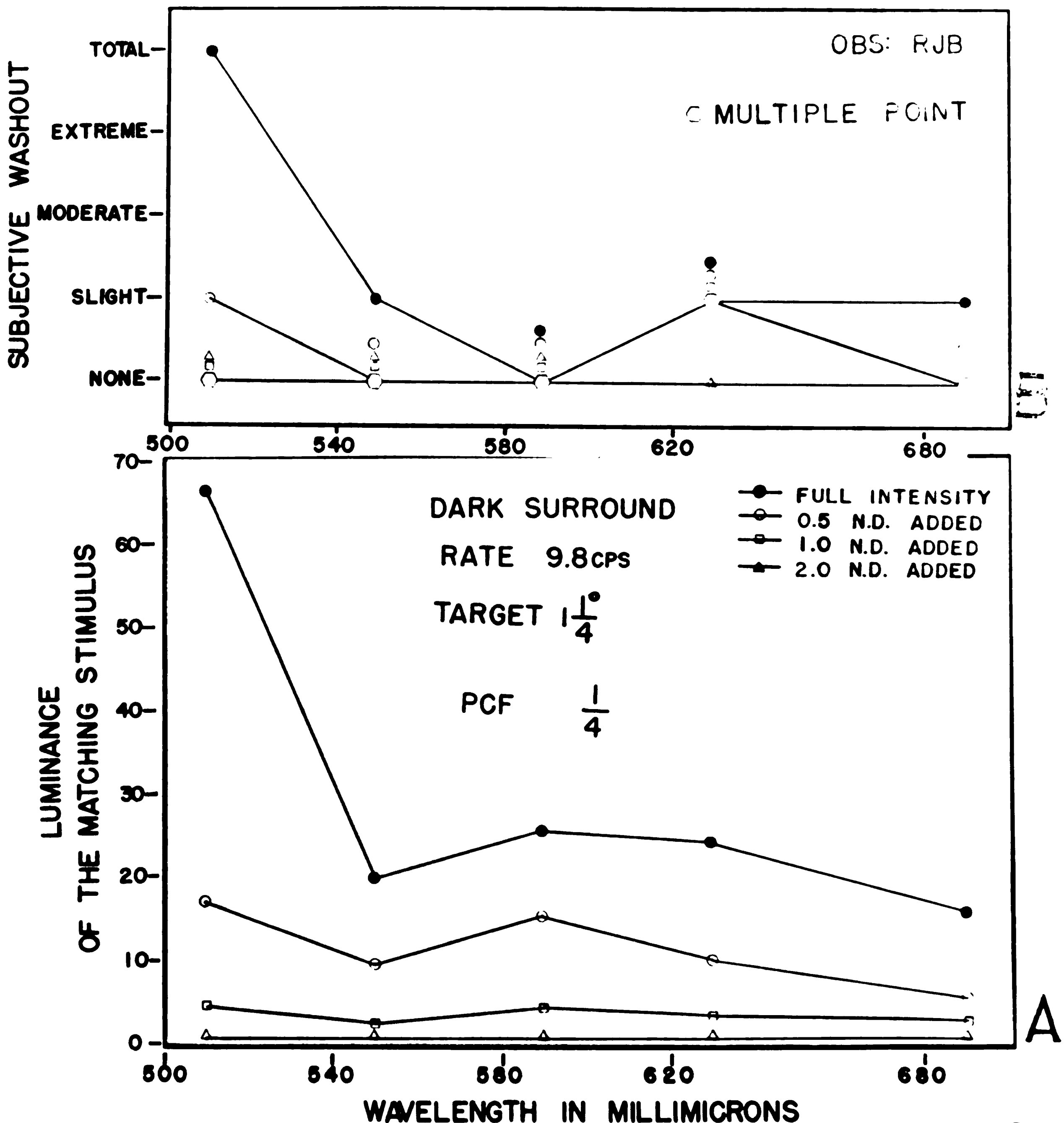

OBS: RJB
C MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
500
540
580
620
680
70
60
50
40
30
20
10
0
DARK SURROUND
RATE 9.8 CPS
TARGET $1\frac{1}{4}°$
PCF $\frac{1}{4}$
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
LUMINANCE OF THE MATCHING STIMULUS
A
WAVELENGTH IN MILLIMICRONS

FIGURE 10

LUMINANCE

SUBJECTIVE WASHOUT

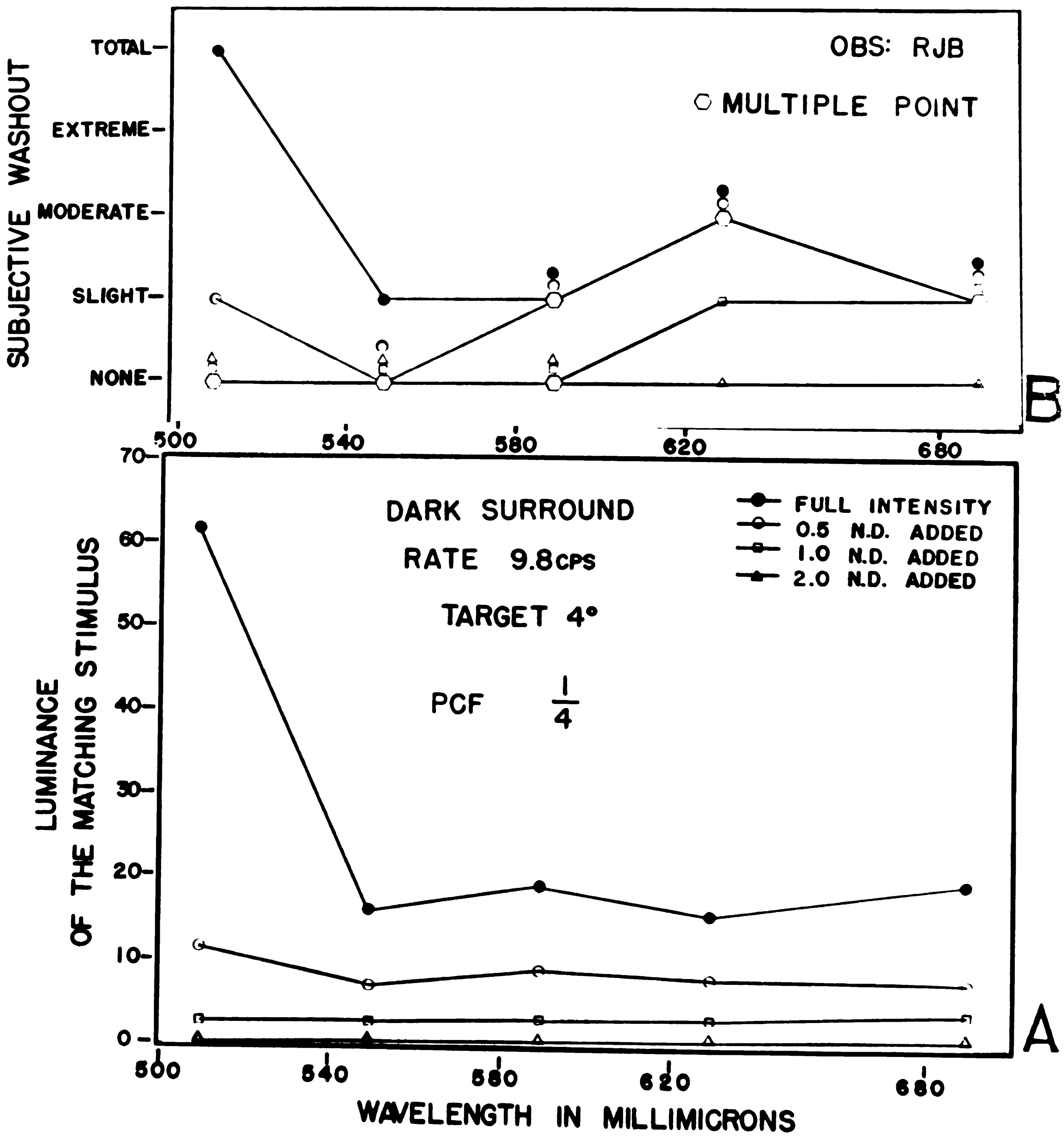

OBS: RJB
○ MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
500
540
580
620
680
B
DARK SURROUND
RATE 9.8 CPS
TARGET 4°
PCF 1/4
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
LUMINANCE OF THE MATCHING STIMULUS
70
60
50
40
30
20
10
0
500
540
580
620
680
WAVELENGTH IN MILLIMICRONS
A

FIGURE 11

SUBJECTIVE WASHOUT

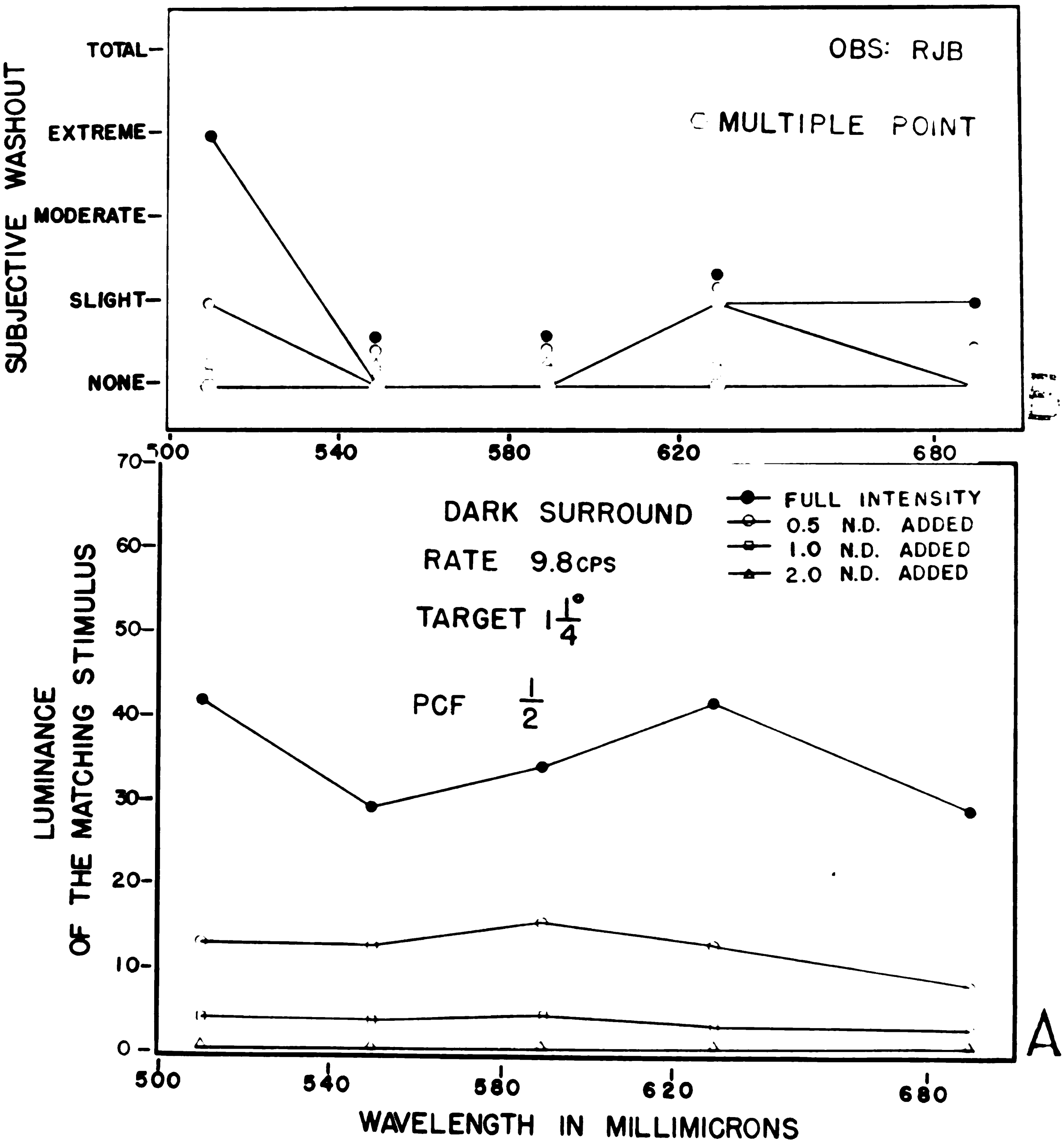
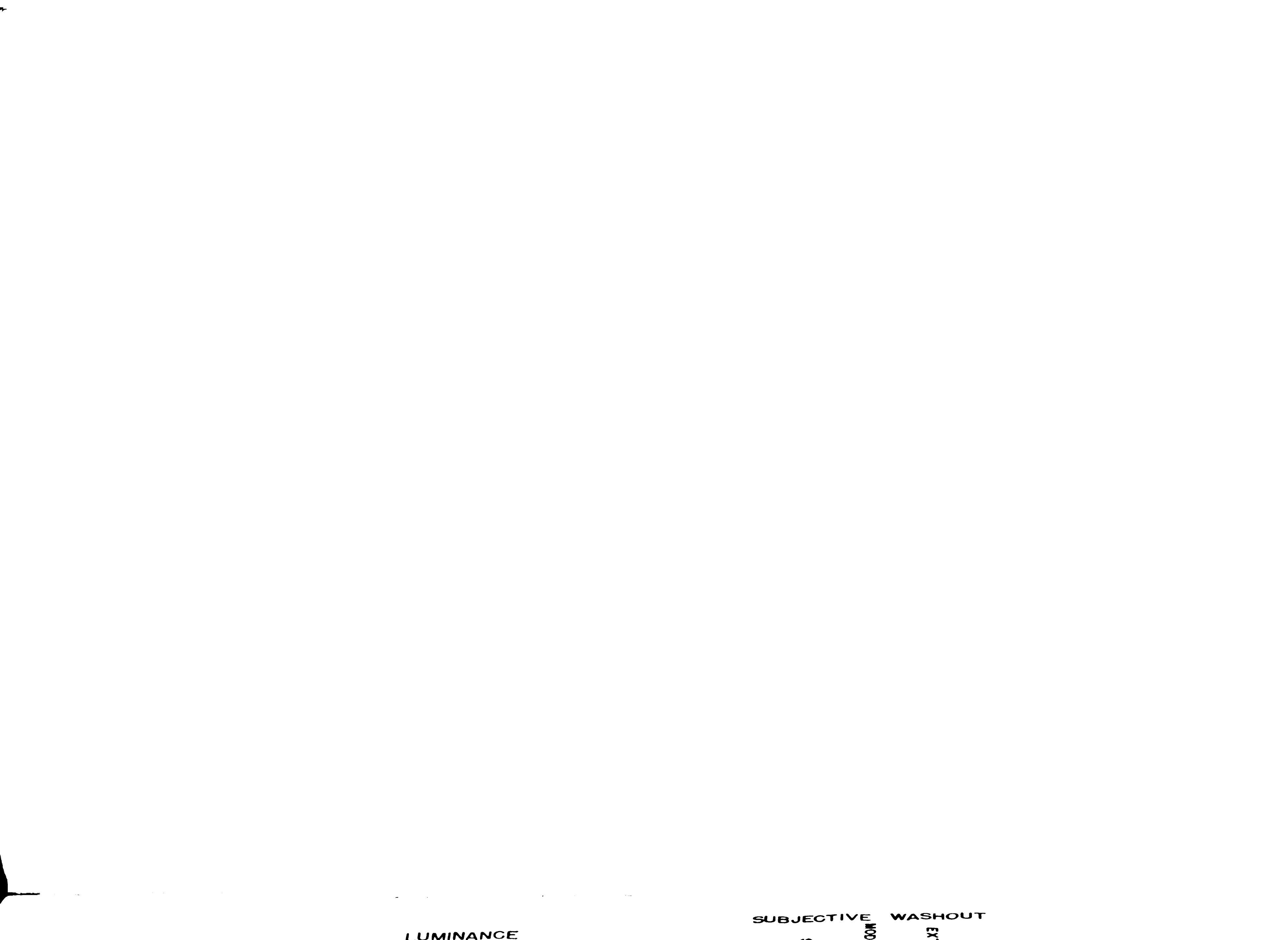

TOTAL
EXTREME
MODERATE
SLIGHT
NONE
SUBJECTIVE WASHOUT
OBS: RJB
MULTIPLE POINT
B
500
540
580
620
680
70
60
50
40
30
20
10
0
LUMINANCE
OF THE MATCHING STIMULUS
DARK SURROUND
RATE 9.8 CPS
TARGET 1 1/4°
PCF 1/2
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
A
500
540
580
620
680
WAVELENGTH IN MILLIMICRONS

FIGURE 12


LUMINANCE
SUBJECTIVE WASHOUT
MOD
EX

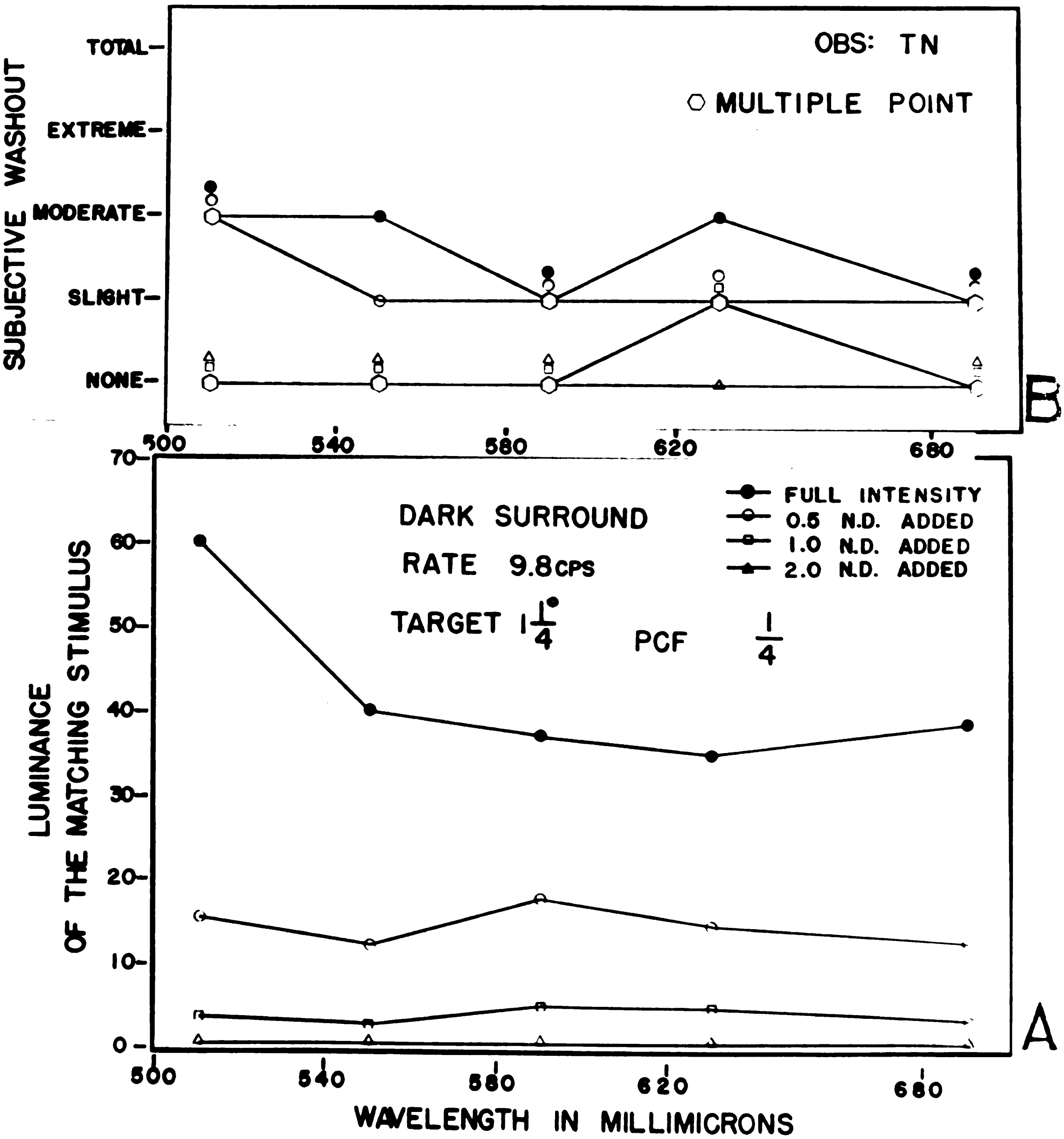
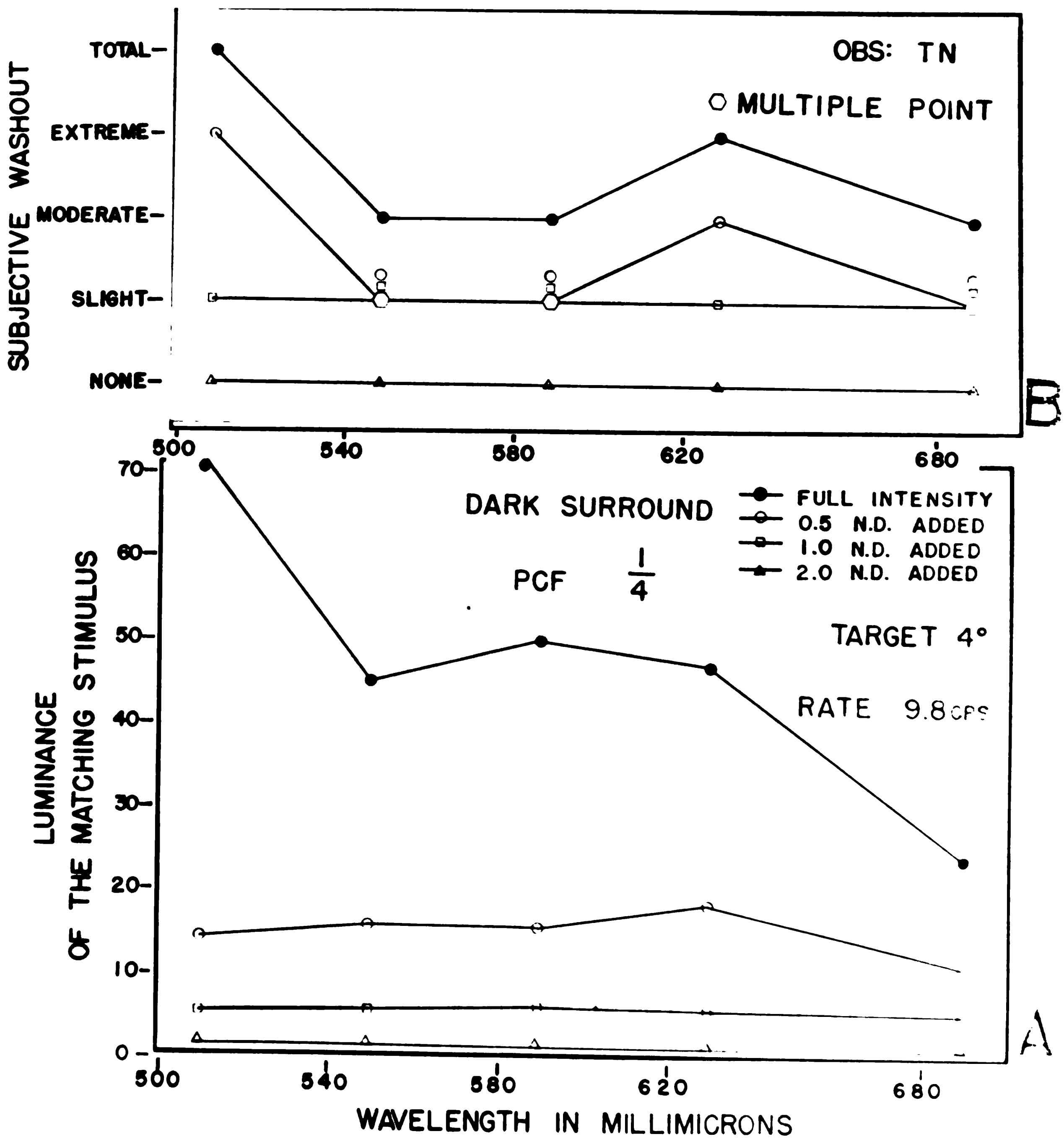

OBS: TN
MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
B
500
540
580
620
680
70
60
50
40
30
20
10
0
LUMINANCE OF THE MATCHING STIMULUS
DARK SURROUND
RATE 9.8CPS
TARGET 1 1/4°
PCF 1/4
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
A
WAVELENGTH IN MILLIMICRONS

FIGURE 13

SUBJECTIVE WASHOUT



SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
OBS: TN
○ MULTIPLE POINT
B
500
540
580
620
680
LUMINANCE OF THE MATCHING STIMULUS
70
60
50
40
30
20
10
0
DARK SURROUND
PCF 1/4
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
TARGET 4°
RATE 9.8 CPS
A
500
540
580
620
680
WAVELENGTH IN MILLIMICRONS

FIGURE 4

LUMINANCE

SUBJECTIVE WASHOUT

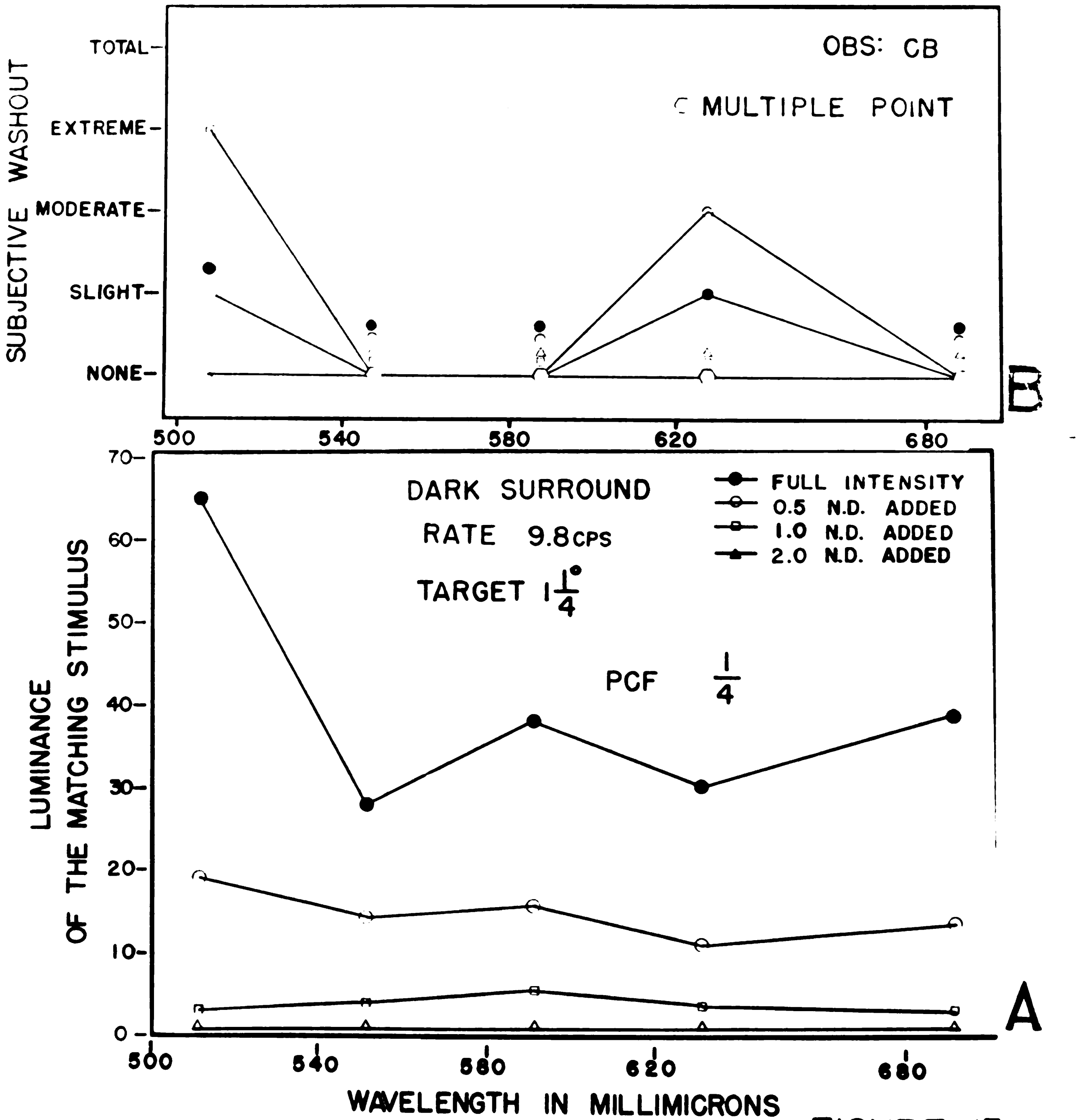
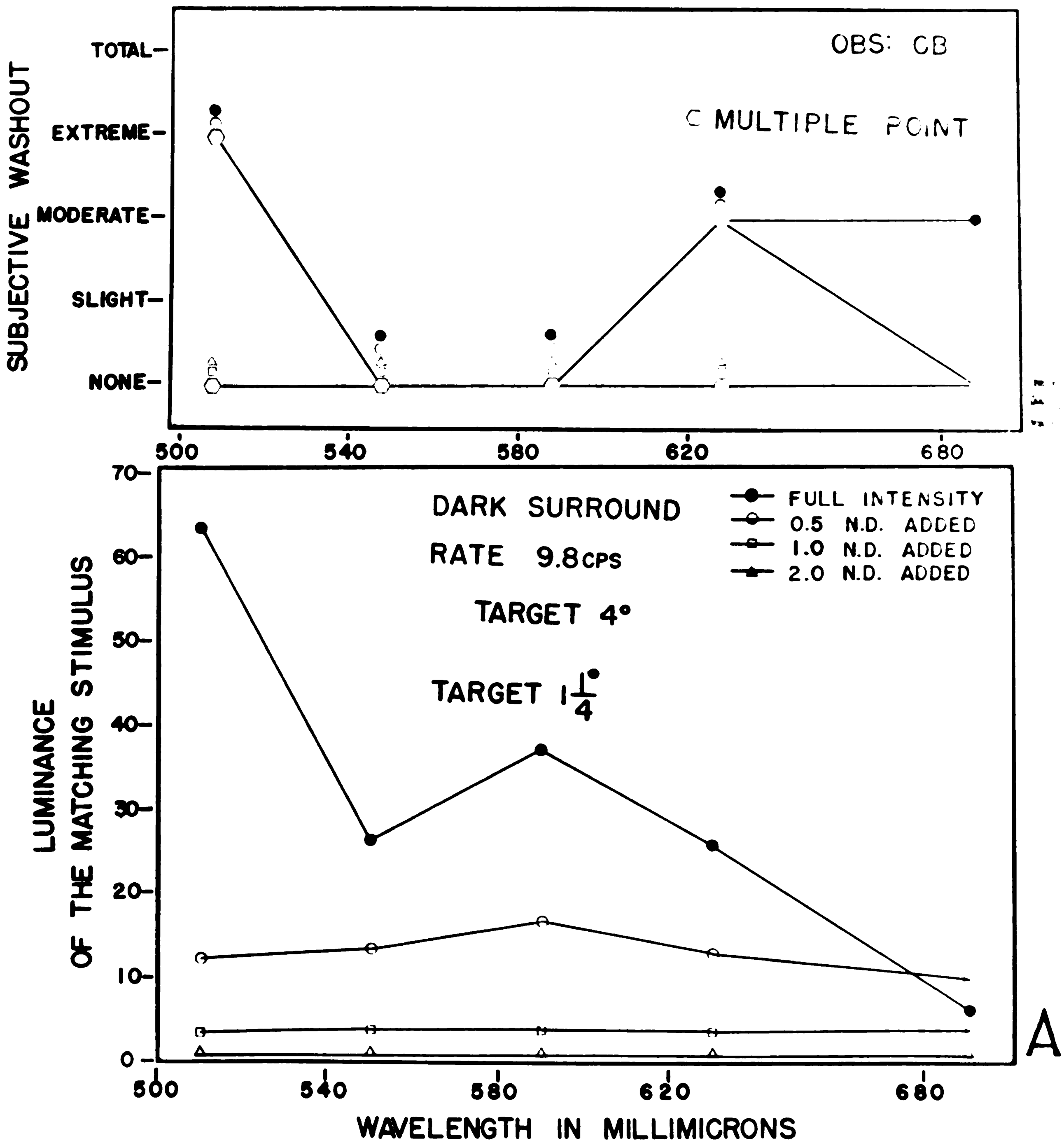

OBS: CB
MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
B
500
540
580
620
680
DARK SURROUND
RATE 9.8 CPS
TARGET $1\frac{1}{4}°$
PCF $\frac{1}{4}$
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
LUMINANCE OF THE MATCHING STIMULUS
70
60
50
40
30
20
10
0
A
500
540
580
620
680
WAVELENGTH IN MILLIMICRONS

FIGURE 15

LUMINANCE

SUBJECTIVE WASHOUT



OBS: CB
C MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
500
540
580
620
680
DARK SURROUND
RATE 9.8 CPS
TARGET 4°
TARGET 1 1/4°
FULL INTENSITY
0.5 N.D. ADDED
1.0 N.D. ADDED
2.0 N.D. ADDED
LUMINANCE OF THE MATCHING STIMULUS
70
60
50
40
30
20
10
0
WAVELENGTH IN MILLIMICRONS
A

FIGURE 16

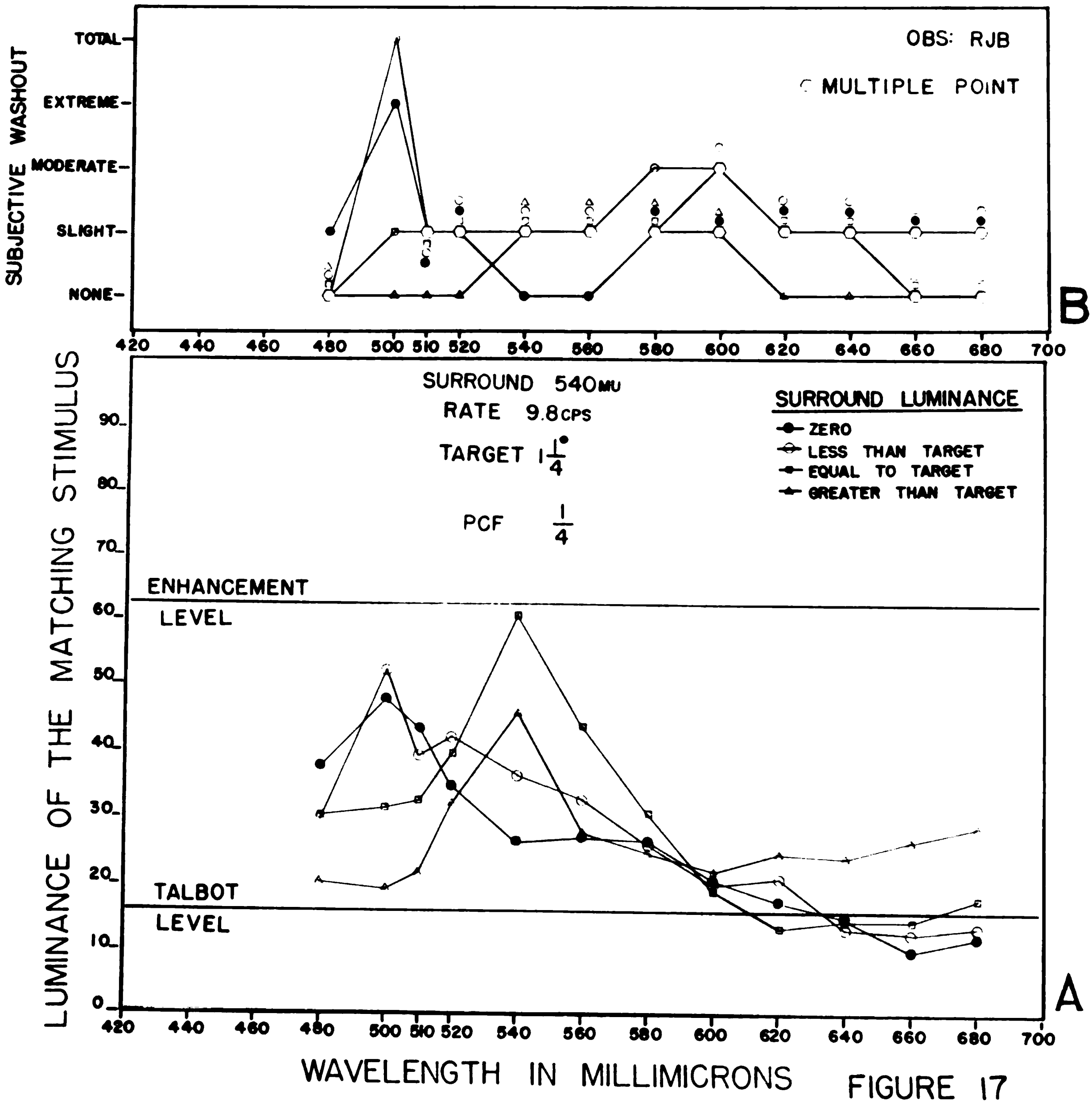

OBS: RJB
MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
B
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
SURROUND 540MU
RATE 9.8CPS
TARGET 1 1/4°
PCF 1/4
SURROUND LUMINANCE
ZERO
LESS THAN TARGET
EQUAL TO TARGET
GREATER THAN TARGET
ENHANCEMENT LEVEL
TALBOT LEVEL
LUMINANCE OF THE MATCHING STIMULUS
0 10 20 30 40 50 60 70 80 90
A
WAVELENGTH IN MILLIMICRONS

FIGURE 17

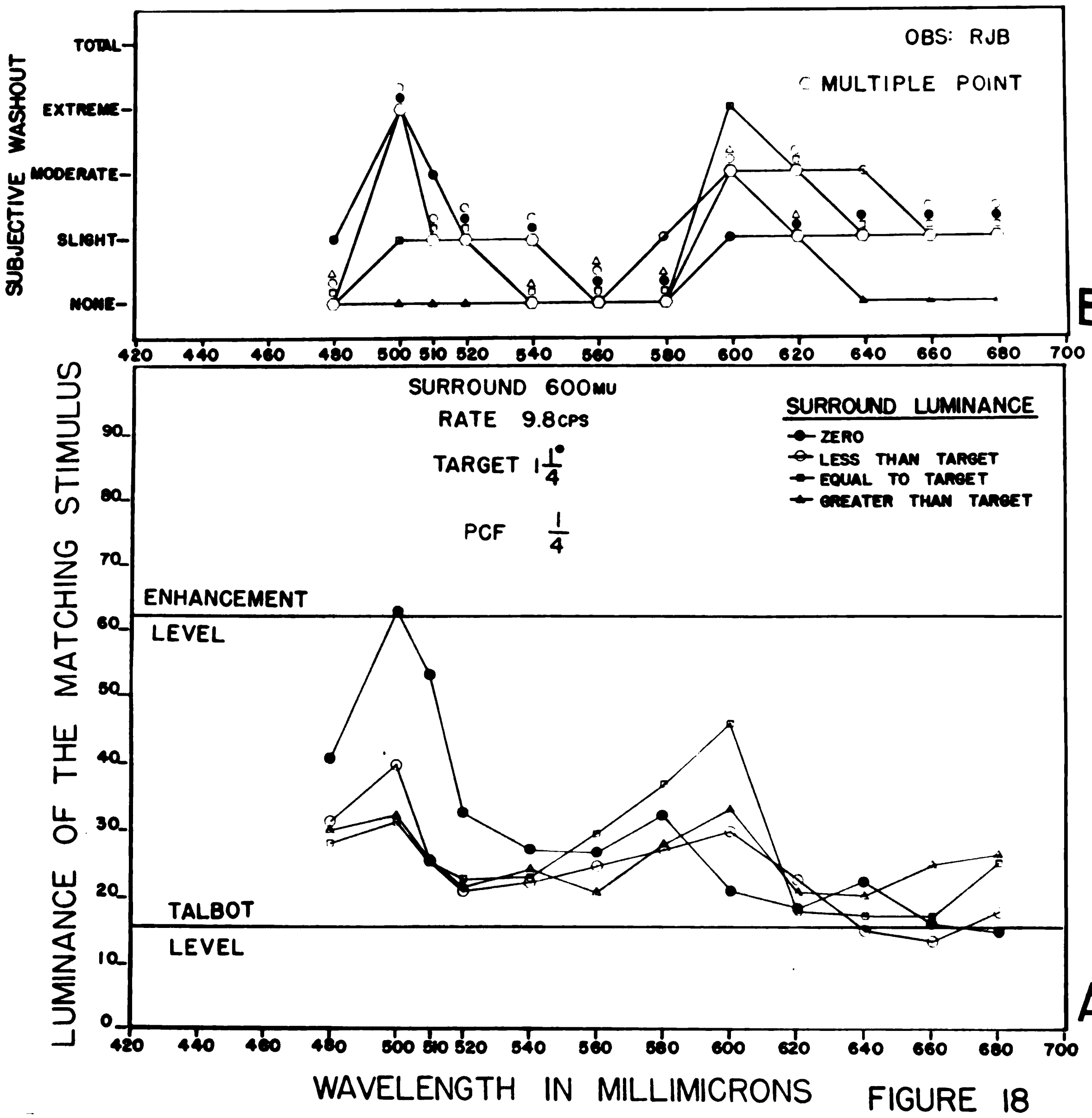

OBS: RJB
MULTIPLE POINT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
SUBJECTIVE WASHOUT
B
SURROUND 600MU
RATE 9.8CPS
TARGET 1 1/4°
PCF 1/4
SURROUND LUMINANCE
ZERO
LESS THAN TARGET
EQUAL TO TARGET
GREATER THAN TARGET
ENHANCEMENT LEVEL
TALBOT LEVEL
LUMINANCE OF THE MATCHING STIMULUS
A
420 440 460 480 500 510 520 540 560 580 600 620 640 660 680 700
WAVELENGTH IN MILLIMICRONS

FIGURE 18

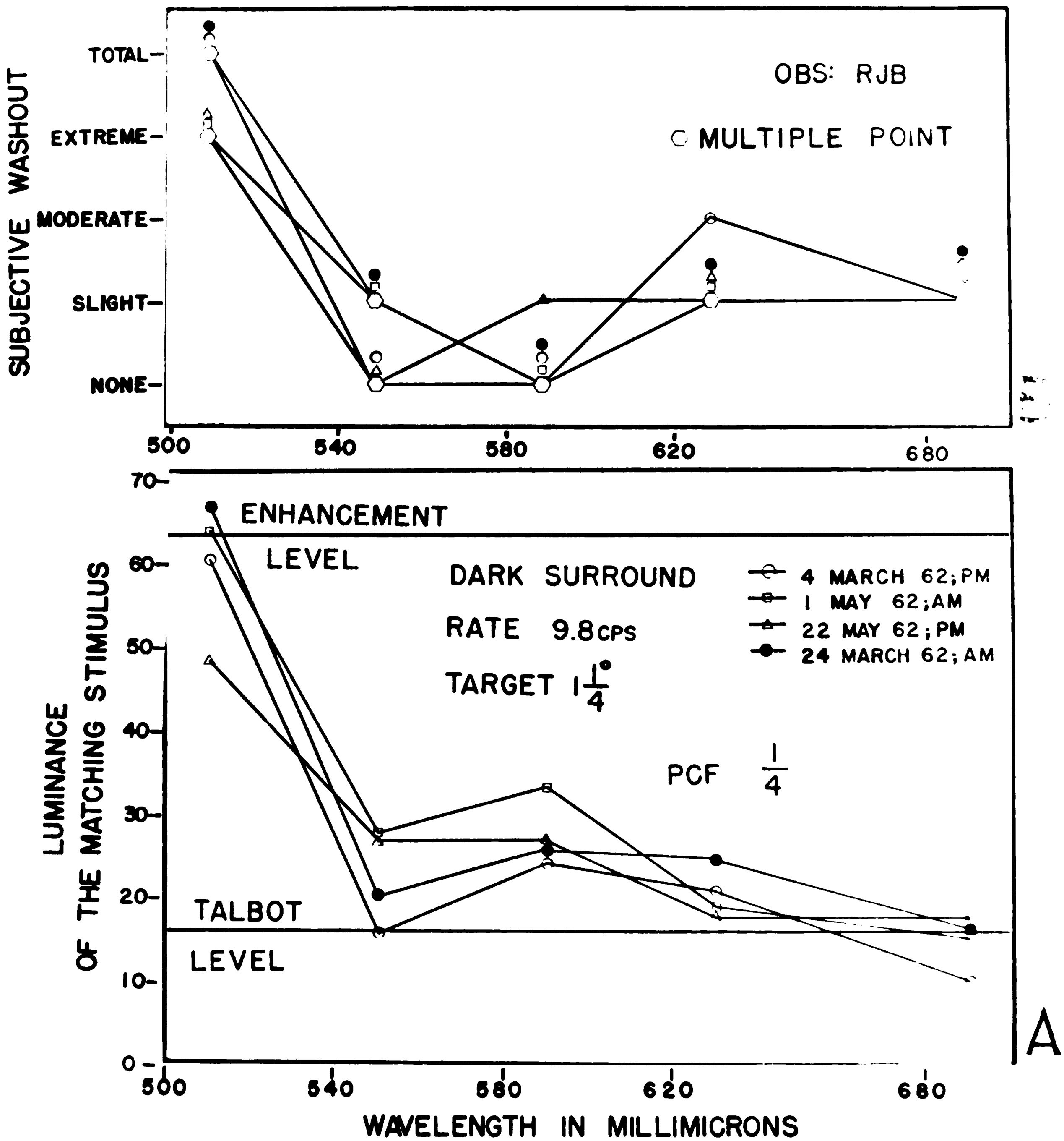
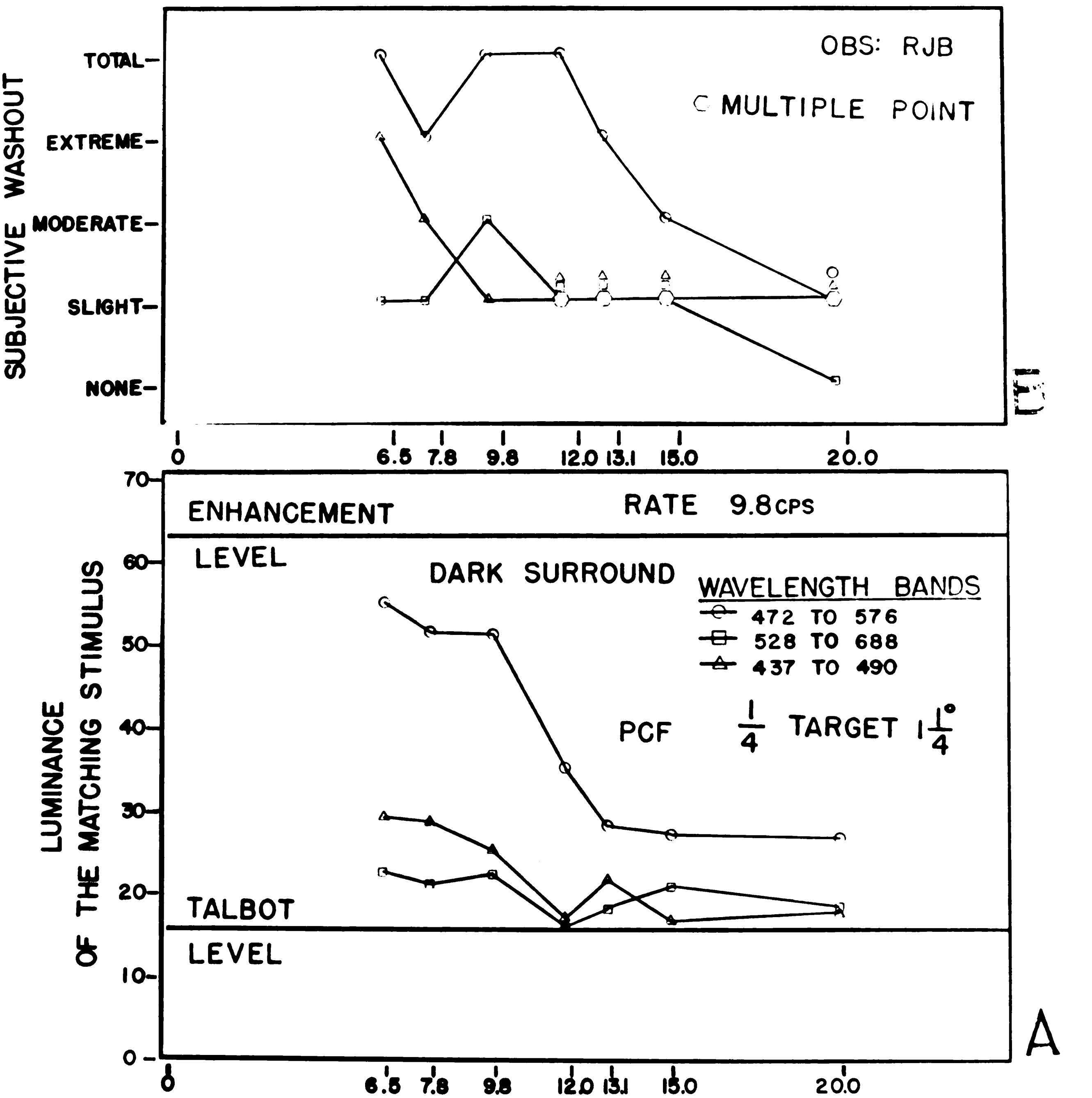

SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
OBS: RJB
○ MULTIPLE POINT
500
540
580
620
680
LUMINANCE OF THE MATCHING STIMULUS
70
60
50
40
30
20
10
0
ENHANCEMENT LEVEL
DARK SURROUND
RATE 9.8 CPS
TARGET $1\frac{1}{4}$°
PCF $\frac{1}{4}$
4 MARCH 62; PM
1 MAY 62; AM
22 MAY 62; PM
24 MARCH 62; AM
TALBOT LEVEL
A
WAVELENGTH IN MILLIMICRONS

FIGURE 19



OBS: RJB
C MULTIPLE POINT
SUBJECTIVE WASHOUT
TOTAL
EXTREME
MODERATE
SLIGHT
NONE
B
0
6.5 7.8 9.8 12.0 13.1 15.0 20.0
70
60
50
40
30
20
10
0
ENHANCEMENT
LEVEL
RATE 9.8 CPS
DARK SURROUND
WAVELENGTH BANDS
472 TO 576
528 TO 688
437 TO 490
PCF 1/4 TARGET 1 1/4°
TALBOT
LEVEL
LUMINANCE OF THE MATCHING STIMULUS
A
0
6.5 7.8 9.8 12.0 13.1 15.0 20.0
RATE IN CYCLES PER SECOND

FIGURE 20

PCF	Rate	Size	Sur. I	Sur. mμ	460	480	500	510	520	540	560	580	600	620	640	660	680
1/16	6.5	S	0	-	-	D	U	U	U	U	-	-	D	D	D	D	D
1/16	9.8	S	0	-	-	-	U	U	U	U	-	-	D	D	D	D	D
1/16	15.0	S	0	-	-	-	-	-	-	-	-	-	D	D	D	D	D
1/4	6.5	S	0	-	D	D	W	U	U	U	-	-	D	D	D	D	D
1/4	7.8	S	0	-	D	D	W	-	U	U	-	-	D	D	D	D	D
1/4	9.8	S	0	-	D	-	W	U	U	U	-	-	D	D	D	D	D
1/4	12.0	S	0	-	-	-	-	U	U	-	-	-	D	D	D	D	D
1/4	13.1	S	0	-	-	-	U	U	U	U	-	-	D	D	D	D	D
1/4	15.0	S	0	-	-	-	-	U	U	-	-	-	D	D	-	-	-
1/4	20.0	S	0	-	-	-	-	-	-	-	-	-	D	-	D	-	-
1/4	6.5	L	0	-		D	-	-	U	U	U	-	D	D	D	D	D
1/4	7.8	L	0	-		D	-	U	U	U	U	-	D	D	D	D	D
1/4	9.8	L	0	-		D	W	U	U	U	U	-	D	D	D	D	D
1/4	12.0	L	0	-		D	W	U	U	U	-	-	D	D	D	D	D
1/4	13.1	L	0	-		D	W	U	U	U	-	-	D	D	D	D	D
1/4	15.0	L	0	-		D	-	U	U	U	-	D	D	D	D	D	D
1/4	20.0	L	0	-		-	-	U	U	U	-	D	D	D	D	D	D
1/2	6.5	S	0	-	D	D	U	U	U	U	-	-	D	D	D	D	D
1/2	7.8	S	0	-	D	D	U	U	U	U	-	-	D	D	D	D	D
1/2	9.8	S	0	-	D	D	U	U	U	U	-	-	D	D	D	D	D
1/2	12.0	S	0	-	D	-	-	U	U	U	-	-	D	D	D	D	D
1/2	13.1	S	0	-	-	-	-	U	U	U	-	D	D	D	D	D	D
1/2	15.0	S	0	-	-	-	U	U	U	U	-	-	D	D	D	D	D
1/2	20.0	S	0	-	-	-	-	-	U	-	-	-	D	D	-	D	D
3/4	6.5	S	0	-	-	-	-	-	-	U	-	-	-	-	D	D	D
3/4	9.8	S	0	-	-	-	-	-	-	-	-	-	D	D	D	D	D
3/4	15.0	S	0	-	-	-	-	-	-	-	-	-	-	D	D	-	D
1/4	9.8	S	0	-		D	U	U	U	-	-	-	D	D	D	D	D
1/4	9.8	S	Less	540		-	W	U	U	U	U	-	-	D	D	D	D
1/4	9.8	S	=	540		-	-	-	U	U	-	-	D	D	D	-	-
1/4	9.8	S	More	540		-	-	-	-	-	-	-	-	-	-	-	-
1/4	9.8	S	0	-		-	U	U	U	U	-	-	D	D	D	D	D
1/4	9.8	S	Less	600		-	-	U	U	U	-	D	D	D	D	D	D
1/4	9.8	S	=	600		-	-	-	-	-	-	-	-	D	D	D	D
1/4	9.8	S	More	600		-	-	-	-	-	-	-	-	D	-	-	-

Figure 22. Hue shift for experimental conditions using five wavebands.

PCF	Rate	Size	Obs.	Sur.	N.D. Added	500	540	580	620	680
1/8		S	RJB		0	U	U	-	-	D
1/8		S	RJB		.5	-	-	-	D	-
1/8		S	RJB		1.0	-	-	-	-	-
1/8		S	RJB		2.0	-	-	-	-	-
1/2		S	RJB		0	U	U	-	D	D
1/2		S	RJB		0.5	U	U	-	D	D
1/2		S	RJB		1.0	-	-	-	D	-
1/2		S	RJB		2.0	-	-	-	-	-
		S	RJB		0	W	U	-	D	D
		S	RJB		0.5	-	-	-	D	D
		S	RJB		1.0	-	-	-	-	-
		S	RJB		2.0	-	-	-	-	-
		L	RJB		0	W	U	D	D	D
		L	RJB		0.5	-	U	-	D	D
		L	RJB		1.0	-	-	-	-	-
1/4	9.8	L	RJB	0	2.0	-	-	-	-	-
		S	TN		0	U	U	-	D	D
		S	TN		0.5	U	U	-	D	D
		S	TN		1.0	U	-	-	D	-
		S	TN		2.0	-	-	-	-	-
		L	TN		0	W	U	-	D	D
		L	TN		0.5	U	U	-	D	D
		L	TN		1.0	U	U	-	D	D
		L	TN		2.0	-	-	-	-	-
		L	CB		0	-	U	-	D	D
		L	CB		0.5	-	U	-	D	-
		L	CB		1.0	-	-	-	-	-
		L	CB		2.0	-	-	-	-	-