

# E R R A T A

| Page | Line |     |                                               |      |                                                 |
|------|------|-----|-----------------------------------------------|------|-------------------------------------------------|
| 19   | 16   | FOR | mercury charge                                | READ | mercury discharge                               |
| 22   | 12   | "   | 10 arrangements of the same hue               | "    | 10 different arrangements each of a certain hue |
|      | 13   | "   | different chromaticities                      | "    | different chromaticities (i.e. saturation)      |
|      | 14   | "   | chromatics                                    | "    | chromatic                                       |
| 28   | 11   | "   | adapt                                         | "    | adopt                                           |
| 64   | 25   | "   | chart                                         | "    | chart                                           |
| 110  | 20   | "   | was                                           | "    | were                                            |
| 133  | 2    | "   | patter                                        | "    | pattern                                         |
|      | 21   | "   | figure                                        | "    | figures                                         |
| 162  | 6    | "   | blue                                          | "    | red                                             |
| 187  | 14   | "   | lightness                                     | "    | brightness                                      |
| 201  | 9    | "   | three                                         | "    | two                                             |
| 192  | 15   | "   | away from the red                             | "    | towards the red                                 |
|      | 22   | "   | emperical                                     | "    | empirical                                       |
| 197  | 15   | "   | "                                             | "    | "                                               |
| 201  | 23   | "   | "                                             | "    | "                                               |
| 204  | 4    | "   | appearane                                     | "    | appearance                                      |
|      | 22   | "   | emperical                                     | "    | empirical                                       |
| 221  | 20   | "   | shows                                         | "    | show                                            |
| 245  | 4    | "   | successive colour contrast                    | "    | simultaneous colour contrast                    |
| 254  | 3    | "   | adaptation                                    | "    | aberration                                      |
| 259  | last | "   | or                                            | "    | of                                              |
| 261  | 9    | "   | $1 : 2(Y_A/Y_C) \Delta_A$                     | "    | $100 : 2(Y_A/Y_C) \Delta_A$                     |
|      | 11   | "   | $1 : 4(Y_A/Y_C) \Delta_A$                     | "    | $100 : 4(Y_A/Y_C) \Delta_A$                     |
| 273  | 23   |     | against the equations obtained by RGB mixture | "    | against the RGB mixture                         |
| 289  | 16   |     | uniform chromaticity                          | "    | uniform chromaticity chart                      |
|      | 18   | "   | "                                             | "    | "                                               |

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—

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY.

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TECHNICAL OPTICS SECTION

—

TECHNIQUES FOR SUBJECTIVE COLOUR MEASUREMENT AND THEIR APPLICATION TO

COLOUR CONTRAST PHENOMENA.

THESIS SUBMITTED FOR THE

Ph.D. (PHYSICS)

by

SOBH Y SAM AAN G I N D Y.

—

1963.

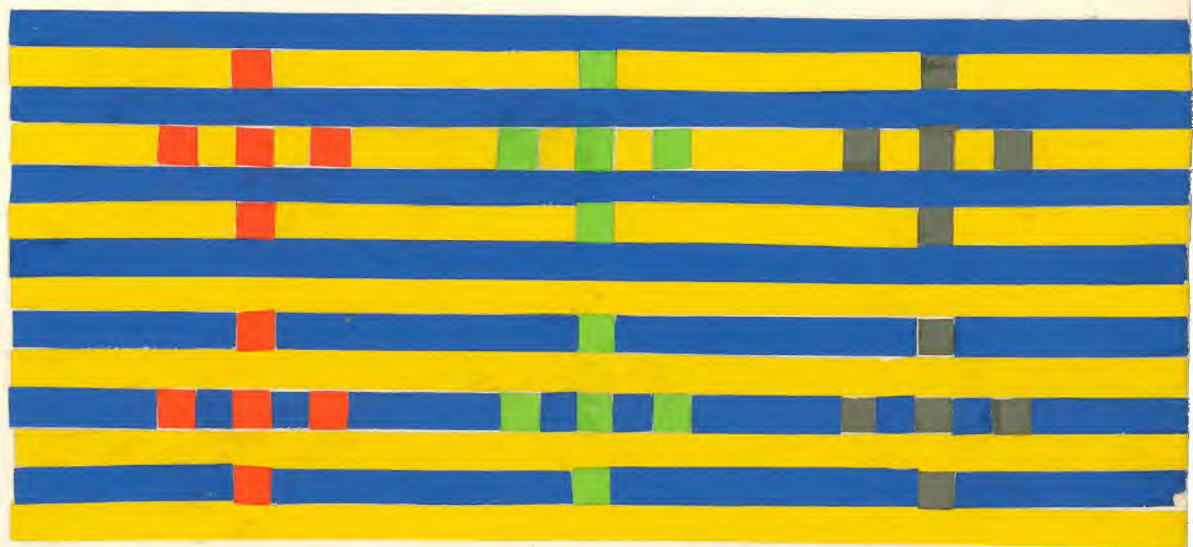


PLATE ( 1 - a & b )

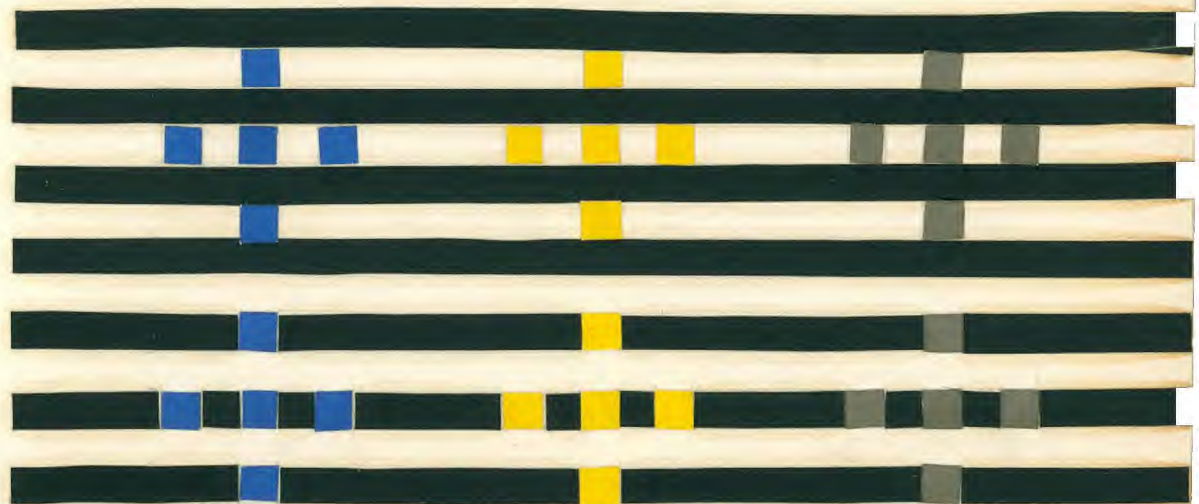
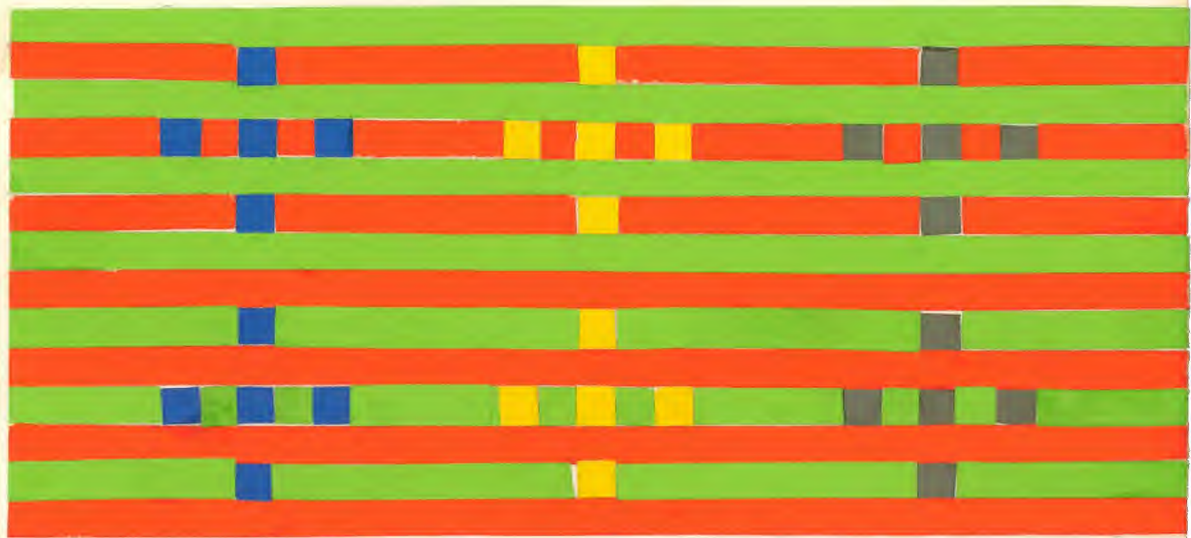


PLATE ( 2 - a & b )



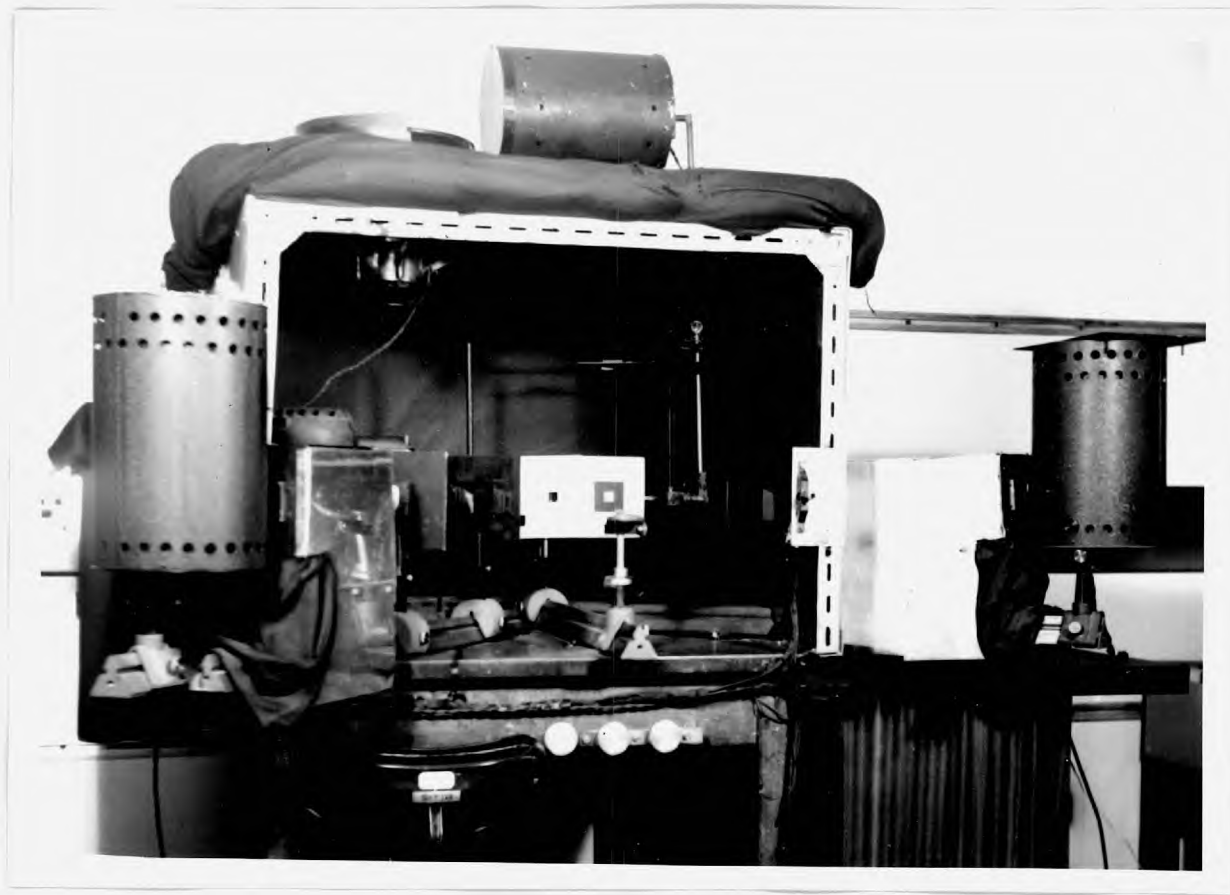


PLATE (3).   THE APPARATUS.

### ABSTRACT.

Striking changes in colour appearance can arise when small areas of colour are seen in juxtaposition against a coloured background. These changes are of great interest as a problem in visual physiology since many factors may contribute to the effect. They are also of practical importance since they may have a major influence on colour design.

Different techniques of subjective colour measurement are surveyed. Two methods are used to measure these colour changes as a basis for the quantitative study of the colour contrast phenomena.

In the first method: Standard source  $S_A$  is used for illumination of the test colour in its surround, and its appearance is compared with a red-green-blue mixture from a modified form of Donaldson Colorimeter using monocular vision.

In the second method: Natural daylight is used as illuminant and the colour appearance is matched by a number of observers having normal colour vision by comparison with colour samples in the Munsell Book of Color.

The effects of different simple and compound, one colour and two colour surrounds, are analysed. Also the effects of the following different viewing conditions are studied:

- (1) The luminance of the surround of the comparison patch.

- (2) The luminance of the surround of the test colour.
- (3) The luminance of the whole test patch.
- (4) The angle of subtense of the test patch.
- (5) The inclination of the test patch.
- (6) The orientation of the coloured stripes of the surround.
- (7) The movement of the test patch (The dynamic colour contrast)

Some possible causes of such colour contrast phenomena in the fields of physics, physiology and psychology are discussed.

Two simple linear equations (for the cases of one and two colour surrounds) are suggested to relate the unit trichromatic equation of the colour appearance of any test colour on any surround to those of the test and surrounding colours as viewed against a white background.

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INTRODUCTIONCOLOUR AND COLOUR VISION.(A) HISTORICAL:

From the beginning, man must have viewed and enjoyed colour in nature: (1) the blue sky, the spectrum colours of the rainbow, the green foliage of the fields with different coloured flowers and fruits, the various colours of the animal kingdom: insects, butterflies and birds. When he started to express himself in sculpturing, engraving and painting, he used colours. The use of colour can be traced from the ancient civilizations of Egypt, Greece, Rome and the Renaissance in Western Europe to the modern times.

The dawn of the science of colour appeared in the Greek philosophy 24 centuries ago. Depending on keen observation and clear thought and without doing any experiments, Aristotle realised that objects appear with different colours because they contaminate or impose blackness to different extents on white light falling on them. Our modern concept of selective absorption can be seen as a modification of Aristotle's idea.

The modern science of colour was founded by Isaac Newton <sup>(2)</sup> (1666). He proved experimentally that white sunlight is compound, and by passing it through a prism, can be split into its seven component colours called the spectrum. Each of these colours can not be changed by further refraction or reflection. He constructed a hue circle, with white at its centre, and its circumference is divided into these seven colours, and the radial distance represents the intensity of the colour. He suggested the centre of gravity principle of colour mixture. He said that coloured

objects reflect or transmit the rays of its own colour more than the rest, and from their excess and predominance in the reflected or transmitted light, these objects have their colour.

### THE TRICHROMATIC NATURE OF COLOUR.

Trichromacy means that any colour can be matched by adjusting the intensities of a mixture of any three independent colours. The eye can not distinguish any difference between this colour and the matching mixture.

Trichromacy <sup>(3)</sup> became universally accepted as a well-known fact in the second half of the 18th century after a long history of mixing colours.

Thomas Young <sup>(4)</sup> (1802) suggested that there was a continuous series of kinds of light, but only three kinds of sensitive particles in the retina, each preferentially, but not exclusively sensitive to light from one part of the spectrum. He said also, that each sensitive filament of the nerve may consist of three portions, one for each primary colour. This suggestion has been the foundation on which most of other theories of human colour vision have been built.

Helmholtz <sup>(5)</sup> (1852) substituted for Young's "sensitive particles of the retina" or "sensitive filaments of the nerve", the theoretical concept, "elementary sensations". He also explained the differences between additive and subtractive colour mixture and made important contributions to our understanding of colour vision. Since then, the trichromatic hypothesis of colour vision has been called the "Young-Helmholtz theory".

Grassmann <sup>(6)</sup> (1853) put his law of additivity as a result of his experiments on mixing of colours. It leads to the centre of gravity

principle of colour mixture which had been suggested by Newton. This principle is the mathematical basis of colour matching. Recently, this law was checked by Trezona, <sup>(7)</sup> and the colour matching functions were investigated by Stiles, <sup>(8)</sup> which lead to further examination of additivity.

Then Maxwell, <sup>(12)</sup> (between 1860-1865) determined the intensities of red, green and blue, necessary to match each spectrum colour. He also produced the first colour photograph. What Maxwell achieved, a century ago, is the basis of modern colorimetry and colour reproduction.

Wright <sup>(9)</sup> and Guild <sup>(10)</sup> determined the relative amounts of three specified primary stimuli required to match the colours in the spectrum, whose average was used in 1931 by the "Commission Internationale de L'Eclairage" (C.I.E.), to standardise the colour mixture characteristics of a normal observer, as a standard framework for colour specification. <sup>(11)</sup>

#### (B) THE PERCEPTION OF COLOUR:

The perception of colour is a complicated process <sup>(13,14,15,16)</sup>  
Physics, physiology and psychology are involved in this process.

From the physics point of view: The perceived colour of any coloured object, depends on the spectral energy distribution of the incident light and the spectral reflection or transmission characteristic of the viewed object. The refracting system of the eye forms an image of the object on the retina, which consists of elements of different densities and spectral compositions of light flux. Some of this energy is absorbed by the photo sensitive pigments of the light receptors of the retina (the cones and the rods), according to their spectral sensitivities.

From the physiological point of view: The energy absorbed within

the cones and rods, causes a pattern of nerve impulses which are carried through the neurones to the fibres of the optic nerve, and finally produce a corresponding pattern of nerve activity in the visual cortex.

From the psychological point of view: The actual colour perceived is the subjective interpretation of the neural activity in the visual cortex.

Any coloured object can be defined physically by the spectral energy distribution of the light emitted or reflected from it. This is the spectrophotometric characteristic of the colour and it is called the objective aspect. The special theme in this investigation is the subjective aspect of colour, that is to say, what we actually see.

### (C) SUBJECTIVE PHENOMENA OF COLOUR PERCEPTION:

There are several phenomena of colour perception which ought to be explained satisfactorily by any accepted theory of colour vision:

#### (1) ADAPTATION:

It is well-known from ordinary everyday experience that, on entering a dark room from bright sunlight, nothing, at first, can be seen, then the eyes become accustomed to the new conditions, and after some time objects in the room can easily be distinguished. Conversely, on going out of doors, the eyes are at first dazzled by the excess light and after some time, they become accustomed to this light. These phenomena are called dark and light adaptation respectively. Similarly, if the eyes are exposed for a sufficient time to coloured lights, big changes occur in the appearance of coloured objects seen afterwards. This is called colour adaptation.

It was found that colour matches made between any two lights of



different spectral compositions (i.e. metameric pairs), are not upset by colour adaptation. Von Kries (1878) deduced from Helmholtz trichromatic theory that no colour match should be disturbed by adaptation. He verified this by matching ordinary white light against mixtures of pairs of complementary spectral lights before and after adaptation, to various coloured lights, and he did not detect any change in the amounts or wavelengths of the complementaries used. However, Wright <sup>(17)</sup> found that monocular matching broke down by using very bright adapting colours. Colour adaptation was recently studied by Wright, <sup>(18)</sup> Schouten, <sup>(19)</sup> Walters <sup>(20)</sup> and MacAdam, <sup>(21)</sup> by adjusting stimuli until the same quality of sensation was obtained from two areas of the retina which were in different states of adaptation. MacAdam used monocular matching technique i.e. focussing the two stimuli on different parts of the same retina. Wright, Schouten and Walters used binocular matching technique, i.e. the stimuli are focussed on non corresponding parts of the retinas of the two eyes.

Wright <sup>(22)</sup> explained the results of adaptation as follows: Assume that the right eye observed a test stimulus whose appearance was matched against a mixture of three primary stimuli. The right eye is then adapted to the adapting stimulus under investigation, and the effect of the adaptation on the appearance of the test stimulus was recorded by matching the test patch as seen in the light adapted right eye, against the mixed stimuli as seen in the constantly dark adapted left eye. He gave the following conclusions:-

(a) All adapting stimuli lower the general light sensitivity of the retina. The reduction in the sensitivity increases with the intensity

of the adapting stimulus and its duration.

(b) After short period adaptations, the recovery of sensitivity is rapid. After prolonged adaptations, the recovery is slower and in some cases, follows an approximately linear course, at least for the first minute or two of recovery. This linearity is not observed at all in the case of the blue response.

(c) When a red adaptation is used, the red sensitivity suffers the greatest depression, with a green adaptation the green sensitivity is most depressed. This shows itself in a change in the hue of the appearance of the test colour in the form of a shift towards the green or the red for red or green adaptation respectively. In the case of blue adaptations the specific depression of the blue sensitivity is less certain.

(d) With test stimuli in the red-yellow-green range of the spectrum, the appearance of the test patch after adaptation is often mixed with blue even if the adaptation itself is blue. This positive blue may be due to an after-image, and may arise through some secondary physiological reaction occurring at a post-receptor stage in the visual chain.

## (2) SUCCESSIVE CONTRAST AND AFTER-IMAGES.

When, after looking fixedly at any brightly illuminated object, the eye is closed or turned to fixate at a point in a uniform surface, an image of the same shape as the original object is seen for a period varying from a few seconds to several minutes. Such images are known as after images since they appear after the cessation of the original stimulus. Some restrict the name "after images" to those seen against a dark background, and call the rest "Successive Contrast Phenomena".

Some call them positive and negative after-images respectively. The positive appearing of approximately the same colour as the original object, and the negative of approximately the complementary colour. This distinction is not sharp since some after-images are neither of the same colour nor of the complementary.

Padgham (24, 25) has done a quantitative study of the positive visual after-image of white and green light, by using binocular matching technique. After dark adapting both eyes sufficiently, he exposed one eye to a very bright stimulus. The sensation of brightness of the after-image produced in this eye, after removing the stimulus, was balanced by the sensation caused by a comparison white light stimulus in the other eye for about one minute.

### (3) SIMULTANEOUS CONTRAST:

A small neutral grey patch on a white background appears darker than a similar one on a black background. If it is placed on a strongly coloured background, such a grey patch looks slightly coloured (usually tinged with the complementary colour of the surround). If the grey appears in small elements in a heterochromatic picture, it ~~appears in~~ different colours and nobody can say that they are grey unless their adjacent surrounds are totally screened. These, and related changes in the appearance of objects according to the brightness and the colour of their surrounds, are known as simultaneous contrast phenomena.

Abney (25) and Helson (26) have made quantitative assessments of simultaneous contrast by adjusting the physical composition of two fields until they look alike, despite being seen against different backgrounds. Abney measured the effect of coloured background on the appearance of a

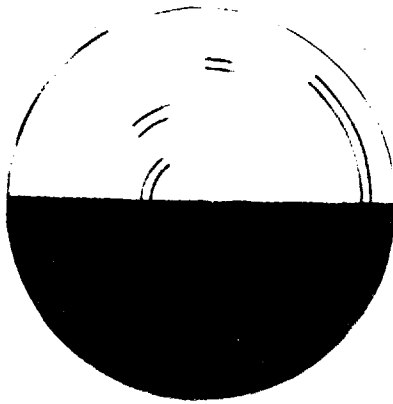


Figure (1) Benham's Top.

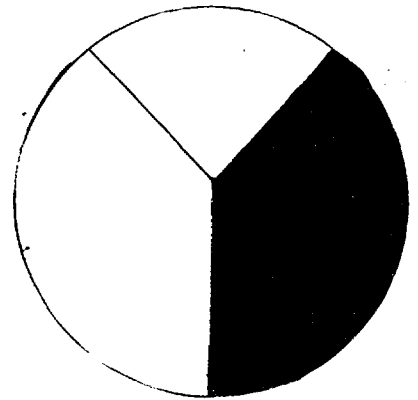


Figure (2) Bidwell's Disc.

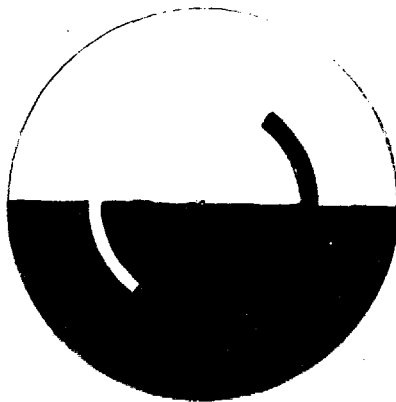


Figure (3) Sherrington's Disc.

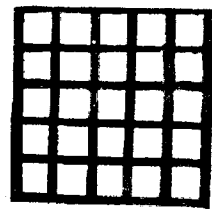


Figure (4) Square grid on the coloured ground.

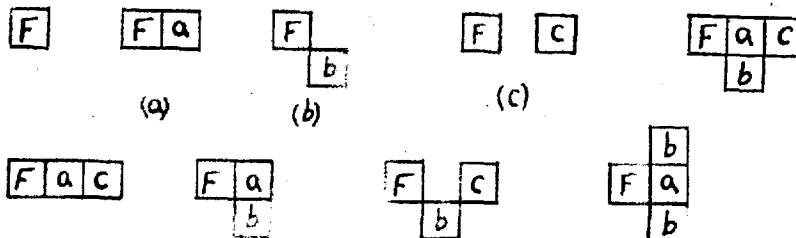


Figure (5) The test pattern consisting of the focal area (F) and inducing area combinations in different contiguities (a), (b), and (c).

white stripe. Holson was concerned with the study of colour constancy using neutral colours (i.e. greys, white and black) as test patches and backgrounds.

Van Bezold <sup>(27)</sup> described what he called "spreading effect" which acts opposite to what is known about simultaneous colour contrast. This effect is illustrated by Evans <sup>(15)</sup> in his book "An Introduction to Colour", in four charts of red and blue colours, with very fine lines of white and black drawn on them. The red and blue colours with the black lines look darker and more saturated than those with white lines.

Recently Warburton and Lund <sup>(28)</sup> made a qualitative study on modification of colour due to juxtaposition and its application to textiles. Jameson and Hurvich, <sup>(29)</sup> very recently made a quantitative study of the effect of different patterns of surround on the appearance of a test colour. Since the theme of this investigation is the study of the colour contrast phenomena, these experiments will be discussed in more details later in this chapter.

#### (4) OTHER COLOUR PHENOMENA:

There are some spatio-temporal striking colour phenomena which have not been fully explained yet. The following are three such phenomena:

(a) BENHAM'S TOP: <sup>(30)</sup> (1894) It consists, as shown in figure (1) of a circular disc half black and half white with four pairs of concentric fine black arcs of different radii and length. If it is rotated clockwise at about 6 revolutions per second, and viewed in bright white light, the innermost of the arcs appears vividly red, the next brownish, the next olive green, and the outermost dark blue. With anti-clockwise rotation, the order of colours is reversed. Changing the speed of the

top or the intensity or spectral composition of the light used to illuminate it, alters the appearance of the colours. Even in monochromatic light the apparent colours of the arcs look very different.

(b) BIDEWELL'S DISC:<sup>(31)</sup> It consists, as shown in figure (2) of a circular shutter half white and half black with a segment cut away. When it is rotated at a speed giving no flicker, the colour of a light<sup>(B)</sup> seen through the aperture is changed to its complementary. This may be due to the after-image of the light seen against the neutral background due to the fused two halves of the disc.

(c) SHERRINGTON'S DISC<sup>(32)</sup> It consists, as shown in figure (3) of a circular disc, half white and half black except 2 circular stripes of the same radius, from each half extending to the other half. When it is rotated at a suitable speed, there is a fusion of the whole disc, except for flicker in a central ring, produced by the enhancement due to contrast of the white stripe which is surrounded with black. This simultaneous contrast is associated by successive contrast because the movements of the eyes alter the retinal areas affected.

#### (D) THEORIES OF COLOUR VISION.

Le Grand<sup>(16)</sup> surveyed the main theories of colour vision which will now be summarised:

##### (1) THE YOUNG HELMHOLTZ TRICHROMATIC THEORY:

Young<sup>(4)</sup> assumed that there are three types of retinal receptors with different spectral sensitivities corresponding to the principal colours, and each sensitive filament of the optic nerve may consist of three corresponding portions. At first he suggested that the principal

colours are the red, yellow and blue, and later he changed them to the red, green and violet.

Young's theory was revived by Helmholtz <sup>(5)</sup> who suggested that it is unnecessary to assume three types of fibers, since each could transmit three types of messages (sensations). Maxwell, <sup>(12)</sup> influenced by Young's ideas, undertook the measurements which gave this theory an experimental foundation.

#### THE FUNDAMENTAL SENSATIONS:

If the three types of retinal receptors were  $G_1$ ,  $G_2$  and  $G_3$ . Their spectral characteristics were  $g_{i1}$ ,  $g_{i2}$  and  $g_{i3}$ . Then their responses  $G_{i1}$ ,  $G_{i2}$  and  $G_{i3}$  for radiation of spectral energy distribution  $E$  may have the form:

$$G_{i1} = \int g_{i1} E_{\lambda} d\lambda, \quad G_{i2} = \int g_{i2} E_{\lambda} d\lambda, \quad G_{i3} = \int g_{i3} E_{\lambda} d\lambda$$

The sensation of colour is a function of the relative values of the three responses  $G_{i1}$ ,  $G_{i2}$  and  $G_{i3}$ . The sensation of lightness <sup>(L)</sup> is a linear function of the three responses:

$$L = l_1 G_{i1} + l_2 G_{i2} + l_3 G_{i3}$$

where  $l_1$ ,  $l_2$  and  $l_3$  are constants.

Grassmann's law of additivity follows from the linear character of these assumed equations.

Several trials were made to determine the spectral characteristics of the fundamental sensations from which the following are examples:

(a) Helmholtz <sup>(5)</sup> showed that dichromatic vision may be a reduced form of normal vision with either a missing receptor or the fusion of two receptors. In the first case, the confusion lines, in the

chromaticity chart meet at a point representing the missing receptor and are parallel in the second case. Depending on this, Pitt<sup>(33)</sup> determined the red receptor from the protanopic confusion loci and the blue receptor from the tritanopic loci.

(b) Wright<sup>(22)</sup> assumed that the fundamental sensations are those produced by stimuli whose hues remain unchanged after adaptation. Experiment shows that such stimuli are not real, since all monochromatic stimuli change hue. However the red end of the spectrum and a blue close to 460 m. $\mu$ . are least affected. Recently, Thomson and Wright<sup>(34)</sup> determined the blue receptor from their study of the tritanopic confusion loci, which is in good agreement with Pitt's determination. They also extrapolated for the green receptor and their determination is near to that obtained by Walters<sup>(20)</sup> from adaptation experiments.

(c) Stiles<sup>(35)</sup> proposed a new method in which the subject looks at the centre of a field of  $10^\circ$  diameter of luminance  $L_e$  of monochromatic light  $\lambda$ . At the centre of this field short flashes of monochromatic light  $\lambda'$  of luminance  $L'_e$  are superposed over area of  $1^\circ$  diameter.  $L'_e$  is varied until the test flash is just perceptible (in luminance and colour when  $\lambda \neq \lambda'$ ). The curves of  $(\log L'_e)$  as a function of  $(\log L_e)$  show a sharp bend (a point of discontinuity) which was assumed to indicate the passage from one receptor to another. He determined by this way the three fundamental sensations:

#### HOW EXACT IS TRICHROMACY:

(a) THE FOVEA: For fields between  $30'$  and  $1^\circ$ , trichromacy is exact at moderate and high luminances. Smaller fields are dichromatic;<sup>(36)</sup> in which colours can be matched with red and blue primaries only. For



fields between  $1^\circ$  and  $2^\circ$ , no deviations from exact trichromacy have been detected in the enormous amount of thorough investigations. Stiles<sup>(37)</sup> noticed that trichromatic matches established on  $2^\circ$  foveal fields are slightly imperfect at the margin of the field when it is perfect at the centre and vice-versa. For larger fields no adjustment of the trichromatic mixture allows the centre and periphery to be matched at the same time, the centre can be matched if the outer part is ignored and vice-versa. This may be due to screening the receptors by the macular yellow pigment.

(b) THE EXTRA-FOVEAL RETINA: It has been assumed that foveal trichromacy depends on cones (since the fovea is nearly free from rods), and it was expected that for extra-foveal fields where rods also are illuminated, colour discrimination will be, at least, tetrachromatic. Wright,<sup>(22)</sup> Gilbert,<sup>(38)</sup> Moreland<sup>(39)</sup> and Clarke<sup>(40)</sup> did not notice any deviation from trichromacy.

### THE PHYSIOLOGICAL BASIS OF THE TRICHROMATIC THEORY <sup>(3)</sup>

There are at least three possible hypothesis:

(a) Three photosensitive pigments: with three kinds of receptors or more.

(b) Three receptors: with probably more than three pigments.

(c) Three channels in some central part of the visual pathway: (neurones) with possibly more than three kinds of pigments and receptors.

The following practical evidence available are in favour of the three photo-sensitive pigments hypothesis:

(a) The stability of matches with chromatic adaptation.

(b) The validity of Grassmann's law of additivity.

The objective measurements of human foveal pigments are satisfactorily consistent with the three pigment hypothesis.

### (2) GRANIT'S THEORY (22)

Granit divides the retina into receptor units, each consists of a group of cones and rods which are connected with a single ganglion cell, or with several ganglions which synchronize their discharges. These units are classed, according to their response as picked up by a micro electrode into two types: Dominators and Modulators. The dominators (about 95%), have a wide spectral sensitivity curve which indicates that they are responsible for the sensation of luminosity. The modulators show a selective sensitivity and hence considered as responsible for colour discrimination. Granit, (41) could discover seven kinds of modulators but they can be classified as three principal types, or as the result of interactions between three types of receptors which in a way confirms the trichromatic theory.

### (3) HERING'S OPPONENT COLOURS THEORY:

Hering (42) proposed that the six distinct sensations should be arranged in three opposing pairs: white-black, yellow-blue, and red-green. Jameson and Hurvich, (43) tried to apply this theory quantitatively on the basis of the C.I.E. colour mixture data for the standard observer, to account for the psychological aspects of colour; brightness, saturation and hue, and their change with adaptation. They tried also to use it to explain their results on simultaneous colour contrast phenomena. (29)

The only physiological basis for such mechanisms in the retina, is that of the "on" and "off" responses grouped in two pairs red-green,

and yellow-blue that the recent researches of electrophysiology, ascribe to a single retinal receptor.

#### (4) ZONES THEORIES:

Zones theories were suggested by Donders, Von Kries, Muller and Adams, (44) The essential idea consists in connecting Young's trichromatic system with the photochemical receptors of the retina, while Hering's opponent colours theory controls the higher levels of physiological vision in the optic nerve. Muller's theory has been developed mathematically by Judd (45) and physically by Talbot, (46).

If three different photosensitive pigments were isolated in the retina, giving Young's theory a definite experimental foundation, it will be necessary to explain how the corresponding nerve impulses transmit the necessary information by a suitable 'frequency code' and how the brain decodes this message. This may show that there is room for a Zones theory of some type to associate with the trichromatic theory.

#### (E) THE THEME OF THIS INVESTIGATION:

This investigation is concerned with the quantitative study of the colour contrast phenomena. It is very important to do such a study because colour contrast is one of the subjective colour phenomena with which we are confronted in our everyday life. We cannot escape the idea of background since everything in life has a background. Whenever there is a background to any object, then the contrast between that object and its background comes into action.

It is also essential, for those who are technically interested in colour to know the actual changes in the appearance of any colour when

seen against different backgrounds. These changes are of practical importance since they may have major influence on colour design in Art and Industry.

They are also an interesting problem in visual physiology, since it seems likely that various factors may contribute to the effect. As the study of chromatic adaptation played a major role in developing our ideas about colour vision, so the study of other colour phenomena may lead us to better understanding to the complex functions of colour perception.

The field of colour contrast phenomena is a very wide one indeed, in which very little, if any, quantitative measurements have been done. The literature available now in this field is short, compared with that in other fields of colour vision, and most of it is based on either classical ideas or qualitative observations or preliminary measurements, which, even if accurate enough, are not sufficient to draw useful scientific conclusions, and any new contribution to the science of colour vision.

This present study is no more than a short introduction to such a wide field. The author hopes that it will stimulate many others to do more measurements, in order to compare the results, and lay a concrete basis to start a profitable generalised analysis to such effects.

#### (F) PREVIOUS WORK:

It is useful at this point to analyse the experiments of Warburton and Lund, (28) and Jameson and Hurvich, (29) mentioned previously, about colour contrast.

(1) Warburton and Lund studied qualitatively the modification of

colour due to surround. In their first experiment, the 8 standard colours of the Ostwald NA were used in turn as background and each of the other colours were applied as a square grid on the coloured grounds as shown in figure (4). The corresponding angles of subtense are:  $12'$  for element square background,  $3'$  breadth of the grid band, i.e.  $18'$  the square element.  $1^{\circ} 30'$  for the whole square of each combination of 2 colours. The seven patterns of each standard colour background together with a square of that colour in the centre (as reference), were mounted on one sheet of black paper. These sheets were illuminated by a normal Mazda 60 watt fluorescent lamp, together with daylight from adjacent windows (conditions varied from clear to cloudy sky). Ten observers (who passed Ishihara test <sup>(47)</sup> for colour vision) viewed each card separately and were asked to state the combination which gave the maximum change in appearance from the original colour, and that of minimum change. This means that they gave a general impression of difference in colour and not a specific change in hue, saturation or value. (These terms will be explained in Chapter II). Their results showed that:-

(a) The value has a greater effect than hue on the power of a colour to change an associated colour. e.g. blue and yellow (with high difference in value), showed a maximum change, red and blue-green (of nearly equal values) showed a minimum change.

(b) Light colours on dark backgrounds and dark colours on light backgrounds gave a maximum change on colour appearance.

In the second experiment: a trial was made to estimate the change in hue of the bands of the square grid with the background. A square

of the colour of the grid is provided for reference. The observers were asked to say on which ground the change is towards one of the well-known colours, red, yellow, green and blue: (1) Most of the results showed that the hues of the colour and the surround are additive, (2) The observers being asked to, chose 4 cases out of 8, so most of the observers related the changes in hue to the combinations of two colours which are near to each other in the hue circle. (3) It was noticed also from the results that complementary colours when combined together, do not cause any change in the hue of each other.

In the third experiment: a study of the effect of the angle of subtense on changes in colour appearance was made. Cards of red squares on green surrounds were made of different sizes of ratios 1:2:3:6, and were attached to the end of the sticks. The pattern of the biggest size was fixed at a long distance from the observer, such that a change in hue due to the surround is noticed, and an experimenter moved the pattern of the next size along the viewing direction towards or away from the observer. The observer was asked to say when the reds in the two cards matched. The same was done with the other two sizes. The whole experiment was then repeated for patterns of red on blue background. The results obtained show that: (1) The matching occurred at the distances giving the same angle of subtense as the reference card. (2) The smaller the angle of subtense the bigger the change in appearance.

Commenting on that study, the author would say that the first two experiments are purely qualitative and only the third experiment is partly quantitative. The experiments were not carried on, in the same conditions of lighting, since big differences in the quality and quantity

of daylight in clear and cloudy sky were allowed. It is essential in colorimetry to keep the illuminating and viewing conditions the same. (13)

As it will be shown in Chapter VIII of this investigation that big changes of the level of illumination of the pattern under test change the colour appearance, so summation of results or taking means in that study is incorrect. It may be argued that this was done to study the changes in colour appearance at different lighting conditions as we usually find in practical life. To do this it would have been better to do the whole experiment under the same conditions, and then repeat it for other different conditions and compare the average results of each. Also it is not preferable to mix fluorescent light with natural daylight in these experiments. Perhaps this was done to provide adequate lighting on a cloudy day. However, this adds more complications to the problem:

The ordinary fluorescent light is in general, different from natural daylight (13) in two aspects: (a) The yellow, green and violet lines of the mercury charge are mixed with the continuous spectrum from the fluorescence of the phosphors used. (b) The deficiency at the red end of the spectrum. This mixture would have been all right if the daylight conditions were constant, but in this case, the fluorescent light was dominant on a dull day and the daylight was dominant on a sunny day.

As for the first experiment, the second result (namely, that light colours on dark surrounds, and vice-versa give maximum effect) seems logical. The first result (namely, that the value has greater effect than hue on changing colour appearance) was not based on enough evidence from the actual data of such a quantitative experiment. The example given about the case of the red and blue-green giving maximum change was an

exception, since in all other cases, the maximum change in appearance was given by combinations of either complementary or near complementary colours.

As for the second experiment it seems that the three given conclusions are not in harmony with each other, because if the hues are purely additive (1st conclusion), then the combinations of colours which are far from each other in the hue circle, ought to have more effect than those of near colours (since the slightest addition in the former case shows more than that of the latter), which is against the two other conclusions. This discrepancy may arise from the fact that the effects of the surround involve both additive and subtractive processes as will be shown repeatedly in this present investigation. It is not understood why the change in the appearance was observed for the background in the first experiment and the gird bands in the second. So the results of the two experiments can not be compared because the area of the squares of the background are different from those of the bands.

The first conclusion of the third experiment (namely, the dependence of the appearance on the angle of subtense) is very good for such varying conditions, but no measurement was taken for the second conclusion (namely, the effect of the angle of subtense on the appearance) which makes it purely qualitative.

Nevertheless, the writers showed in their first paper, as an illustration, two plates which stimulated Mr. S.J. Belcher of this laboratory to design a chart which is similar to plate (Ia) shown in this thesis. The first of their charts consists of alternate stripes of black and blue with rectangular purple patches mounted in two columns.



one on the blue stripes, the other on the black. The patches of the first column look darker than those of the second. The second chart is similar to the first with alternate violet and green stripes, and yellow rectangular patches. The yellow patches mounted on the violet stripes look greenish and those mounted on the green stripes look more orange. These plates were out of the scope of their study, but they commented on them by saying that the effect in the first chart is positive due to additivity of reflected light, and that shown in the second chart is negative due to simultaneous contrast.

Plates (1 a & b) and (2 a & b) were designed by the author after Belcher's chart (similar to plate 1a), and they were the basis of the study of colour contrast phenomena in this investigation. Simple and compound, one colour and two colour similar patterns were studied at different illuminating and viewing conditions. Each of Natural Daylight and Standard source  $S_A$  were used for illumination. Also the effects of levels of illumination to which the observer's eye was adapted, the angles of subtense and inclination of the test patch were studied.

(2) The experiment of Jameson and Hurvich<sup>(29)</sup> can be summarised as follows:-

Two projectors provided with two neutral density slides (which were made up of square elements of different densities), the first projector has in addition, a coloured filter, project on a translucent diffusing screen two overlapping images forming a pattern of squares of the same colour, but of different luminances (from the first projector) and saturations (due to the diluting neutral light from the other projector). These elements squares are of the same size, each subtending an angle of  $3^\circ$  at the observer's eyes. The whole field of view is  $11^\circ 50'$  by

10° 20'. One of these element squares is taken as the focal area under test, the others presented in different configurations as shown in figure (5), as the surround whose effect on the appearance of the focal areas to be measured.

The observer matched the appearance of this focal area presented in dark surround and then in different sets of simple and compound surrounds, by comparing it with charts of constant hue in the Munsell Book of Color put in a cubicle at his side and illuminated by standard source  $S_A$ . The matches are done by successively glancing at the test pattern and then looking at the Munsell coloured chips.

The results were transformed to the C.I.E. system. The average results for 5 observers in each of 10 arrangements of the same hue but of different chromaticities and luminances were transformed to the quantified chromatics response values of the opponent colours theory ( $\pm r'$ ,  $\pm y'$ ). Then the differences between these values for the focal area in isolation and as seen in different surrounds gave the changes in these perceived colours ( $\pm \Delta r'$ ,  $\pm \Delta y'$ ). It was found that these changes vary with the contiguity of the element square surround with respect to the focal area (a) common side, (b) common corner, (c) separation equal to the size of element square (see figure 5). As a first approximation, they found that the effect of (a) was twice as that of (b), and that of (b) was twice as that of (c). So the inducing area response activities were weighted by factors 4:2:1 for these contiguities respectively.

The change in chromatic responses ( $\pm \Delta r'$ ,  $\pm \Delta y'$ ) of the test area for one single surrounding area, were plotted against the contiguity weighted chromatic responses ( $\pm r'$ ,  $\pm y'$ ) respectively. The regression lines have a slope = - 0.14 in the two cases. This meant, that the

chromatic response activity ( $\pm \Delta r'$ ,  $\pm \Delta y'$ ) induced in a focal area by a neighbouring inducing stimulus for any given contiguity, is opponent to and proportional in magnitude to the chromatic response activity aroused by the surrounding inducing stimulus ( $\pm r'$ ,  $\pm y'$ ). They expressed this mathematically in the form  $\pm \Delta r' = -k (\pm r')$  and  $\pm \Delta y' = -k (\pm y')$ , where  $k$  is an empirical constant called induction coefficient given by  $k = 0.56$ ,  $0.28$  and  $0.14$  for the three contiguities (a), (b) and (c) (just mentioned previously) respectively. According to the opponent colours theory, the more redness or yellowness of the inducing area, the more greenness or blueness effect on the focal area respectively.

For compound surrounds consisting of more than a single inducing area, they said that it is more likely that the mutual interactions occurring would tend to counterbalance the effect of increasing the total area of surround stimulation. So they thought that this will result in an averaging, rather than a summation of the individually effective surround stimuli. Hence, they plotted the values of ( $\pm \Delta r'$ ,  $\pm \Delta y'$ ) against the average values of ( $\pm r'$  &  $\pm y'$ ) respectively for the compound surround in one graph, together with those of single surround areas, and found that the slope of the regression line was practically the same ( $-0.145 \pm 0.012$ ).

Commenting on this experiment, the author should say that their idea in forming the test pattern is ingenious. However it is very surprising indeed to solve such a complicated subjective phenomena as simultaneous colour contrast by such a simple linear analysis, leading to such smooth and self consistent results by using the opponent colours theory whose physiological or psychological basis has not yet been

established and is not widely accepted. It seems unlikely that the procedure employed, should lead to the conclusion formed for the following reasons:

(a) THE TEST PATCH: It will be seen from this investigation (as was seen from the third experiment of Warburton and Lund discussed previously), that the changes in colour appearance due to surround increase with the decrease of the angle of subtense. As will be seen later (in chapter VII) that a test colour of angle of subtense  $2^\circ$  with a contour surround of a different colour or colours (which ought to give bigger colour changes than those reported in that paper) showed very small differences. Those changes were enhanced gradually as the angle of subtense was decreased (the smallest element used was  $6'$ ). It would have been expected, in such an experiment with a big field of view ( $11^\circ 50'$  by  $10^\circ 20'$  with a  $3^\circ$  element) and using the same hue with different luminance and saturation for both the test and single surrounding areas in different contiguities, that the changes in colour appearance would be very small. However, the reported differences were big.

(b) THE MEANS OF MEASUREMENT, used is not accurate enough to show the small differences in the colour appearance. Using the charts of constant hue in the Munsell Book of Color with steps of hue = 5 and steps of chroma = 2 and missing the chips of chroma 2 for 10 intermediate hues is not by any means accurate enough.

Also the Munsell scale is claimed to be subjectively uniform in daylight in which it is originally calibrated. This uniformity is spoilt if it is used in any other source ( $S_A$ ). The authors asked their observers in cases where a perfect colour match could not be found in

the available array of samples, to select the two bounding samples between which the derived match step appear to fall. What then? The authors did not say how could they make the actual reading of that match. Possibly they took the mean value of the two chips chosen by the observer, which is incorrect in such a non-uniform scale with big steps between the adjacent Munsell coloured chips.

(c) THE OBSERVERS: It was not reported if the colour vision of the observers was tested or not. It is essential in studying such subjective colour phenomena to use observers with normal colour vision. The authors did not say if the observers repeated the matches and how consistent their readings were. Nothing was said about the consistency of the different observers among themselves. These conditions are very basic in taking means and applying statistical analysis.

(d) THE ANALYSIS: It is an over-simplification to: (1) Take the induction coefficients in the simple ratio 4:2:1 according to contiguity, (2) Try to avoid the complications of the physiological mutual interactions of the effects of different elements of compound surrounds, by averaging instead of summation of the individual effective surround stimuli.

## CHAPTER II

### COLOUR AND COLOUR MEASUREMENT.

In the first chapter, colour was studied from the perception point of view, i.e. the different subjective colour phenomena and theories of colour vision. The concern of this chapter is to deal with colour from another point of view, how it can be measured i.e. the means and methods of measurement, the scales and units in which the results can be expressed.

#### (A) MEANS AND SCALES OF COLOUR MEASUREMENT.

##### (1) SPECTROPHOTOMETERS:

Physically, any colour can be defined by the spectral energy distributions of light transmitted through or reflected from the object under test. This can be obtained by measuring the transmission or reflection factor ( $T_\lambda$  or  $R_\lambda$ ) of the sample at different wavelength ( $\lambda$ ) across the visible spectrum using any spectrophotometer. The transmission factor at any wavelength is obtained by comparing the intensity of light transmitted through the sample with that of light coming directly from the same source illuminating the sample in the same conditions. The reflection factor is obtained by comparing the intensities of light reflected from the sample and from fresh magnesium oxide surface which is considered as standard reflecting and diffusing surface.

The different spectrophotometers<sup>(13)</sup> can be classified as follows:-

(a) Visual Spectrophotometers: as Guild<sup>(48)</sup> and Konig-Martens<sup>(49)</sup> spectrophotometers.

(b) Photoelectric Spectrophotometers: which can be sub-divided into two categories.

(1) Non-Recording Instruments: as Wright <sup>(50)</sup> and Beckmann <sup>(51)</sup> spectrophotometers.

(2) Recording Instruments: as the General Electric Hardy <sup>(52)</sup> (redesigned by Pitchard and Holmwood) <sup>(53)</sup> and Beckmann <sup>(54)</sup> recording spectrophotometers.

In this investigation, Wright non-recording and Beckmann recording spectrophotometers were used.

However, these relative spectrophotometric values which are purely physical cannot, by any means, specify the colour of the object as seen by the observer. To do this, the effectiveness of the luminous radiation in stimulating the eye and producing visual sensation must be taken into account. In other words, the spectral sensitivity of the observer's eye must be obtained. This is provided in the C.I.E. system.

## (2) THE C.I.E. SYSTEM:

Everyone with normal colour vision, can compare two colour patches and say if they match or whether one is lighter or darker, weaker or stronger, redder or bluer than the other. Although the sensitivity of the human eye is rather high in detecting small differences in colour appearance, yet it varies from one observer to the other. This is a source of error and uncertainty in colour matches. That is why the "Commission Internationale de l'Eclairage" (C.I.E) agreed on a standard system which, when applied to the spectrophotometric measurements, colour specifications can be derived which are independent of the colour vision of any particular individual and which will be comparable between one laboratory and another. This system depends on three main pillars:

(a) The Relative Luminous Efficiency ( $V_\lambda$ ) Curve: which was adopted by the C.I.E. in 1924. It defines the relative contributions which each

wavelength makes in an equal energy spectrum to the total light flux.

(b) The Colour Matching characteristics of the Standard Observer for 2° Field: The spectral chromaticity co-ordinates (giving the amounts of three stimuli required to match the colours through the spectrum), were measured independently by Wright, <sup>(9)</sup> for ten observers and Guild <sup>(10)</sup> for other seven observers, each using his own visual colorimeter, <sup>(55), (56)</sup> and his own system which were different from each other. The average results of the two investigations were transformed by Guild to the same system of reference stimuli (monochromatic radiations of 700, 546.1, 435.8 m  $\mu$  wavelengths for R, G & B), with the units based on the N.P.L. white. They were in close agreement which led the C.I.E. in 1931 to adopt <sup>o</sup> their mean values as the spectral chromaticity co-ordinates of the standard observer. From these values (based on the same reference stimuli but with T-units adjusted to be equal in a match of equal energy white), and the relative luminance efficiency  $V_\lambda$ , the distribution coefficients for equal energy spectrum  $\bar{r}_\lambda$ ,  $\bar{g}_\lambda$  and  $\bar{b}_\lambda$  were calculated.

This [RGB] system consisted of some negative values of both the chromaticity co-ordinates and the distribution coefficients which makes the evaluation of the tristimulus specification by calculation from such a system rather complicated. It was agreed to transfer the [RGB] system to an all positive system (XYZ) and adopt this new system as the standard reference for colour specification. The new system has another advantage that the red and blue reference stimuli have zero luminous efficiencies so that the amount of light represented by any colour equation is given directly by the green tristimulus value.

In this standard (XYZ) system, the chromaticity co-ordinates are



$x_\lambda$ ,  $y_\lambda$  &  $z_\lambda$  and the distribution coefficients are  $\bar{x}_\lambda$ ,  $\bar{y}_\lambda$  &  $\bar{z}_\lambda$ .

Figure (6) shows the C.I.E. chromaticity chart plotted in terms of reference stimuli (X), (Y) & (Z), with units based on equal energy white E. Any colour lies within this spectrum locus.

(c) The Standard Illuminants  $S_A$ ,  $S_B$  &  $S_C$ : were adopted by the C.I.E in 1931. They were based on work carried out by Davis and Gibson. (57)  $S_A$  consists of a gas-filled tungsten lamp operating at a colour temperature of  $2854^\circ$  K. Sources  $S_B$  and  $S_C$  to represent sunlight and daylight (the corresponding colour temperatures are approximately  $4900^\circ$  K and  $6700^\circ$  K respectively). They can be obtained by using  $S_A$  in conjunction with liquid colour filters of specified chemical composition and thickness.

THE CALCULATION OF THE TRISTIMULUS SPECIFICATIONS FROM SPECTRO-PHOTOMETRIC DATA: If  $B_\lambda$  is the spectral luminance factor (for either reflection or transmission) of the coloured sample under test as obtained by any spectrophotometer then its tristimulus values are:

$$X = \sum B_\lambda P_\lambda \bar{x}_\lambda \quad (1)$$

$$Y = \sum B_\lambda P_\lambda \bar{y}_\lambda \quad (2)$$

$$Z = \sum B_\lambda P_\lambda \bar{z}_\lambda \quad (3)$$

where  $P_\lambda$  is the spectral energy distribution of the light source illuminating the sample which can be any of the standard illuminants  $S_A$ ,  $S_B$  &  $S_C$  or any other illuminant of known spectral energy distribution.

The values  $P_\lambda \bar{x}_\lambda$ ,  $P_\lambda \bar{y}_\lambda$  and  $P_\lambda \bar{z}_\lambda$  are calculated for each of the standard sources  $S_A$ ,  $S_B$  &  $S_C$  by Smith and Guild, (58) choosing a factor giving  $\sum P_\lambda \bar{y}_\lambda = 100$ . Thus  $Y = \sum B_\lambda P_\lambda \bar{y}_\lambda$  gives directly the percentage luminance of the sample. The unit trichromatic co-ordinates of the sample  $x$ ,  $y$  &  $z$  are given by:

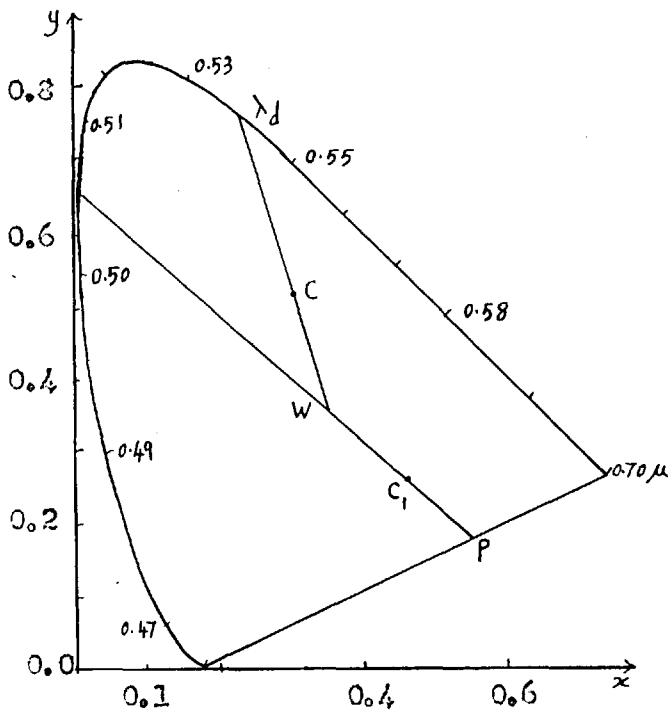


Figure (6) The chromaticity chart showing colour specification in terms of dominant wave length and purity.

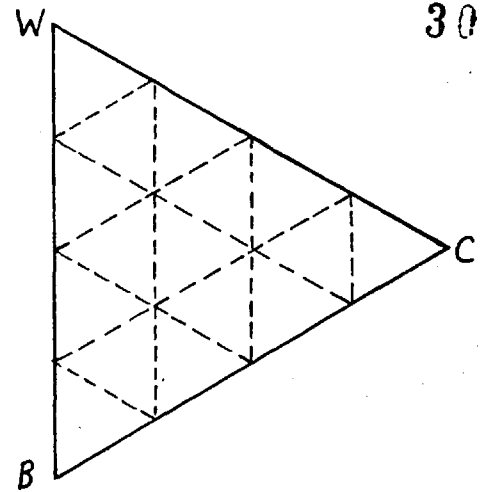


Figure (7) Coordinates of the Ostwald system for a given hue plane.

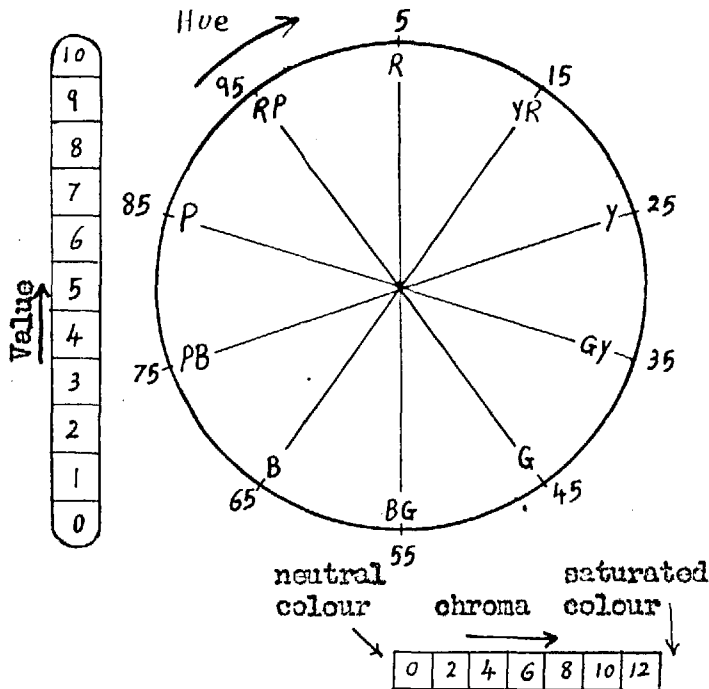


Figure (8) Hue, value and chroma in the Munsell system.

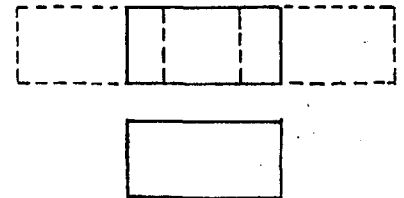


Figure (9) Fields of view in binocular system.

$$x = X / (X + Y + Z) \quad (4)$$

$$y = Y / (X + Y + Z) \quad (5)$$

$$z = Z / (X + Y + Z) \quad (6)$$

Usually  $x$ ,  $y$  and  $Z$  are used as the C.I.E. trichromatic specification of the sample.

#### Colour Specification in Terms of Dominant Wavelength and Purity:

Once the chromaticity co-ordinates ( $x$ ,  $y$ ) of any colour are known, the colour can be represented by point (C) in the chromaticity chart as shown in Figure (6). A line can be drawn from the white point W ( $x = 0.333$ ,  $y = 0.333$ ) through (C) to the wavelength  $\lambda_d$  on the spectrum locus. (C) can then be specified by: (1) the value of  $\lambda_d$  which is known as the dominant wavelength. (2) the excitation purity:  $P_e = CW/\lambda W = (x - x_W) / (x_d - x_W) = (y - y_W) / (y_d - y_W)$  where  $\lambda_d$  is given by  $x_d$  and  $y_d$ .

For colours in the purple segment of the chromaticity chart as  $C_1$ , the dominant wavelength is defined by its complementary wavelength  $\lambda_c$ , and its excitation purity is given by  $P_e = C_1W/PW = (x - x_W) / (x_p - x_W) = (y - y_W) / (y_p - y_W)$ .

The dominant wavelength / purity specification of chromaticity has the advantage that it is closely correlated with the subjective attributes of colour (hue and saturation respectively).

#### (3) COLORIMETERS:

There are two main categories of colorimeters (a) Visual and (b) Photo-electric Colorimeters. The visual colorimeters are subdivided into two groups: Additive and Subtractive Colorimeters.

##### (a) Visual Colorimeters:

In these colorimeters a colour is matched and measured visually

against a mixture of reference light stimuli of defined specification.

(1) Additive Colorimeters: in which the mixture of light stimuli is additive as Wright, <sup>(55)</sup> Guild, <sup>(56)</sup> Donaldson <sup>(59)</sup> and Stiles <sup>(60)</sup> colorimeters. In the Wright and Stiles colorimeters, (the latter being called a trichromator), the three primary stimuli, the test stimulus, and its desaturating beam, are pure spectral colours. They are isolated and then recombined by normal prismatic dispersion, and their intensities are controlled by using photometer wedges. In Guild and Donaldson colorimeters, the three primary stimuli and the desaturating beam of the test stimulus are red, green and blue colour filters, and shutters are used to control their intensities. The mixing of the primaries is done, in Guild instrument, by mounting the primary filters in a rotating sector and, in Donaldson instrument, by using an integrating sphere. Donaldson <sup>(61)</sup> introduced a six stimulus instrument (by adding orange, yellow green and blue green filters), acting on the same principle as his three stimulus colorimeter, including Lummer-Bradthun contrast field of view.

In general, the colorimeters using pure spectral colours as primary stimuli suffer from limited precision of setting and large variations from observer to observer, since the spectral composition of the test and comparison patches are totally different (metameric pairs). In the same time they have an advantage in the study of individual differences of colour vision. Using three coloured filters as primary stimuli will slightly reduce the degree of metamerism (especially if the colour filters used have wide spectral transmission curves), but using six colour filters will largely eliminate metamerism.

In this investigation, Wright colorimeter was used to test the colour

vision of the author, and a modified form of Donaldson trichromatic colorimeter was used in the actual matching of the appearance of the colour samples in their surrounds.

(2) Subtractive Colorimeters: They operate by the absorption (subtraction) of light from an initially white beam as the Lovibond Tintometer (62) and its modified form, (63) whose readings can be readily converted to the C.I.E. system. In the tintometer, sets of graduated series of red, yellow and blue glass slides, ranging from slight tint to deep colour, provide the subtractive primaries. White light passes through a system of one or more of each of these sets together. The matching is basically similar to that in any additive colorimeter, where the observer chooses the group of slides of the three different colours of suitable luminance whose combination matches the colour under test. The accuracy of this instrument is limited by the steps which separate one glass slide from the next in its series.

(b) Photo-Electric Colorimeters.

The principle of this type depends on using three photo-cells with spectral sensitivity curves similar to the  $\bar{x}_\lambda$ ,  $\bar{y}_\lambda$  &  $\bar{z}_\lambda$  equal energy distribution curves. This is very difficult to realise. However, one photo-cell combined with three filters, one at a time, to give sensitivity curves which are linear transformation of the C.I.E. distribution curves, would give standard data. This is achieved in Hilger and Watts photo-electric colorimeter (64). Also Glasser's 'colormaster' differential colorimeter, (65) is another example of photo-electric colorimeter which employs two matched filter photo-cell units. Wright photo-electric spectrophotometer, (50) can be used as tristimulus colorimeter by using 3

templets (one at a time) in the path of its long spectrum and using a curved mirror which unites the spectrum and reflects the light back. The templets are accurately cut to represent filters which when combined with the sensitivity of the photo-cell, give  $\bar{x}_\lambda$ ,  $y_\lambda$  or  $\bar{z}_\lambda$ . Winch and Machin<sup>(66)</sup> have developed another templet colorimeter and photometer which is used as a commercial instrument.

#### (4) SUBJECTIVE JUDGEMENT OF COLOUR APPEARANCE:

It has been dealt, so far, with the universally accepted standard C.I.E. system and the spectrophotometers and colorimeters which give their results in its terms. Nevertheless, the primary interest of most people in colour is aesthetic and would prefer to choose their colour from a colour atlas rather than chromaticity diagram. There are three main systems used in subjective colour measurement, namely: (1) Systems depending on colour naming, (2) Ostwald Colour System, (3) Munsell Colour System.

##### (a) Systems depending on colour naming:

Everyone with normal colour vision knows what is meant by red, yellow, green, blue and purple, and a simple colour system could be established by colour naming alone. As an example, the ISCC-NBS system<sup>(67)</sup> reported in the United States, which divides the colour solid, arbitrarily, into about 300 separate compartments each designed by its hue name preceded by modifiers, (light, dark and weak, strong, vivid) indicating the lightness and saturation of the perceived colour. This system has been used in some industrial and artistic fields.

Another example is the Macerz and Paul Dictionary of Color<sup>(68)</sup> which contains about 7,000 different samples of colour printed on semi-glossy paper and a list of about 4,000 colour names drawn from usage in scientific, industrial and artistic fields, and are keyed to the colour samples.

There are a number of other dictionaries applied for different aspects of colour use. However, such systems cannot be used in accurate measurement of colour, especially as the colour differences get smaller.

(b) The Ostwald Colour System. (13,69)

The Ostwald system is based on the assumption that any colour can be regarded as an additive mixture of White (W), black (B) and Colour (C) with the sum of their contents equal to unity i.e.

$$W + B + C = 1$$

Once any two components are known, the third can be calculated. The complete Ostwald system consists of 24 hues, each is approximately of the same dominant or complementary wavelength, of an arbitrary but approximately uniform perceptual scale. Figure (7), shows the co-ordinates of the Ostwald system for any hue. The corners of the equilateral triangle represent the white (W), Black (B) and full colour (C) pigments. Colours located along lines parallel to WC are of constant black content and are called isotones, those along lines parallel to BC are of constant white content and are called isotints, and those on vertical lines parallel to WB are of equal full colour content and are called isochromes (ideally they have the same chromaticity). The proportions of white, black and colour contents have been adjusted to give a uniform spacing of colours. The colour solid is produced by rotating the triangle WBC about the WB axis, and the colours having constant black, white and colour content but differ in hue are called isovalent colours.

The Ostwald notation consists of a number from 1 to 24 and two letters from a to p. The number indicates the hue, the first letter indicates white content where a = 0.8913 which is the nearest practicable

approach to 1, the second letter indicates the black content where  $a = 0.1087$  which is the nearest practicable approach to 0.

Although the Ostwald system is based in principle on additive colour mixture which can be defined chromatically, but its value depends largely on its close correlation with the subjective assessment of a surface colour in terms of its whiteness, blackness and colourfulness. The system is of particular value in the aesthetic use of colour since any natural or artificial colour can be associated in four different meaningful ways (namely isotint, isotone, isochrome and isovalent) with samples in the Ostwald solid.

There are two colour atlases designed on the Ostwald system:

- (1) The Ostwald Colour Album,<sup>(70)</sup> and (2) The Color Harmony Manual <sup>(71)</sup>

In the latter the chips are produced from a transparent cellulose acetate base to which a pigment layer has been applied. One side of the chip is glossy and the other is matt. Also 6 intermediate hues have been added to improve the spacing of the original 24 hues. Each hue chart normally contains 28 chips.

Although the Color Harmony Manual has very great merits, yet it suffers from two disadvantages (1) the lettering system used to locate a colour in a hue chart is difficult to remember and does not permit to interpolation between patterns, (2) Since the gamut of colours in any given hue is determined by the pigment used to represent the full colour, hence there is no room in the system for any newly discovered brighter pigments.

Granville and Jacobson<sup>(72)</sup> have made a spectrophotometric study of the colour chips of the Color Harmony Manual and provided tables including the



luminance reflectance (Y) and chromaticity co-ordinates (x, y) of each. This enables the users of the Manual to record their results in the standard C.I.E. system.

(c) The Munsell Colour System (13)

The Munsell system is based on the conception of a colour solid whose central vertical axis represents the locus of neutral colours (greys), with black at the bottom and white at the top, the different vertical planes around the axis represents the different hues, and the distance of the sample in any of these planes from the axis represents the saturation of the colour. The Munsell specification of any colour sample is given in terms of (1) The Hue: which shows its relation to red (R), yellow (Y), green (G), blue (B) and purple (P). (2) The value: which represents the lightness (brightness) of the sample. (3) The Chroma: which represents the saturation (intensity) of its colour.

This system of co-ordination is shown in figure (8). The value scale (along the central vertical axis) is divided into 11 levels approximately subjectively equally spaced, with a perfect black as 0, and a perfect white as 10. Levels from 1 to 9 are those normally used in the atlas. The chroma scale is divided into a series of approximately subjective equal steps numbered from the neutral axis outwards, the grey having zero chroma. The whole solid being arbitrarily divided into ten approximately subjective equal vertical segments, including the five principal hues: R, Y, G, B & P and the intermediate hues, YR, GY, BG, PB & RP. Each segment is divided into ten equal sections numbered 1 to 10. So each hue can be designated by a number to indicate the section of the segment in which it occurs followed by symbols showing that segment. In the present investigation an easier hue designation was used in a pure number since

the numbering system can be made continuous from 0 to 100, around the hue circle, as shown in figure (8).

The Munsell specification of any colour can be written in the form: hue value/ chroma for example the colour defined as (7.5 YR 5/6), has the hue (7.5 YR), value (5) and chroma (6).

The disadvantages of the Ostwald system are eliminated by the Munsell system. The latter has the merits of being (1) Easy to use and interpolate between adjacent chips. (2) Any newly discovered pigment of higher chroma can be easily added to the system.

There are the Standard Edition and Pocket Edition of the Munsell Book of Color.<sup>(73)</sup> The former consists of 20 hues spaced by steps = 5, the latter consists of 40 hues spaced by steps = 2.5.

The Munsell chips have been measured by means of the spectrophotometer and the C.I.E. specification (x, y & Y) were determined for source C.<sup>(74, 75)</sup> The final report of the Committee of the Optical Society of America<sup>(76)</sup> led to the definition of smooth contours of the Munsell hue, value and chroma, in terms of the C.I.E. co-ordinates.

In this investigation the Munsell Book of Color in its standard and pocket editions were used by a number of observers to match the appearance of test colours in charts similar to plates (1 a,b and 2 a,b). The tables provided in the final report of the Committee of the Optical Society of America were used to transform the results from the Munsell system to the C.I.E. system.

#### (5) THE C.I.E. SYSTEM REPRESENTING THE SUBJECTIVE SPECIFICATION OF COLOUR.

It has been mentioned in the last section that the colour samples in

both Ostwald and Munsell systems are measured spectrophotometrically and thus expressed in the standard C.I.E. system. So it must not be thought that the colour chips are more subjective than their C.I.E. specifications. The colour chips are physical objects sending physical stimuli into the eye by which they can be perceived, selected and spaced subjectively and can be subjectively used in matching the appearance of any other test colour for specification. These physical stimuli can be defined accurately in the C.I.E. system.

That is why, in this investigation, the changes in appearance of any test colour due to simultaneous contrast with different colour surrounds are shown in the chromaticity chart as shifts from a reference point representing the appearance of the test colour against a reference background (e.g. white). These shifts, showing the effects of simultaneous colour contrast on different test and surround colours with respect to the whole gamut of colours in the chromaticity chart, have their subjective significance. In order that the magnitudes and directions of these shifts may be considered quantitatively, the chromaticity chart has to be subjectively uniformly spaced which, unfortunately, is not the case.

Wright,<sup>(77)</sup> Judd<sup>(78)</sup> and MacAdam,<sup>(79)</sup> investigated the non-uniformity of the chromaticity chart. Wright measured the just noticeable difference in colour due to change in wavelength of monochromatic light, or due to change in proportion of a mixture of two monochromatic lights taken from opposite sides of the spectrum locus, or of a mixture of one monochromatic light with any of three chosen purples. The subjectively equal steps were represented by short lines in the chromaticity chart and it was found that the lengths of these lines varied largely on the

chart e.g. the ratio between the shortest to the longest step is at least 1:20. Judd based his investigation on data on purity discrimination and on sensitivity to changes in colour temperature. In MacAdam's investigation, the observer made a large number of matches on a series of test colours located at various points in the chromaticity chart. The spread in the readings was taken as a measure of sensitivity to colour differences and was plotted in the form of ellipses of varying size in the C.I.E. chart.

Some trials were made by Judd, <sup>(78)</sup> MacAdam, <sup>(80)</sup> Breckenridge and Schaub <sup>(81)</sup> and others, to get some linear transformation of the C.I.E. chromaticity diagram (conical projection), which renders it uniform. No linear transformation leading to an exactly uniform chart is yet available. MacAdam's transformation from the (XYZ) system to the (UVW) system lead to a roughly uniform scale of chromaticity with the additional advantage that the reference stimuli (U) and (W) have zero luminance. He used the following simple transformation equations:

$$U = \left(\frac{2}{3}\right) X, V = Y \text{ and } W = -\left(\frac{1}{3}\right) X + \left(\frac{3}{2}\right) Y + \left(\frac{1}{2}\right) Z.$$

From which  $u = 4x / (x + 15y + 3z)$ ,  $v = 6y / (x + 15y + 3z)$  and  $V = Y$ . This transformation was used in this investigation to show the shifts due to simultaneous colour contrast in this nearly uniform system.

#### (B) TECHNIQUES OF VISUAL COLOUR MEASUREMENT.

There are three well-known techniques of (visual) colour measurement:

- (1) Monocular Matching (2) Binocular Matching and (3) Memory Matching.

In any of these techniques, the observer matches the colour under test against a comparison patch which may be an adjustable mixture of

red-green-blue light, or material colour samples from a colour atlas.

These methods will now be discussed briefly.

(1) Monocular Matching Technique:

In this technique the matching is done by using one eye. So the test and comparison patches form two adjacent halves of the field of view with a sharp separating line. Many instruments were designed to apply monocular matching as Wright,<sup>(55)</sup> Guild,<sup>(56)</sup> Donaldson<sup>(60)</sup> <sup>(61)</sup> colorimeters Stiles trichromator<sup>(60)</sup> and Lummer-Brodhun photometer,<sup>(82)</sup> by using a suitable photometer prism. There is another application of monocular matching in heterochromatic photometry where the test and comparison patches are of different colours. They are exposed to the observer's eye alternately in the flickering technique and the intensity of the comparison patch is adjusted until the flickering disappears, and then the two patches will be equal in brightness.

The monocular matching technique was used by many investigators and it proved to be the easiest and most accurate of all other matching methods, since the two patches to be compared are in contact with each other which facilitates the judgement.

Wright<sup>(22)</sup> used the monocular matching technique in his colorimeter to measure the relative luminous efficiency curve, the spectral chromaticity co-ordinates, wavelength and brightness discrimination.

A monocular matching technique was modified in the present investigation for subjective colour measurement to study the appearance of different test colours against different backgrounds. The following two techniques are usually used in subjective colour measurement.

## (2) Binocular Matching Techniques:

In this technique the observer looks at the test patch with one eye and matches it by looking at the comparison patch with the other eye. Wright colorimeter <sup>(55)</sup> can be adapted to be used for binocular matching. Wassif <sup>(83)</sup> designed a binocular viewer using two  $45^\circ$  prisms reflecting the light coming from the test and comparison patches on the observers two eyes as shown in figure (22).

The two patches as seen by the observer's two eyes should appear as in figure (9), but changes in observer's convergence will cause one patch to move horizontally relative to the other as indicated by dotted lines. If the observer's muscle balance is not quite normal, a small angle prism can be inserted in the path of one of the beams to correct either for a vertical or a horizontal divergence. Although, it would be preferred, for accuracy of matching that the two patches should be contiguous with one another as in the case of monocular matching, yet a small vertical separation is necessary to prevent the fusing of patches.

Wright <sup>(22)</sup> and Tadros <sup>(84)</sup> used this binocular matching technique to study the phenomena of visual adaptation. The validity of this technique depends on the assumption that the sensitivity of one eye remains constant during the experiment and can therefore be used as a reference standard against which changes in the other eye can be recorded. This assumption is not strictly correct, but experiments showed definitely that the effect of the adaptation of one, on the other eye is very small compared to the changes produced on the adapted eye, such that it can be neglected. Another problem is that of local adaptation that must be produced by the test patch and RGB mixture in the two eyes on which they are exposed.

This action cannot be prevented but can be reduced by: (a) using a much brighter adapting field than the test colour (and hence the matching RGB mixture), and (b) arranging that the two patches are viewed for short periods during observation.

There is another possible problem, that there may be a difference between the colour perception of the two eyes. Massif, using Wright colorimeter, could find a difference in her two eyes, and so she repeated her experiments on the binocular viewer, interchanging the test and comparison patches.

### (3) Memory Matching Technique.

Generally speaking, colour appearance, in the popular sense, implies a remembered appearance. Memory matching was used by some investigators as Crawford <sup>(85)</sup> for the study of the problem of colour rendering specification, and Helson <sup>(86)</sup> for the study of the effects of colour adaptation on the appearance of neutral samples. In general, memory matching suffers from lack of precision.

Crawford used two general ways of measurement depending on memory. Two conditions to be compared by the observer, and he has to say whether they appear the same or not: (a) The comparison may be made by looking first at one condition and then, after a suitable interval of adaptation, looking at the other condition. Or (b) The comparison may be made by looking first at one condition, which is changed gradually and continuously to the other condition.

In Helson's experiment, the observer was trained on Munsell Book of Color so that he could name from memory, the hue, value and chroma of the sample. His method is extremely difficult and most probably inaccurate.

(4) The Technique Used in The Present Investigation.

It was suggested by Professor W.D. Wright that this investigation may be done by using the monocular matching technique, since plenty of work has been done in his laboratory, using the binocular matching technique, for the study of appearance of surface colours by Hunt,<sup>(42)</sup> Tadras<sup>(84)</sup> and Gibson. (thesis under preparation).

Since the theme of this investigation, is the effect of the surround on the appearance of the test colour, the test and comparison patches cannot be in contact since they may have a mutual influence on the appearance of each other. Therefore the two patches were separated from each other, and the observer looks at them alternately until he reaches a satisfactory match. This method involves a very quick memory matching. The full details of the method will be given in Chapter III.



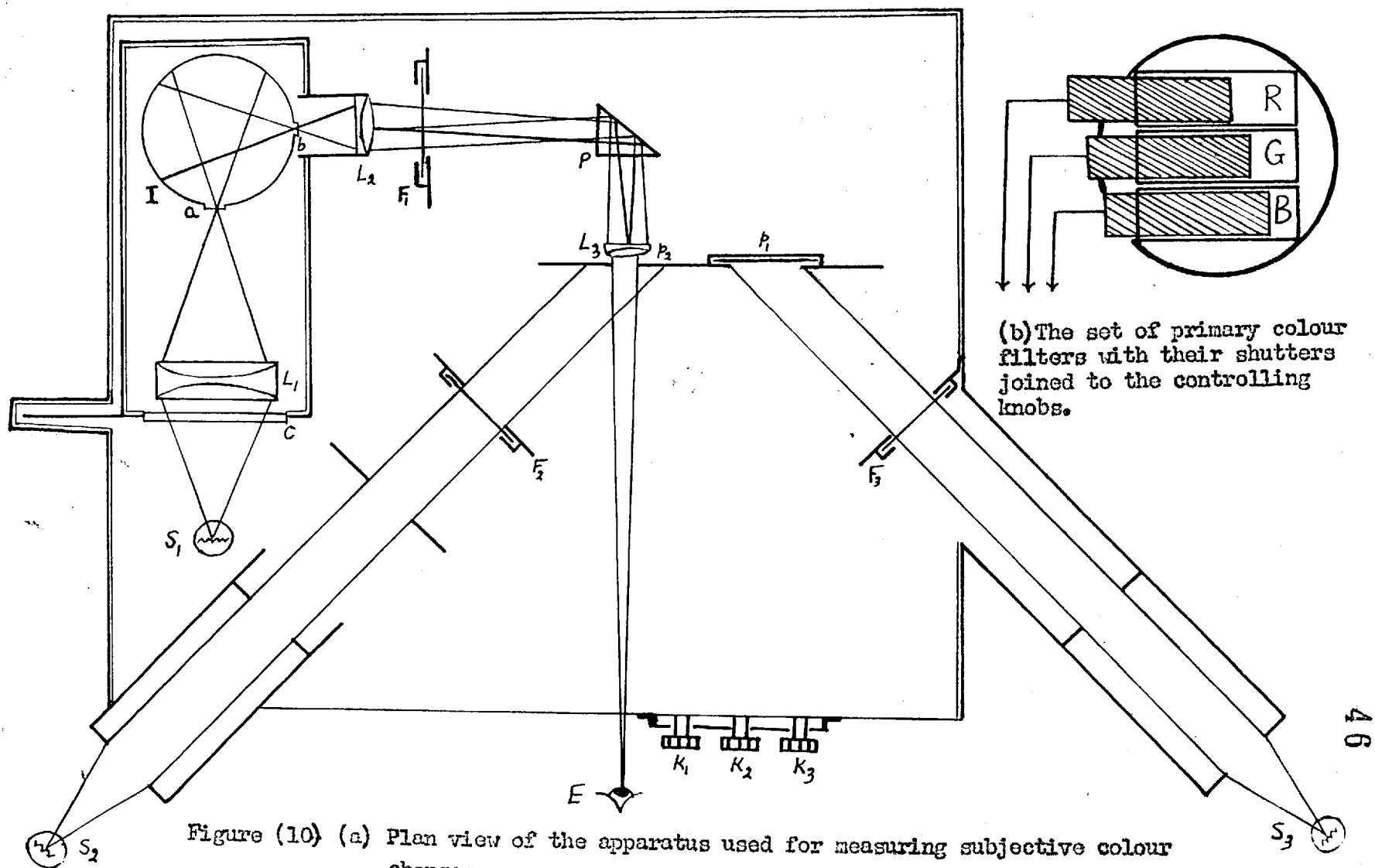


Figure 10 (a) Plan view of the apparatus used for measuring subjective colour changes.

### CHAPTER III.

#### INSTRUMENT AND EXPERIMENTAL ARRANGEMENTS.

##### (A) INSTRUMENT.

Figure (10) shows a plan view of the apparatus. The field of vision consists of two square patches separated from each other.

(1) THE TEST PATCH ( $p_1$ ): consists of a central square of the colour under test in a symmetrical square surround of three times its size. The whole is illuminated by a beam of light incident at an angle  $45^\circ$ , from a projector lamp ( $S_3$ ) and a system of screens with a neutral density filter ( $F_3$ ) to change the brightness of the test patch as necessary.

(2) THE COMPARISON PATCH ( $p_2$ ): consists of a square aperture (of 2 cms. side subtending an angle of  $2^\circ$  at the observers eye), filled with a red-green-blue mixture of light from a modified form of Donaldson's trichromatic Colorimeter (59). Its surround is illuminated by a beam of light incident at an angle  $45^\circ$  from a projector lamp ( $S_2$ ) and a system of screens with a neutral density filter ( $F_2$ ) to change the brightness of the surround of the comparison patch.

In studying the effect of the surround on the appearance of the test colour, the comparison patch must be separated from the test patch, lest some mutual effect may occur between the two patches. The distance between the centres of the two patches is 12.0 cms. subtending an angle of  $12^\circ$  at the observers eye.

THE OPTICAL SYSTEM OF THE COMPARISON PATCH: (59) (Figure 10.)

A beam of light from projector lamp ( $S_1$ ) falls on the three

primary filters: red, green and blue (C), provided with shutters and calibrated scales which can be controlled by the observer. The red, green and blue beams are focused by the condenser lens ( $L_1$ ) on to the entrance aperture (a) of the integrating sphere (I), the inner surface of which is coated by magnesium oxide. Through reflections in all possible directions in the sphere, a mixed beam of red, green and blue light emerges from the exit aperture (b) of the integrating sphere, condensed by lens ( $L_2$ ), reflected at  $90^\circ$  by a  $45^\circ$  prism (P) forming an image on field lens ( $L_3$ ) which brings the image to a focus in the right eye of the observer at (E). A holder for a neutral density filter ( $F_1$ ) is provided in the path of the mixed beam of red, green and blue to vary its intensity.

Plate (C) has three rectangular apertures each of 8.5 cms. length and 2.0 cms breadth, provided with shutters sliding in V-shaped grooves. Each shutter is operated by a separate rack and pinion and has a scale mounted on each and a fixed pointer on plate (C) allowing the extent of the opening of the shutters to be read. The edges of the shutters and apertures are bevelled and special attention has been paid to the fit when the shutter is on the point of closing.

The pinion of each shutter is joined to a flexible driving cable, whose other end is fixed to a controlling knob fitted in the edge of the table in front of the observer. By adjusting these knobs ( $K_1$ ,  $K_2$  &  $K_3$ ), the observer can vary the length of the apertures in front of the primary filters to match the appearance of the test colour in the test patch by the proper mixture of red, green and blue in the comparison patch.

Friction in the shutter system, combined with the cable length caused some lag between the rotation of the pinion at one end and the rotation of the controlling knob <sup>or</sup> at the other end. More the less, the controls were satisfying for adjusting the shutters during matching and this lag does not affect the actual readings which are taken from the scales fixed to the shutters themselves.

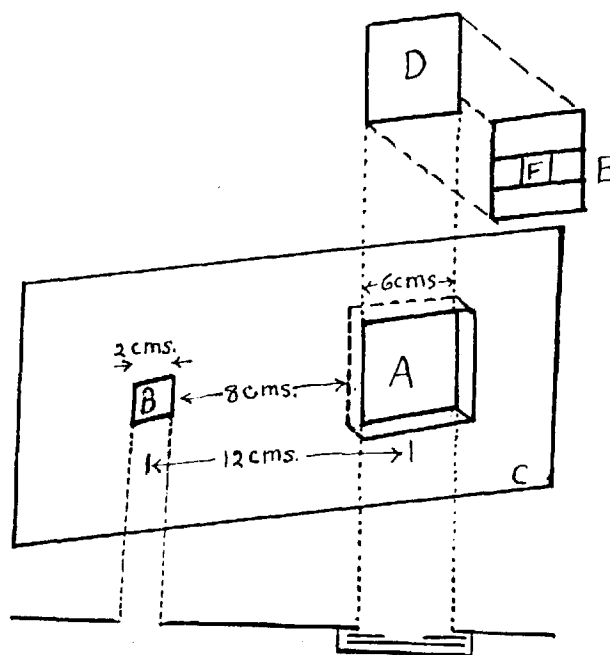
Behind the apertures are mounted the primary colour filters: red, green and blue. For reasons of permanence, glass filters were used in this work.

The condenser lens ( $L_1$ ) is of the usual type. Its diameter is 6 inches and the radius of curvature of the curved surfaces is also 6 inches.

The integrating sphere is 6 inches in diameter and is made of copper and its inner surface is silver plated and coated by a layer of magnesium oxide in the usual way. Magnesium oxide is the accepted photometric standard diffuser and reflector. <sup>(88)</sup> The apertures (a) and (b) are 1.3 inches and 0.25 inch respectively in diameter. Glass windows covering these apertures prevent the magnesium oxide from being contaminated with dust.

Lenses ( $L_2$ ) and ( $L_3$ ) are ordinary achromatic lenses of focal lengths: <sup>3.5 20 cms.</sup> and respectively. Prism (P) is an ordinary  $45^\circ$  prism of 2.0 inches side and 1.2 inches height.

The whole apparatus is kept on a table and covered with a light tight box, with its inner surfaces painted matt black, the front side of the box being replaced by a black curtain to allow the observer to do his matching from inside. This is done to ensure that the eye of the observer is kept away from any light from outside the box and any stray

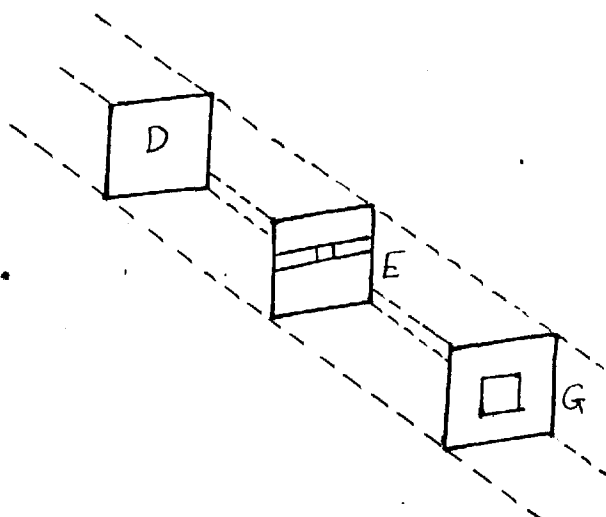


(a) The cardboard with the comparison patch and the pocket holder of the test patch.

The test colour.

The surround mask.

The black mask.



(b) The system of the test patch for varying size.

Figure (11)

light from inside it, during the matching.

#### THE CONTROL OF THE TEST PATCH:

The test patch, as shown in figure (11a) consists of a surrounding mask (E), with a 2 cms. square central aperture (F) in front of the test colour square sheet (D). Both are placed in a pocket holder (A) with a 6 cms. square aperture on a vertical white sheet of cardboard (C) containing the comparison patch (B). This system is employed because it enables the experimenter to use the same square of the test colour for the different backgrounds and the same masks of the backgrounds for the different test colours. This, not only saves much time and effort in accurately sticking squares of test colours on stripes of background in each case, but it also enables the same samples of coloured paper to be used in all the different cases.

In this investigation the effects of the angle of subtense (i.e. the angle subtended by the test patch at the observer's eye) and the inclination (i.e. the angle between the direction of vision and the plane of the test patch), on the colour contrast phenomena were studied.

#### (A) THE SYSTEM FOR THE STUDY OF THE EFFECT OF THE ANGLE OF SUBTENSE.

The two following procedures were used:-

(1) The viewing distance (i.e. the distance between the plane of the comparison and test patches, and the observer's eye), was kept constant 58 cms. and the size of the test patch was varied.

To vary the size of the test patch; the same pocket holder was provided for each required size with two square masks which were placed on top of the same square of the test colour paper (figure 11b). The

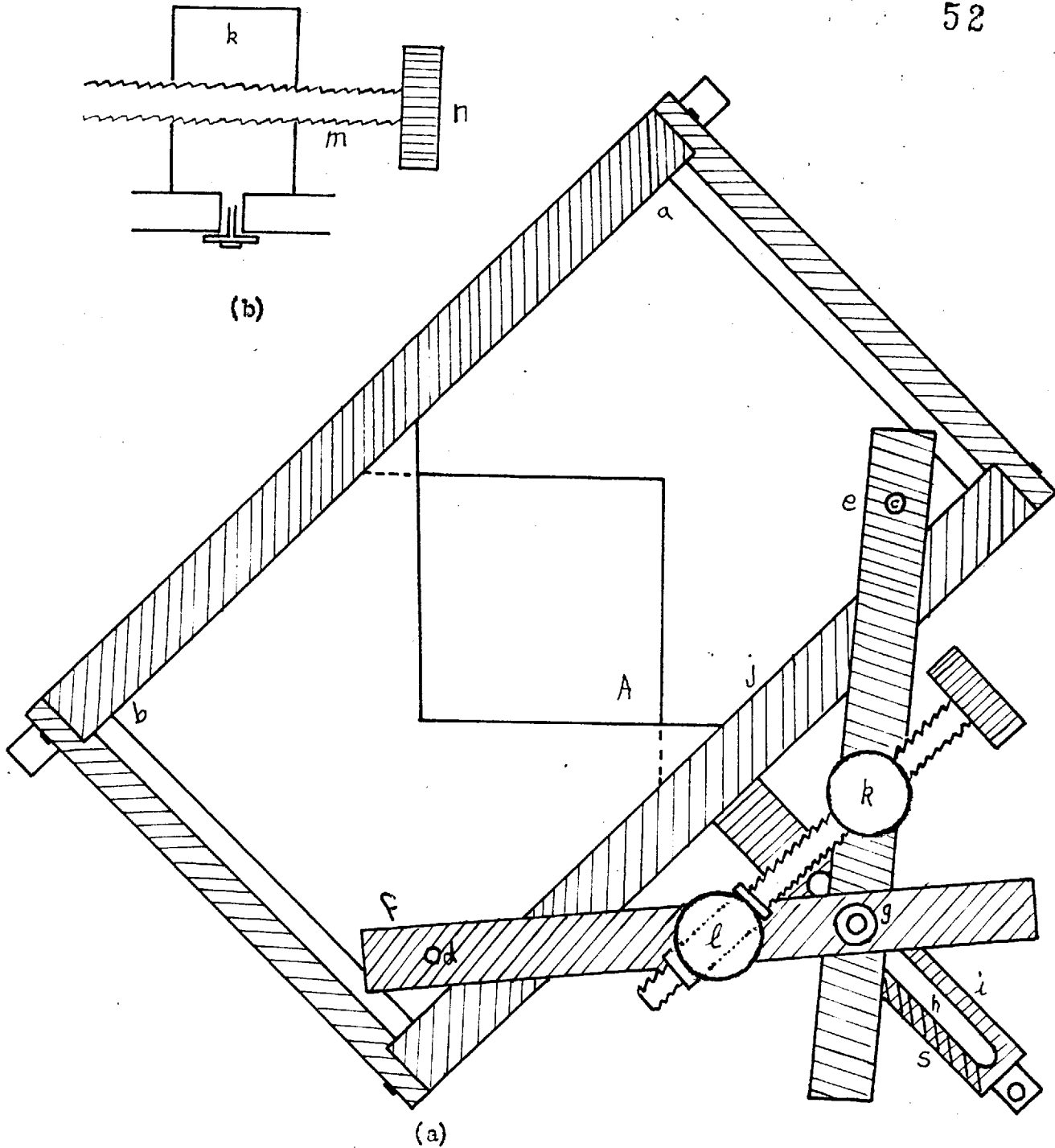


Figure (12) The mechanical system of the adjustable square aperture.

first mask was that of the surround with central aperture of the required size and was placed next to the test colour. The second mask was made of black paper with a central square aperture of three times the size of the aperture of the first mask. This black mask absorbs almost all light incident on it, hence the reflected light received by the observer's eye, comes from the test colour and its surround in the new size.

The dimensions of the test colour and surround were as follows:-

square test colours of 2.0, 1.0, 0.5 and 0.25 cms. side.

square surround of 6.0, 3.0, 1.5 and 0.75 cms. side.

The corresponding angles of subtense of the test colour were:  $2.0^\circ$ ,  $1.0^\circ$ ,  $30'$  and  $15'$  respectively, and those of the surround were:  $6.0^\circ$ ,  $3.0^\circ$ ,  $1^\circ$ ,  $30'$  and  $45'$  respectively.

(2) Models of charts (as shown in plates 1, a, b and 2 a, b) were constructed. The squares were of 1 cm. side and the stripes were also of 1 cm. breadth. The viewing distances were 2.90 and 5.80 metres. The corresponding angles of subtense of the squares were  $12'$  and  $6'$  respectively and for the whole pattern were  $1^\circ 24'$  and  $42'$  respectively.

In procedure (2), the test patch being kept outside the box covering the apparatus, an adjustable aperture was needed so that the observer's eye may receive only the beam of light reflected from the test patch when placed at any distance. This adjustable aperture (figure 12a) was fixed to the back side of the box to cover a 7.0 cms. square aperture in it. It consists of two square brass plates (a & b) of 12.0 cms. side. A  $45^\circ$  equilateral triangle is cut from one end of each plate. The two plates are fitted in a rectangular brass frame with two



parallel grooves along the long sides, so the plates can slide smoothly in them, their cut sides facing each other to form a square aperture (A) at any setting. (c & d) are two normal stands fixed to the two plates near one of their right angled corners. (e & f) are two brass arms, each having two holes near the ends. The two holes at one end of each arm accommodate smoothly the two stands (c & d). The two holes at the other end of the arms accommodate a common stand (g) which can slide smoothly along a slot (h) on a square section rod (i), fixed normally at the centre of one of the long sides of the frame (j). Two short mild steel cylinders (k & l), each ending in a part of smaller diameter, are bolted on the top of the two arms (e & f) (as shown in figure 12b) such that they can rotate smoothly about their axes. Cylinder (k) has a screw thread accommodating a screw (m). The other end of that screw is accommodated in a larger cylindrical hole in cylinder (l), and the screw is clamped by two nuts just outside the cylinder. Rotating the head (n) of this screw, either increases or decreases the angle between the two arms with the common axis of rotation (g) sliding in slot (h) towards or away from side (j), of the frame respectively. This gives rise to an increase or decrease in the size of the square aperture (A) symmetrically about a fixed centre along slot (h). A scale (s) is engraved on the top of rod (i) such that the arm (e) can show the size of the sperture. The whole system is painted matt black to avoid unnecessary reflections causing stray light.

The size of the comparison patch and its viewing distance were kept constant, giving the same angle of subtense, as reference, in order that results obtained for different sizes of the test patch may

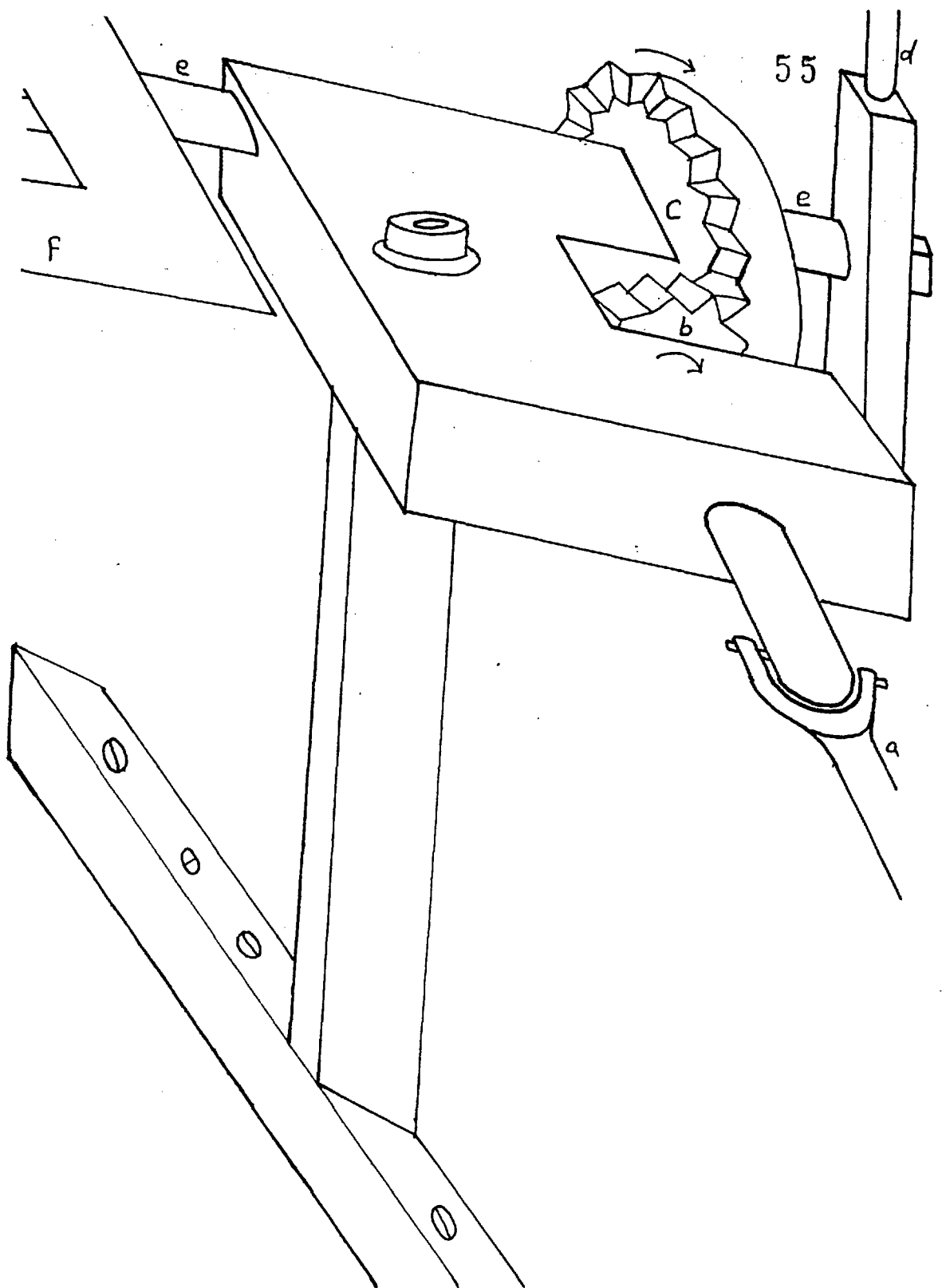


Figure (13) The system of right handed bevelled gears.

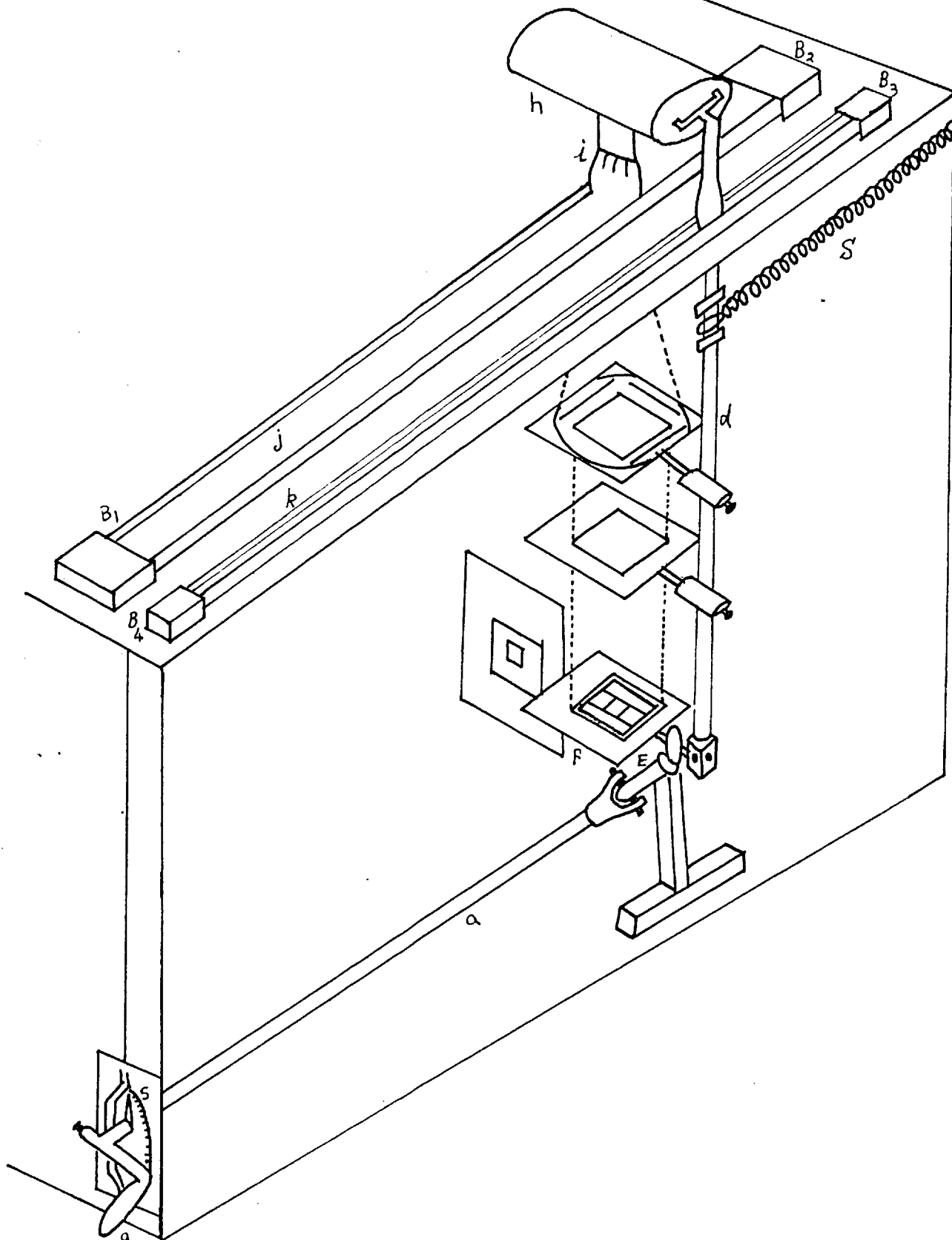


Figure (1.) The mechanical system for rotating the test patch and its illuminating source.

be comparable with each other.

(b) FOR THE STUDY OF THE EFFECT OF THE INCLINATION.

The test patch was rotated about a horizontal axis in its plane, perpendicular to the direction of vision. The direction of this axis passes through the centre of the comparison patch. In this case, the beam of light illuminating the test patch, was incident at 90° to it, at all orientations. This was achieved by the following mechanism (shown in figures 13,14).

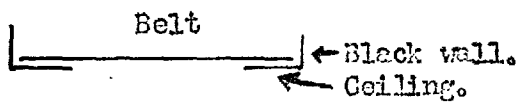
A horizontal adjustment shaft (a) is coupled by a pair of right angled bevel gears (b & c) of ratio 1:3, to an upright shaft (d), supporting a horizontal projector lamp housing (h). Shaft (d) is arranged to rotate in a vertical plane about the main axis (e), which is at 90° to the horizontal adjustment shaft (a). The cardboard test patch holder (f) is fixed to the main horizontal axis (e). The horizontal adjustment shaft (a) passes through a bearing fixed to a vertical side of the front of the frame of the box, and ends in a handle (g) provided with a pointer and circular scale (s). This enables the observer to adjust the system at any required viewing angle.

The projector lamp housing (h) is situated outside the box (just above the ceiling), in order that it may be easily cooled. A cylindrical tube (i), fixed to the circular aperture of the lamp housing, passes through the ceiling of the box and is parallel to shaft (d). Two parallel slots are made in the ceiling to allow for the rotation of the tube (i) and the shaft (d), in two parallel vertical planes during the adjustment of the system at any required inclination.

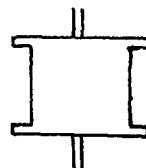
Care was taken to keep the slots light tight. For this purpose,



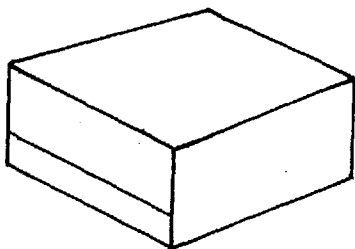
(a)



(c) The light trap



(b) The Roller.



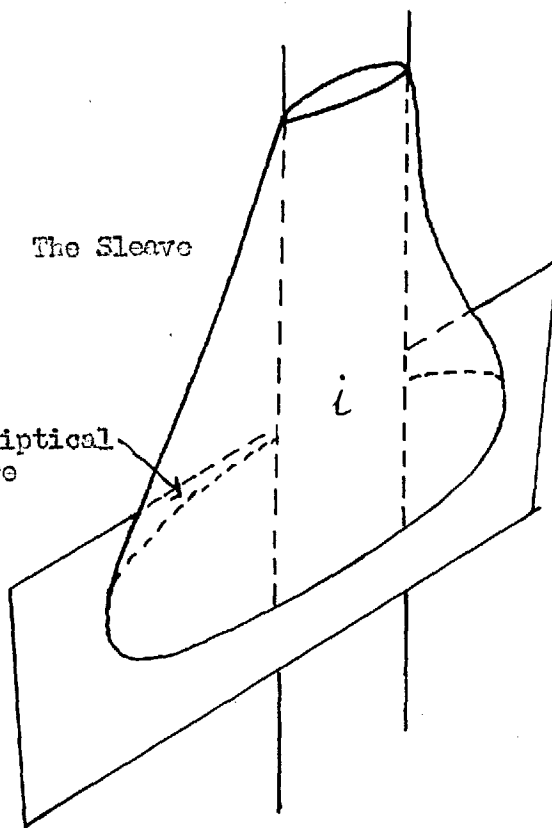
(d) The box covering the roller's Slot.

The Sleeve

The olliptical aperture

 $i$ 

The Slab.



(c)

Figure (15)

two metallic slabs (figure 15a) are made with elliptical apertures through which the tube (i) and shaft (d) pass. These apertures are elliptical to accommodate the tube and shaft at any inclination in the slabs, which should be always horizontal. Each end of these metallic slabs is attached to a strong black plastic belt passing on a wooden roller (figure 15b) rotating on a horizontal axis perpendicular to the slot and near to one of its ends. The closed circuit of each belt is completed by a pair of strong strings made just tight, with the tube (i) or shaft (d) coming in between. The elliptical apertures in the two slabs, are in general larger than the horizontal cross section of the tube (i) and shaft (d) at any direction, so a sleeve-like black cloth is put around each of the tubes and shaft with its upper end kept in light contact by means of a strong elastic band and its lower end sewed tightly to the slab. ( figure 15c) The four slots in the ceiling of the box, accommodating the four rollers are made light tight by covering them with four boxes ( $B_1$ ,  $B_2$ ,  $B_3$  &  $B_4$ ) (figure 16 ), of suitable size (figure 15d). The axes of the rollers are adjusted such that the level of the metallic slabs and the belts is raised just above the ceiling to reduce the friction due to motion to a minimum. To prevent light coming from the sides of the belts due to this adjustment, the belts are made wider than the slots and vertical black walls are fixed at the two sides of the slots between the boxes at the ends, (figure 15c). This system proved to be quite satisfactorily light tight.

The cardboard of the test patch is adjusted to be horizontal when shaft (d) is vertical. The pointer, in this case, indicates zero in the scale. The angle through which the handle (g) is rotated is three times

the corresponding angle of rotation of both the test patch and the illuminating beam of light from tube (i), giving more accuracy in adjusting the viewing angle. During this rotation the metallic slabs are pushed by shaft (d) and tube (i) and may be raised a little above the ceiling allowing light to get into the box. But, as soon as the rotation stops, they drop to their original position due to their weight, and the tension in the belts and strings. . .

A counter balance spring (s) (figure 14) is used, with one end joined to shaft (d) and the other to the vertical frame side of the back of the box. The tension in this spring, with the friction caused by the belts and the rollers, keep the system stable at any inclination. Also, the tension in the spring helps in rotating the handle (g) in returning the system to the vertical position.

A system of screens are clamped to shaft (d) with a neutral density filter holder to limit the beam of light illuminating the test patch, and adjust its intensity. These screens are always parallel to the test patch.

#### LIGHT SOURCES.

Light sources ( $S_1$ ,  $S_2$  &  $S_3$ ) are projector lamps, 500 Watt, 230 volts, of type A1/42. Source ( $S_4$ ) used in the system done for the study of the effect of the viewing angle, is a projector lamp 500 Watt, 230 volts of type B1/3 which can be burnt horizontally. They are manufactured by Messrs. Siemens Edisiwan. The filament of each of these lamps lies in one plane. Their voltages are adjusted to give standard source  $S_A$ . These voltages are lower than 230 volts, which provide longer lifetime and greater uniformity in emission radiation (59).

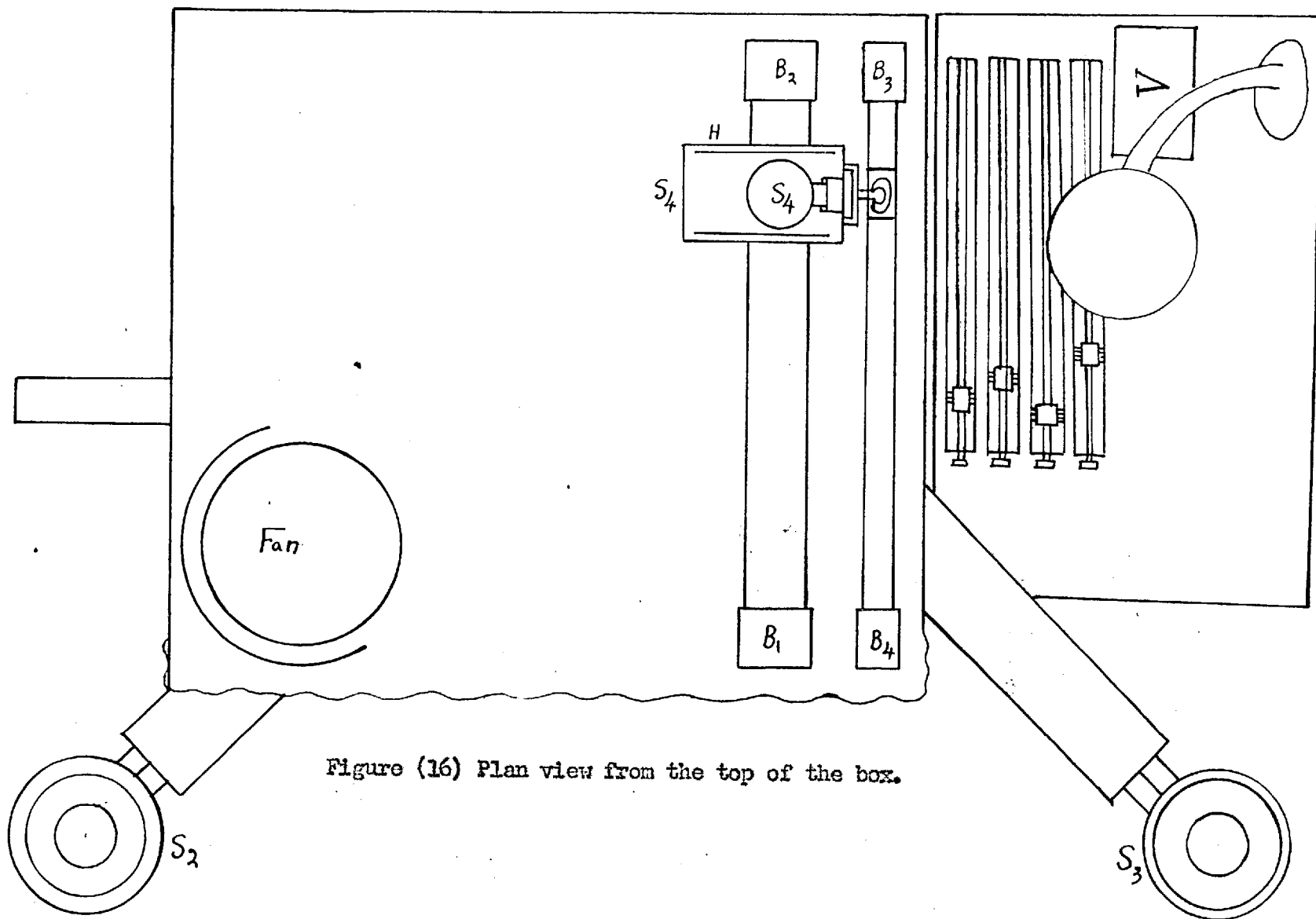


Figure (16) Plan view from the top of the box.



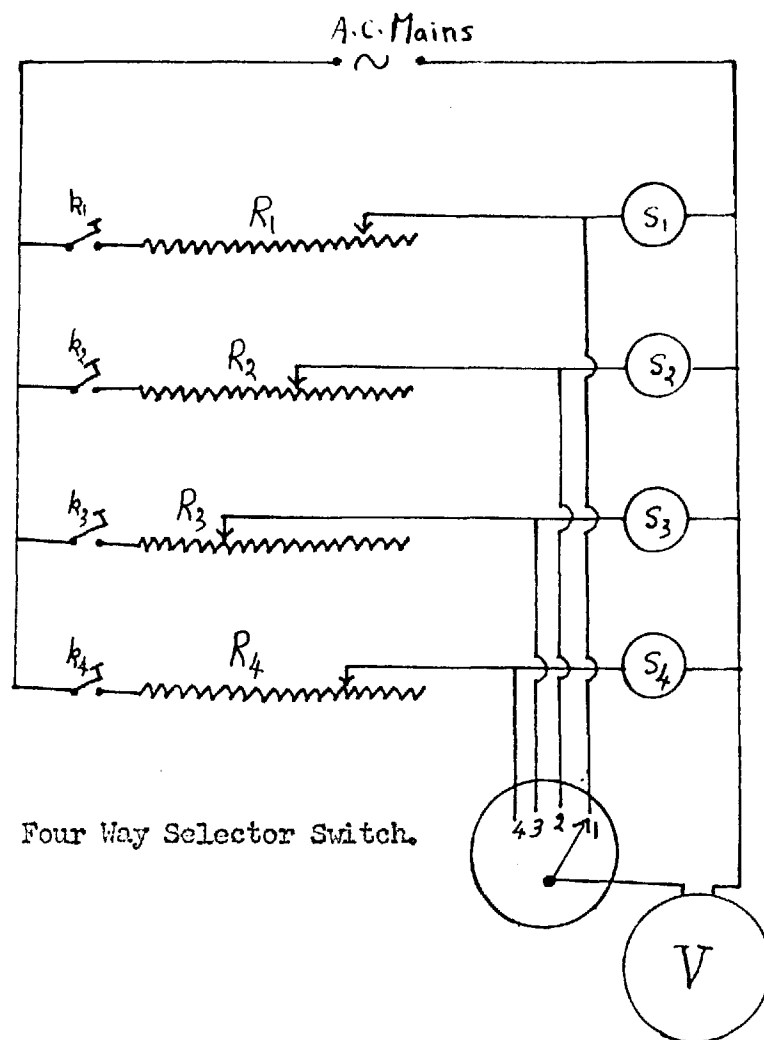


Figure (17) The electric circuit.

The electric circuit used is as shown in figure (17). It consists of each light source connected in series with a rheostat and a switch.

Such systems, for all sources, are connected in parallel with a 240 volts A.C. supply, together with a voltmeter and a 4-way selector switch to read the voltage across each lamp at a time.

The lamp housings of sources  $S_2$ ,  $S_3$  &  $S_4$ , are placed outside the box to be easily cooled and to avoid over-heating the box and its contents during the rather long intervals of matching. The lamp housings of sources  $S_2$  &  $S_3$ , are fixed on a stand sliding on optical benches fixed to the top of the table. Their system of screens are likewise fixed to similar stands sliding on their optical benches.

An electric fan is fixed to the ceiling of the box just above the lamp housing of source ( $S_1$ ) (the only one inside the box), to cool it and help in ventilating the box. (Figure 16).

#### PAPER COLOUR SAMPLES:

In this investigation; the test colours used are grey (g), orange (O), yellow (Y), green (G) and blue (B), and the backgrounds are white (W), black (b), yellow (Y), blue (B), orange (O) and green (G).

The test patch consists of either a simple or compound pattern. The simple pattern consists of one central square of the test colour in a symmetrical square surround of three times its size. The surround is made either of one colour (figure 18a), or two colours (figure 18b, b'-) in the form of three adjacent alternate stripes with the test colour mounted on the central stripe of one colour or the other. The compound pattern consists of five squares of the test colour in the form of a cross, mounted on a square surround of seven times the size of each

of these squares. The surround is made either of one colour (figure 18c) or of two colours (figure 18d, d'), in the form of seven adjacent alternate stripes with the squares of the test colour mounted on the stripes of one colour or the other.

The charts (plates 1 a, b & 2, a, b), are made of elements of these compound patterns on long stripes of two colour surround together with squares of the corresponding <sup>test</sup> colour on white surround <sup>for</sup> reference. This choice of these test colours enables the study of contrast effects on coloured samples located near the centre, red, green and blue ends of the chromaticity chart.

These backgrounds were chosen for the following reasons:-

(1) THE BLACK BACKGROUND: absorbing nearly all light incident on it, enables the study of the appearance of the test colour unaffected by any coloured surround.

(2) THE WHITE BACKGROUND: being almost neutral and reflecting a large proportion of the incident light rather equally all over the spectrum, enables the study of the effect of the brightness of the surround of the test colour (referred to the case of dark surround for black background).

(3) THE YELLOW AND BLUE BACKGROUNDS: were used to study the effects of complementary coloured backgrounds which were expected to give large contrast differences.

(4) THE COMBINATION OF YELLOW AND BLUE: in a two colour background, with the test colour mounted on either the yellow or the blue gave a striking contrast difference in a chart made by <sup>Mr.</sup> S. Bilcher.

(5) THE ORANGE AND GREEN: in one colour or two colour backgrounds

are used to complete the study of the effects of different backgrounds located near the red, green and blue ends of the chromaticity chart as well as the yellow.

(6) THE COMBINATION OF WHITE AND BLACK: in a two colour background enables the study of the effect of the brightness factor with neutral colour.

Desaturated coloured paper was used in this investigation in order that it may be directly matched by the red green blue primaries used, without any further complication of using an additional optical system with the simple modification of Donaldson's Colorimeter (figure 10), to provide a desaturating beam of light to the test colour.

Also coloured paper used was matt for the following two reasons (13):

(1) Matt Colours tend to be slightly desaturated because it is impossible to separate the following two components of reflection (a) the small component occurring on the surface without any coloration, (b) the major component occurring after penetration into the pigment layer where it is partially reflected and hence coloured.

(2) With a true matt surface, the colour is also independent of the direction of illumination, or viewing, since the two components of reflection are diffusely distributed in all directions by the random orientation of the minute facets of the top layer and the tiny particles of the pigment layer. Glossy surfaces possess some degree of specular reflection which modifies its colour.

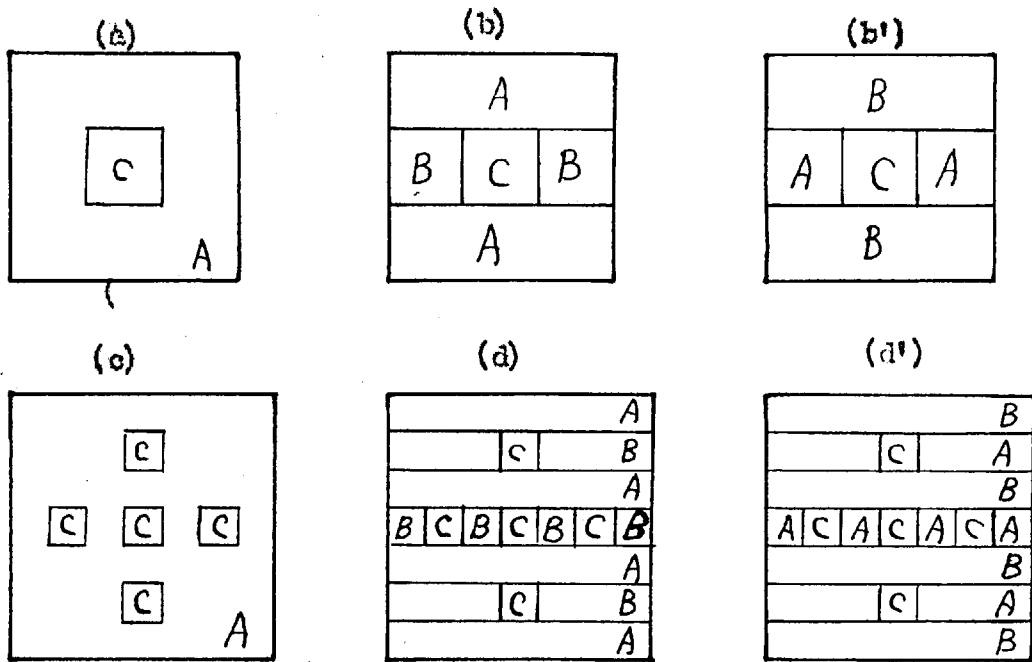


Figure (18) Types of the test pattern. (C) is the test colour, (A) & (B) are the surround colours. Cases (a), (b) & (b') represent the simple pattern and (c), (d) & (d') represent the compound pattern.

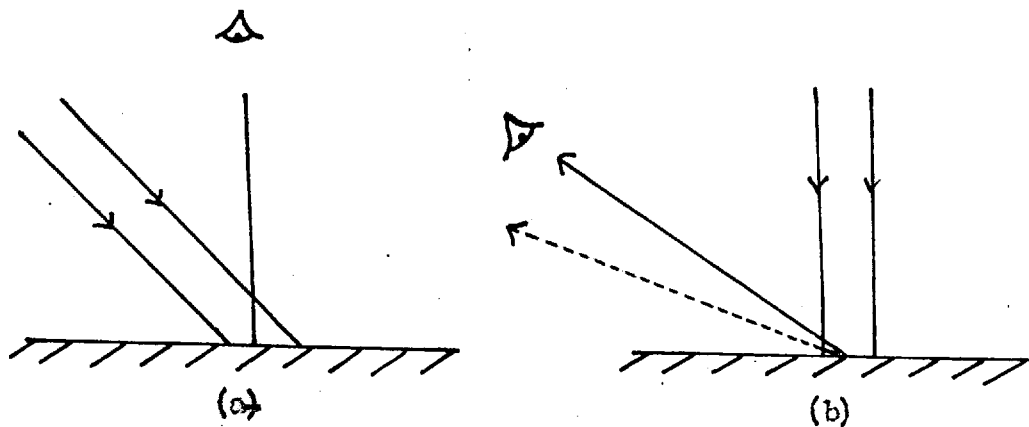


Figure (19) The standard conditions recommended by the C.I.E for illuminating and viewing a surface in measuring its colour.

(B) EXPERIMENTAL ARRANGEMENTS.(1) USING THE COLORIMETER.FIXATION OF OBSERVER'S HEAD:

It is important to keep the observer's head fixed such that the beam of light coming from the comparison patch and focused on his right eye, should pass centrally through his eye pupil during the time of matching.

(22) To achieve this, a mouthpiece mounting is fixed on the optical bench (on which the stands of prism P and lens  $L_3$  (figure 10 ) are fixed), at the observing end of the apparatus. The mouthpiece consists of a small metallic plate partly covered with wax, in which the observer makes an impression of his teeth by biting on it after it has been softened by hot water. When the impression is hard, the plate is bolted to the vertical pillar of the mouthpiece mounting, so that the observer on biting on his impression has his head held rigidly in position, relative to the colorimeter as a whole. The mounting was provided with the necessary adjustments to bring the observer's eye in the proper position to receive the beam of light from the comparison patch centrally. Vertical, lateral and rotational adjustments are possible by means of two screws joined to the stand of the mouthpiece. The whole stand can also be moved backwards and forwards by sliding on the optical bench, to bring the observer's eye at focus of the optical system.

METHODS OF ILLUMINATION AND VIEWING.

The methods of illumination and viewing used in this investigation were those adopted by the "Commission Internationale de l'Eclairage" (C.I.E.) as standard practice, (11) and are shown in figure (19a, b )

(1)  $45^\circ$  illumination and normal viewing was generally used for most of the study, and (2) Normal illumination was used for the study of the effect of inclination.

#### THE SIZE OF THE COMPARISON PATCH:

The comparison patch was made to subtend an angle of  $2^\circ$  at the observer's eye. This size was kept the same throughout the investigation. This size was chosen after the C.I.E. system which was based on the  $2^\circ$  field conditions <sup>(22)</sup> for the following reasons:-

(1) The ~~larger~~ fields are subjectively non-uniform for the macular yellow pigment.

(2) Maxwell's spot appears when looking at large areas of dichroic colours.

(3) In measurement of dark colours (as blue and grey in this work), the illumination might be too low that the visual response would have included a significant rod component if the field had been large. Colour measurement in this work was carried under photopic conditions and thus cone vision alone should be involved in match.

(4) The consistency with the 1924  $V_\lambda$  curve obtained by direct comparison and flicker methods for the  $2^\circ$  field.

#### THE SURROUND OF THE COMPARISON PATCH.

In this investigation the surround of the comparison patch was white and it was illuminated by source  $S_A$  at constant luminance to control the state of adaptation under which the comparison patch is viewed. For the study of the effects of the brightness of the surround of the comparison patch, the luminance of the surround was kept the same for the whole set of matches (i.e. for all the test colours used against their

different backgrounds), and then varied to get another set of matches.

#### MONOCULAR MATCHING TECHNIQUE:

Monocular matching was used in this work in which the observer's eye moves between the test and comparison patches. It constitutes of quick memory matching. The test and comparison patches<sup>es</sup> are imaged alternately, more or less, on the same region of the fovea. For small angles of subtense of the test colour, it was found that if the observer looks at the test patch for a long time (T seconds say), then when looking back at the comparison patch a pattern of after - image of the test patch was seen superimposed on the comparison patch. So the comparison patch looks non-uniform for a short time depending on T. The complementary colours of the surround of the test patch seem to be added to that of the comparison patch, leaving its central square paler (since the comparison patch may be roughly matching the test colour). This may upset the observer, not only during the short time in which it appears, but even after it disappears. To avoid these complications the observer's eye was kept at the focus of the beam of light from the comparison patch during most of the matching time. By glancing quickly at the test patch i.e. the test colour in its surround, an idea of its colour was obtained and then a roughly similar colour was produced by varying the proportions of red, green and blue in the mixture of the comparison patch. The test and comparison patches were then compared by looking quickly at the test patch from time to time and trying to improve the matching in lightness and hue until a satisfactory match was obtained.

Four matches were made for each case. Once the first match was



obtained, as mentioned above, the second was made by increasing one of the components, keeping the other two constant (to restore the brightness of the comparison patch), and then re-adjusting it. This was repeated for the other two components until a new satisfactory match was obtained. The third match was made by decreasing the components and then re-adjusting them one after the other. In the final match the three components were reduced and increased alternately, one at a time, and then re-adjusted. The observer usually closed his eye for a short time during matching so that the final judgement on the match could be made with the eye as fresh as possible. The observer recorded the readings himself, so, at the beginning of each match, he remained for about a minute with his eye looking at the field of vision to get nearly adapted to the conditions of viewing. Total adaptation is attained during matching which takes one or two more minutes.

#### DIFFICULTIES IN THIS MONOCULAR MATCHING TECHNIQUE.

It is obvious that the monocular matching technique used in this work is quite different from the usual monocular matching used in ordinary colour measurement. Comparing this technique with that used, for example, in the Wright Colorimeter, (55) the following main differences are apparent.

(1) The test patch and comparison patch are not of the same nature: The test patch is made of coloured paper and can be seen by reflection of light incident on it, while the comparison patch consists of an aperture filled with red green blue mixture of light transmitted through the optical system shown in figure (10). So the observer finds the difficulty of matching light reflected on a paper surface with light refracted

from a glass surface. In Wright Colorimeter the observer compares two patches of spectral light transmitted through similar optical systems.

(2) The test patch and the comparison patch are separated from each other, because they may have a mutual effect which may spoil colour appearance due to contrast, and hence it can not be measured accurately. This adds another difficulty to the observer, since his eye has to move from one patch to another. It is easier to compare the two adjacent patches in Wright Colorimeter since the final judgement depends on the disappearance of the border line between the two patches such that they appear nearly one homogeneous patch.

(3) The separation of the two patches with the observer's eye looking at them alternately necessitates that the observer uses his memory in remembering what the test colour looked like, while he is matching it by looking at the comparison patch. This is more difficult than seeing the two patches simultaneously, as in Wright Colorimeter.

(4) The problem of after images previously mentioned, arises from the fact that the test patch and the comparison patch are imaged alternately practically on the same part of the fovea. No such difficulty occurs in Wright Colorimeter since the two patches are imaged in adjacent areas of the fovea.

(5) The test patch, even in its simplest form, is of complex nature, consisting of elements of different colours and the observer must be concentrating and paying attention because he is only trying to compare the appearance of the central test colour against its background. Also, it is not of a constant standard form, but varies from one colour surrounds to two colour surrounds in the simple and compound patterns.

(6) To study the effects of angle of subtense of the test patch, the comparison patch must be kept the same size for reference, in order to allow for comparing the results with each other. So the observer has to compare two patches of different sizes which is more difficult than the case of two equal patches in Wright's Colorimeter. Another difficulty arises, in the case of matching the actual charts from outside the box containing the apparatus, namely focusing of the observer's eye alternately for different distances.

(7) To study the effects of the inclination of the test patch, the comparison patch must be kept the same (vertical) as reference for the same reason as in case (6) of comparing the results with each other. The observer faces the additional difficulty of comparing two patches, one of which is vertical and the other inclined. The two patches in Wright's Colorimeter are in the same vertical plane.

(8) To study the effects of the brightness of the surround of the comparison patch, and the luminance of the whole test patch, the observer is left with the two patches being, in general, of different overall brightness, which are difficult to compare. This is another reason why the observer should look during most of the matching time at the comparison patch, and glance quickly at the test patch from time to time to keep his level of adaptation nearly constant.

For all these reasons, which are essential to the nature of the problem and cannot be avoided, considerable training and patience by the observer are required to obtain consistent readings.

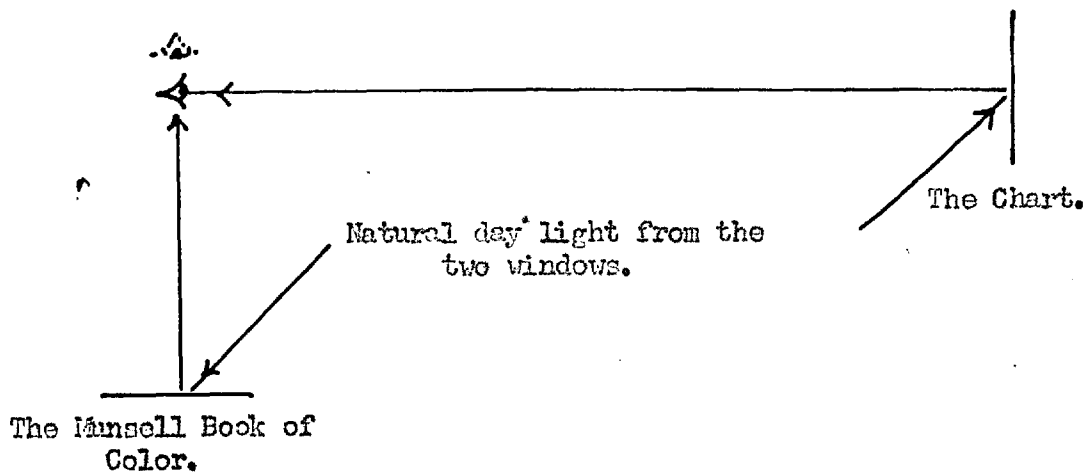


Figure (20) Illumination and viewing of the chart and the Munsell Book of Color.

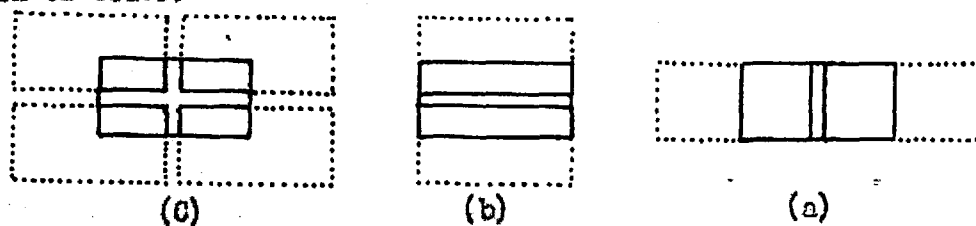


Figure (21) Positions of the Mask used with the Munsell Book of Color to make better judgement in matching.

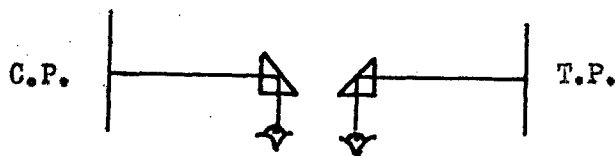


Figure (22) A system for binocular matching technique. The right eye looking at the test patch (T.P.) and matching it with the left eye looking at the comparison patch (C.P.).

## (2) USING THE MUNSELL BOOK OF COLOR.

This method was used to specify the colour appearance of the colour samples in the four charts (plates 1 a,b & 2, a,b. ) The square colours on white surround are of 2.0 cms. side. The squares of the pattern are of 1 cm. side. The stripes are of 1 cm. breadth. The viewing distances used were 2.90 and 5.80 meters. The corresponding angles of subtense of the squares were 12' & 6' respectively and for the whole pattern were 1° 24' and 42' respectively.

Both the standard Edition and Pocket Edition of the Munsell Book of Color <sup>(73)</sup> were used. The first contains 20 hues and the latter 40 hues.

The chart was fixed (vertically) on the wall near the window and the Munsell Book of Color was placed (horizontally) on a desk near another window, as shown in figure (20 ). Natural daylight falls obliquely from the side on both the chart and the book. The only other substitute is using a uniform standard artificial daylight in a big room which was not available during doing this work. The observer looks (with both eyes) alternately at the chart and the Munsell Book of Color. The direction of viewing is perpendicular in both cases. Both the chart and the colour samples in <sup>the</sup> Munsell Book are illuminated and viewed in the same conditions. Direct sunlight was avoided.

The observer was asked to match the colours on different backgrounds as they appear to him, by colour samples in the Munsell Book of Color. This method is also a quick memory matching as in the first method.

The Procedure used: was as follows:

(1) Using the standard edition of the Munsell Book of Color, the observer gets a preliminary match from the two special hue charts

consisting of 20 hues given in values from 2-8 and in the maximum chroma attained for each hue and value. A standard Munsell mask of light grey colour with rectangular hole of equal size as the colour chips is used to obscure the neighbouring colours, and hence enables the eye to see the required colour sample only (unaffected by contrast effects of its neighbours). To make better judgement, the mask can be placed such that its rectangular hole shows parts of two neighbouring chips either in the same row i.e. of the same value, but of different hues as shown in figure (21a) or in the same column i.e. of the same hue but of different values as shown in figure (21b), or even parts of four neighbouring chips covering the last two cases as shown in figure (21c). The characteristics of the nearest matching chip are recorded in terms of hue value and chroma.

(2) Then turning to charts of constant chroma, in the same book, the observer picks the chart of the same chroma as that he gave to the colour under test and search for the chip of the same hue and value as recorded. Using the mask in the same way as in the last step, he can move it up and down in the same column i.e. of the same hue to make better judgement of value, and sideways in the same row, i.e. of the same value to make better judgement of hue. The observer was asked also to interpolate, if possible, between the hues and values of adjacent chips whenever necessary. The new characteristics are then recorded.

(3) Then the observer turns to the charts of constant value, in the same book, picking the chart of the new value determined in the last step, he could make better judgement of chroma by moving the mask along the radius of the hue circle containing the chip of the same hue and chroma

as that of the last step, towards the centre or away from it. Once he decides the right chroma for matching, he can make better judgement of hue by moving the mask around the circle of that chroma. He can also interpolate if possible, between the given chromas and hues whenever necessary. The new characteristics are then recorded.

(4) Instead of using the charts of constant hue in the standard edition of the Munsell Book of Color (containing 20 charts with equal hue steps of 5 units each), the observer is asked to use the pocket edition (containing 40 charts with equal hue steps of 2.5 units each). Picking the chart of hue under consideration and the next two charts and the previous two charts and putting them in order side by side, he can make better judgement of hue by moving the mask from one chart to another for chips of the same value and chroma as those obtained in step (3). Deciding the best matching hue (or interpolating for the best one), he can then move the mask in the same chart (or the nearest to the interpolated value) in the same column, then in the same row to make the best match in chroma and value respectively (or interpolate for the best one). These last characteristics are recorded and are considered as the final and best match which can be obtained by the observer.

This method being easier and quicker than the other method, was carried by a number of observers of those who passed Ishihara test and hence have normal colour vision. The readings of each observer in steps (2) and (3) were usually consistent and either agree with step (4) or differ in hue by 2.5.

Care was taken to get as accurate results as possible to obtain

a true record of what different observers actually see:-

(1) This long procedure mentioned before helps the observer to have better judgement in his matching. His interpolation between the adjacent chips in hue, value and chroma, if possible and whenever necessary, gives him a chance to get more accurate results,

(2) To avoid the variability in brightness and quality of natural daylight, the matching was carried only when the sky was bright. Thus the conditions were practically the same. Also both the chart and the Munsell coloured chips were illuminated by the same brightness and quality of light.

#### THE RESULTS:

The results of different observers expressed in Munsell's system of hue, value and chroma are plotted in a hue circle with chroma indicated as distances from its centre (hue chart). They are also transformed to the C.I.E. system of chromaticity co-ordinates  $x$ ,  $y$  and luminance  $Y$  (76). The corresponding points are then plotted in the C.I.E. chromaticity chart.

#### DIFFICULTIES IN THIS TECHNIQUE OF USING THE MUNSELL BOOK OF COLOR.

It is obvious that this technique used in this method is quite different from the usual technique of using the samples of the Munsell Book of Color. Usually the test sample to be compared is fixed in a mask with a rectangular hole of double the size of the Munsell coloured chips such that the field of vision consists of the test and comparison patches in equal sizes, and adjacent to each other. The comparison in this case is much easier than that used in this work. The nature of the problem of colour contrast necessitates to have the



chart under test away from the observer because, if it is very near to him (on the desk near the Munsell Book of Color), he would hardly see any difference in the appearance of patterns of any test colour on different surrounds. On the other hand, if the Munsell Book of Color is kept away in the same plane as the chart, then two problems will arise, namely:-

(1) This needs another person to assist the observer by moving the mask on the charts of the Munsell Book of Color, until the observer is satisfied with one chip, to match the appearance of the test colour.

(2) From the psychological point of view, the observer in this case will not have his full freedom of moving the mask by himself and choosing the most suitable chip for the best match. Not doing the job himself he may lose interest and can not concentrate for a long time, especially for the difficult judgement he has to do.

In the light of the difficulties mentioned in the first technique using the Colorimeter, it is easy to see that, in this case also, the observer practically faces, more or less, all of them except the first one, since the test and comparison patch<sup>es</sup> are both made of coloured paper and hence have the same nature, and the 7<sup>th</sup> & 8<sup>th</sup> since the effects of the inclination and luminance of the test patch were not studied by this method.

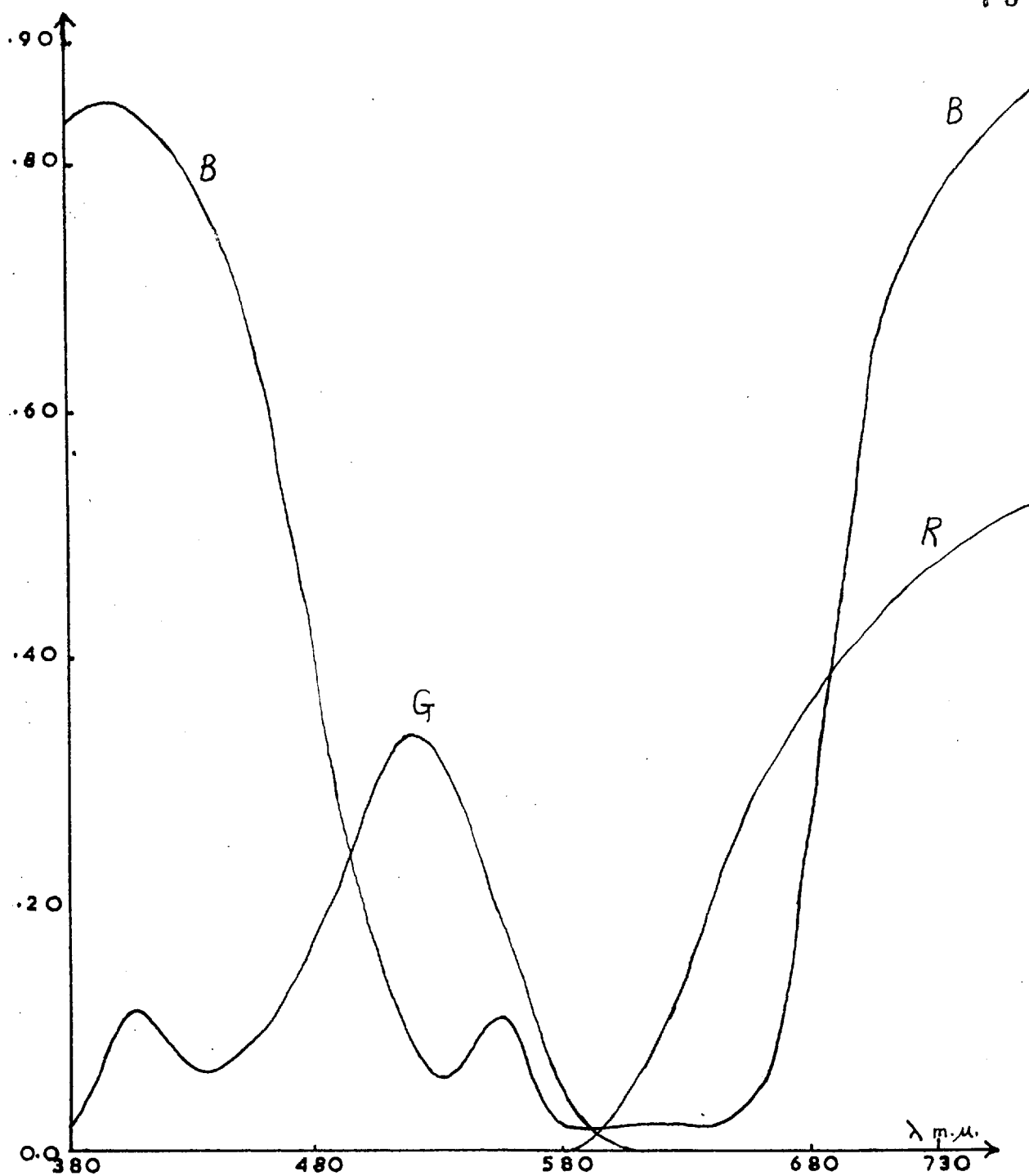


Figure (23) The spectral transmission energy distribution curves of the three Primary Colour Filters (R, G, B) used.

## CHAPTER IV

### CALIBRATION OF THE COLORIMETER AND PRELIMINARY MEASUREMENTS.

#### (A) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE THREE PRIMARY COLOUR FILTERS.

The spectrophotometric transmission characteristics of the three primary filters; red, green and blue, were plotted on a Beckman recording spectrophotometer (54) to give the general shape of the curves. Their transmission factors  $T_\lambda$  were checked using the Wright photoelectric spectrophotometer (50) every 10 m. $\mu$  in the visible spectrum in between wavelengths 380 - 770 m. $\mu$ . The corrected transmission energy distribution curves are shown in figure (23). The C.I.E. tristimulus specification (x, y, z and Y) of each filter was then calculated for standard illuminant  $S_A$ , following the method explained in Chapter II. The results are shown in Table 1.

The unit trichromatic equations (R), (G) and (B) for the utilized red, green and blue colour filters respectively, are formulated as follows:

$$\begin{aligned} (R) &\equiv x_r (X) + y_r (Y) + z_r (Z) \\ (G) &\equiv x_g (X) + y_g (Y) + z_g (Z) \\ (B) &\equiv x_b (X) + y_b (Y) + z_b (Z) \end{aligned} \tag{1}$$

where both (R,G,B) and (X,Y,Z) are expressed in T-units of the C.I.E. system (in which white is matched by equal quantities of (X),(Y) and (Z).

Since all the results in this work were obtained in terms of  $[R], [G]$  &  $[B]$  on the  $[R,G,B]$  system (in which the white is matched by equal quantities of  $[R], [G]$  and  $[B]$  e.g.

$$c [C] \equiv r [R] + g [G] + b [B] \tag{2}$$

Then equations (1) cannot be substituted in equation (2) for  $[C]$ .

To do this the following transformation equations <sup>(13)</sup> are used:

$$[R] \equiv a (R), [G] \equiv b (G) \text{ \& } [B] \equiv c (B) \quad (3)$$

Substituting equations (3) into equations (1) we get:

$$\begin{aligned} [R] &\equiv a x_r (X) + a y_r (Y) + a z_r (Z) \\ [G] &\equiv b x_g (X) + b y_g (Y) + b z_g (Z) \\ [B] &\equiv c x_b (X) + c y_b (Y) + c z_b (Z) \end{aligned} \quad (4)$$

The white point in the two systems of (X,Y,Z) and [R,G,B] is given by:

$$(W) \equiv 0.3333 (X) + 0.3333 (Y) + 0.3333 (Z) \quad (5)$$

$$\text{and } [W] \equiv 0.3333 [R] + 0.3333 [G] + 0.3333 [B] \quad (6)$$

Substituting from Equation (4) into equation (6)

$$\begin{aligned} [W] &\equiv 0.3333 (a x_r + b x_g + c x_b) (X) \\ &\quad + 0.3333 (a y_r + b y_g + c y_b) (Y) \\ &\quad + 0.3333 (a z_r + b z_g + c z_b) (Z) \end{aligned}$$

To avoid unnecessary complication of the algebra by the introduction of superfluous constants, we will assume that:  $(W) \equiv [W]$  and hence by equating coefficients of (X), (Y) & (Z) in equations (5) & (6) we get:

$$\begin{aligned} a x_r + b x_g + c x_b &= 1 \\ a y_r + b y_g + c y_b &= 1 \\ a z_r + b z_g + c z_b &= 1 \end{aligned} \quad ((7))$$

Solving equations (7), the values of a, b & c can be calculated.

Substituting these values in equations (4) we get the required transformation equations between the two systems [R,G,B] & (X,Y,Z), which can be substituted directly in equation (3) of any colour [C] obtained in [R,G,B] system by actual matching.

(TABLE) (1) TRISTIMULUS COEFFICIENTS AND LUMINANCE OF THE THREE PRIMARY FILTER.

| FILTER | X      | Y       | Z       | X+Y+Z    | x      | y      | Z       | Y       |
|--------|--------|---------|---------|----------|--------|--------|---------|---------|
| RED    | 7.3957 | 3.0535  | 0.00065 | 10.45165 | 0.7078 | 0.2921 | 0.00006 | 0.03054 |
| GREEN  | 5.3678 | 12.9662 | 4.5631  | 22.8971  | 0.2344 | 0.5663 | 0.1993  | 0.12966 |
| BLUE   | 7.6454 | 6.7224  | 20.2011 | 34.5689  | 0.2211 | 0.1945 | 0.5844  | 0.06722 |

(TABLE) (2) THE COMBINED TRISTIMULUS COEFFICIENTS AND LUMINANCE OF THE THREE PRIMARY COLOUR FILTERS WITH THE NEUTRAL DENSITY FILTER ( $F_4$ )

| FILTER | X      | Y      | Z      | X+Y+Z   | x      | y      | Z       | Y       |
|--------|--------|--------|--------|---------|--------|--------|---------|---------|
| RED    | 2.6546 | 1.0945 | 0.0002 | 3.7493  | 0.7080 | 0.2919 | 0.00006 | 0.01095 |
| GREEN  | 1.9575 | 4.7270 | 1.6117 | 8.2962  | 0.2360 | 0.5697 | 0.1943  | 0.04727 |
| BLUE   | 2.7079 | 2.4509 | 7.0702 | 12.2289 | 0.2214 | 0.2004 | 0.5782  | 0.02451 |

(TABLE) (6) THE CHROMATICITY CO-ORDINATES FOR  $S_A$  AND ( $S_A$  + CHANCE OB9 FILTER)

| SOURCE             | X       | y       | Z       | X+Y+Z   | x       | y       | Z       | Y      |
|--------------------|---------|---------|---------|---------|---------|---------|---------|--------|
| $S_A$ + CHANCE OB9 | 19.8151 | 20.3258 | 17.3063 | 57.4472 | 0.3449  | 0.3538  | 0.3013  | 0.2033 |
| $S_B$              |         |         |         |         | 0.3484  | 0.3516  | 0.3000  |        |
| ERROR              |         |         |         |         | -0.0035 | +0.0022 | +0.0013 |        |

Results From Table 1: we can formulate:

$$(R) \equiv 0.70780 (X) + 0.29214 (Y) + 0.00006 (Z)$$

$$(G) \equiv 0.2344 (X) + 0.5663 (Y) + 0.1993 (Z)$$

$$(B) \equiv 0.2211 (X) + 0.1945 (Y) + 0.5844 (Z)$$

The calculated values of a, b and c are:

$$a = 0.6660, \quad b = 0.9453 \text{ and } c = 1.7887$$

which give the final equations.

$$[R] \equiv 0.4714 (X) + 0.1946 (Y) + 0.00004 (Z)$$

$$[G] \equiv 0.2216 (X) + 0.5353 (Y) + 0.1884 (Z) \quad (8)$$

$$[B] \equiv 0.3070 (X) + 0.2701 (Y) + 0.8116 (Z)$$

In the cases when the test colour in its surround appeared so dark that very low values of R,G,B mixture might be used to match it (and hence the relative errors in the readings may be considerable), a neutral density filter ( $F_d$ ) was usually placed in the path of R,G,B mixture (such that higher values of the scales of R,G,B may be used in matching and hence the relative error can be reduced). So, it was necessary to calculate the combined trichromatic co-ordinates and luminosities of this neutral density filter with each of R,G & B filters. The same analysis just mentioned before was used taking into account the transmission factor of the neutral density filter ( $T_\lambda$ ) at wavelength  $\lambda$ . The final results are shown in Table (2).

Results From Table(2) we can formulate:-

$$(R) \equiv 0.70803 (X) + 0.29191 (Y) + 0.00006 (Z)$$

$$(G) \equiv 0.22595 (X) + 0.56978 (Y) + 0.19427 (Z)$$

$$(B) \equiv 0.22143 (X) + 0.20042 (Y) + 0.57815 (Z)$$

The calculated values of a, b and c are:

$$a = 0.6626 \quad b = 0.9154 \quad \text{and} \quad c = 1.4220$$

which gives the final equations:

$$\begin{aligned} [R] &\equiv 0.4691 (X) + 0.1934 (Y) + 0.00004 (Z) \\ [G] &\equiv 0.2160 (X) + 0.5216 (Y) + 0.1779 (Z) \\ [B] &\equiv 0.3149 (X) + 0.2850 (Y) + 0.8221 (Z) \end{aligned} \quad (8)'$$

#### (B) CALIBRATION OF LIGHT SOURCES TO GIVE $S_A$ :

All the light sources used in this work were calibrated by comparison with a National Physical Laboratory sub-standard source  $S_A$  whose colour temperature is  $(2854 \pm 10)^\circ \text{K}$ . A photometer bench with Lummer-Brodhun contrast cube <sup>(82)</sup> is used for this purpose in the usual method of substitution. This calibration was checked from time to time.

#### (C) CALIBRATION OF THE SCALES OF THE SHUTTERS OF THE PRIMARY FILTERS:

Donaldson <sup>(59)</sup> stated the factors which tend to destroy the proportionality between scale readings and intensity of stimulus as:

- (1) Uneven horizontal distribution of luminous flux within the cone subtended by the aperture at the source.
- (2) Uneven distribution of light over each aperture due to both
  - (a) varying distance from source, and (b) varying obliquity.
- (3) Non-uniform transmission through the coloured filters.
- (4) Varying reflection and absorption losses in the condenser lens.
- (5) Varying effectiveness of the sphere as an integrator for pencils of light entering at different angles.

On account of the fact that the shutters slide horizontally, vertical variations in the above quantities are of no consequence, only

horizontal variations need to be taken into consideration. The magnitudes of factors (1) and (5) were measured by Donaldson, and he did not find any detectable variation in luminance. He calculated the effect of factor (2) from the inverse square law together with the cosine law. For the effect of factor (4) he traced rays corresponding to certain points in the apertures through the condenser lens, then calculated the reflection losses at the surfaces and measured the thickness of glass traversed, and hence calculated the absorption losses. He did not insist on absolute uniformity of factor (3) and he permitted variations not exceeding 2% in the local transmission through filters.

By combining the effects of factors (2) & (4), he drew a calibration curve for each aperture. The final corrections were much less than had been expected, since effects of factors (2) & (4) work in opposite directions. He modified the width of the apertures by the insertion of templets, which compensate for these variations and so render the scale strictly linear. A final test of the scales in the completed instrument was made by means of sectors, and it showed that they were sufficiently accurate for colorimetric measurement. Generally the departures from linearity were less than 1% except for very small openings, where the scales were found to be true to the limit to which they could be read.

In the present investigation a developed form of the colorimeter, with different type of projector lamp and different glass primary filters was used, in a technique different from that in which it was originally used. So the author recalibrated the scales of the shutters for the new conditions of the colorimeter and its use. The following



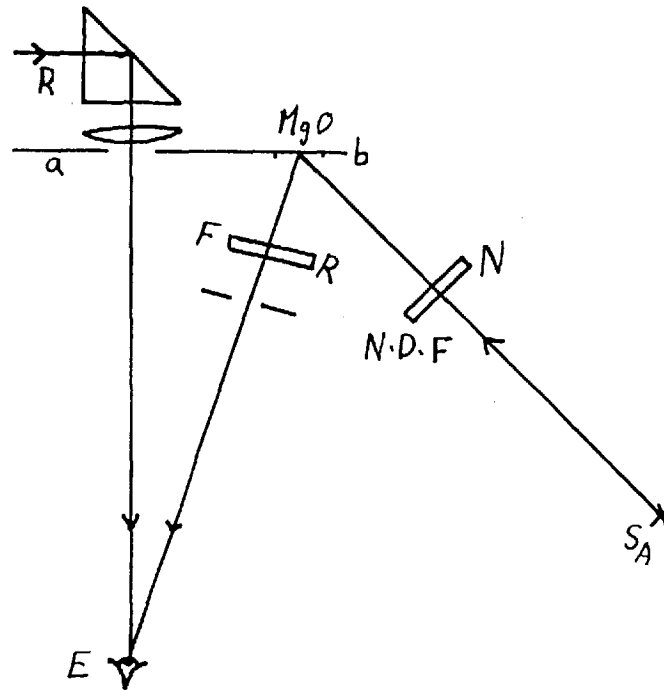


Figure (24) The system for the calibration of the scales of the shutters of the three primary colour filters.

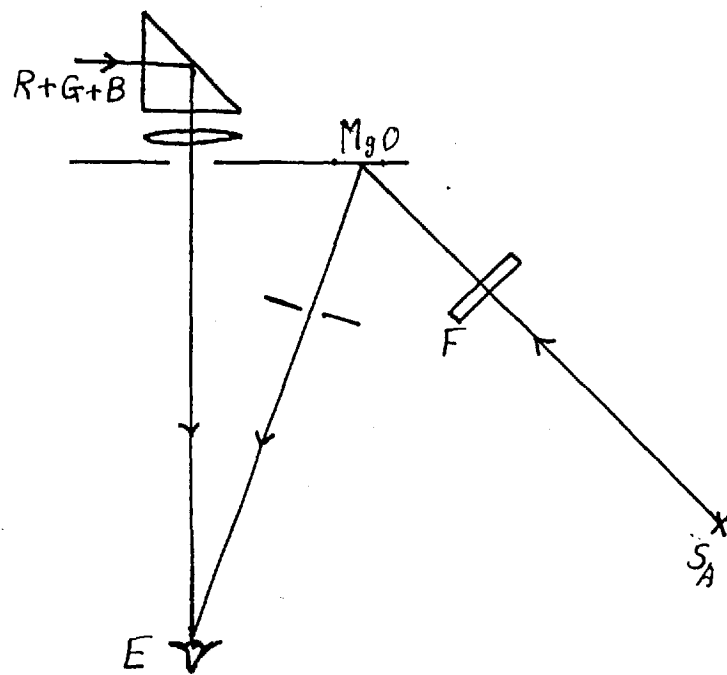


Figure (25) The system for the determination of the white point of the (RGB) system.

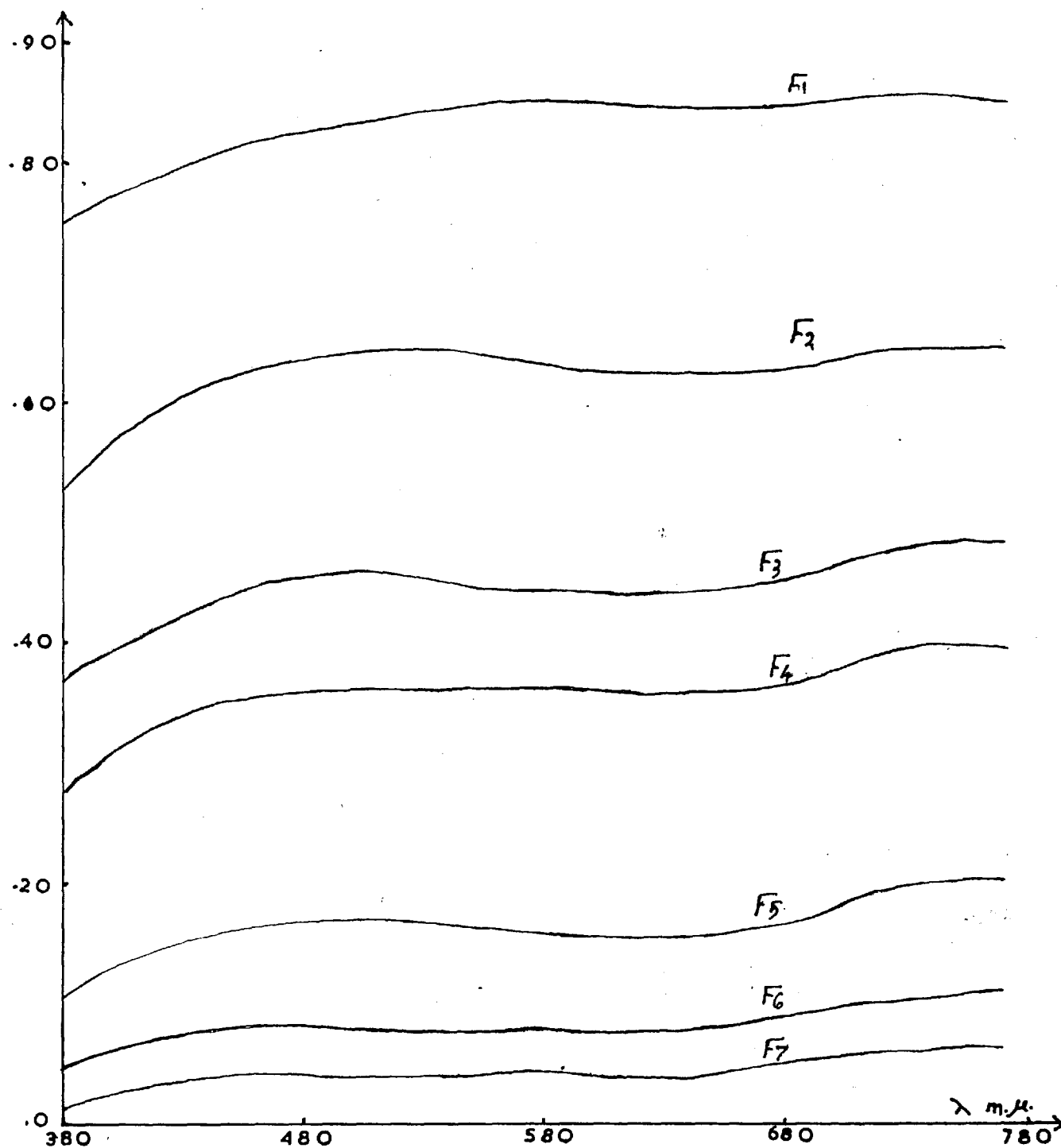


Figure (26) The spectral transmission energy distribution curves of the neutral density filters used.

method was used:

The comparison patch (a) figure(24) was filled with light from one primary colour filter (F) whose shutter was to be calibrated, and its surround was kept dark. The other patch (b) was of the same size as the comparison patch (angle of subtense =  $2.0^\circ$ ), and situated at the centre of the test patch, where it was usually used (angular separation between the centres of the two patches at the observer's eye =  $12^\circ$ ). It consists of a fresh magnesium oxide surface illuminated by a beam of light coming from the source  $S_2$  (adjusted to give standard source  $S_A$ ) through a neutral density filter (N). The reflected beam is received by the observer's right eye, after passing through another piece of the same primary colour filter (F), and an aperture (A) adjusted to allow the required size and position of the test patch. The appearance of the test patch was matched by the comparison patch in brightness, by adjusting the shutter of the primary colour under test. The matching was repeated eight times for each neutral density filter. This procedure was continued, using seven different neutral density filters of densities covering the whole range of the scale of the shutter.

The same procedure was carried out for the other two primary colour filters.

The spectrophotometric transmission characteristics of the neutral density filters used for calibration, were plotted by Beckman recording spectrophotometer. Their transmission factors  $T_\lambda$  were checked on the Wright photoelectric spectrophotometer at 10 points along the visible spectrum. The corrected transmission energy distribution curves are shown in figure(26). The density filters used showed to be practically

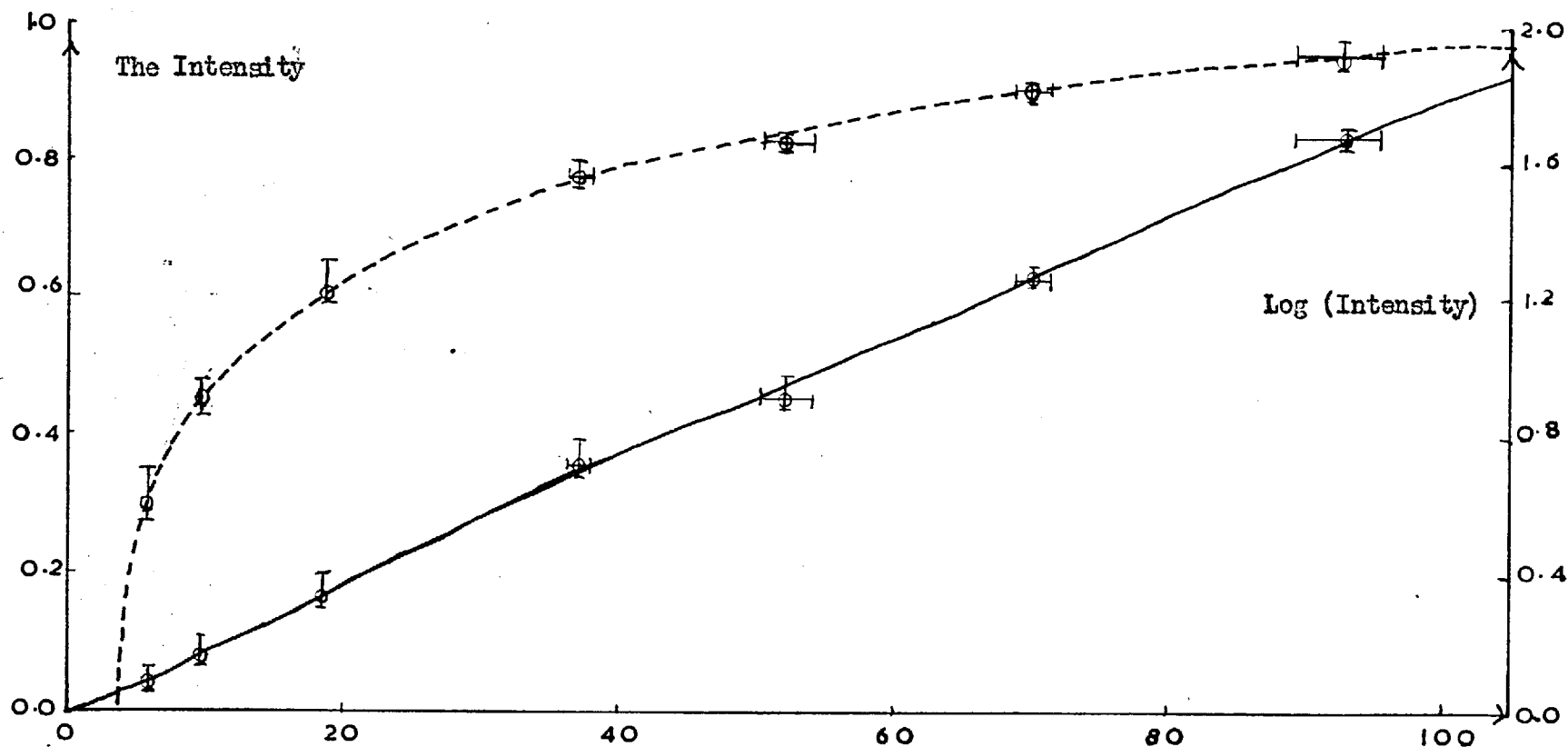


Figure (27) Calibration curve for the scale of the shutter of the Red Primary Colour Filter.  
 (—) represents the intensity, (---) represents Log. the intensity.  
 [ ] represents the limits of scale readings, I represents the tolerance in the neutrality of the neutral density filters used.

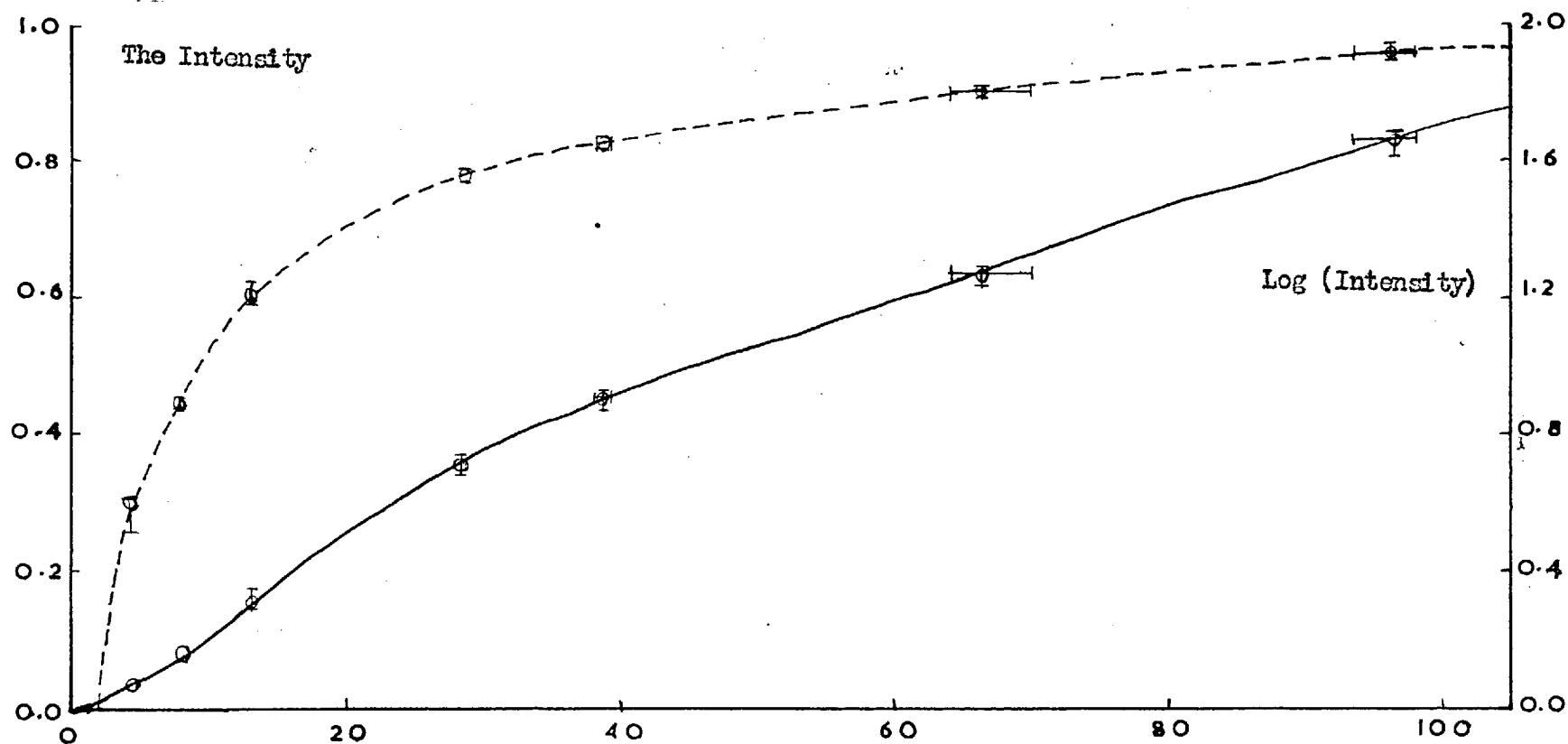


Figure (23) Calibration curve for the scale of the shutter of the Green Primary Colour Filter. The Intensity (—), Log (Intensity) (---), — represents the limits of scale readings, | represents the tolerance in the neutrality of the neutral density filter used.

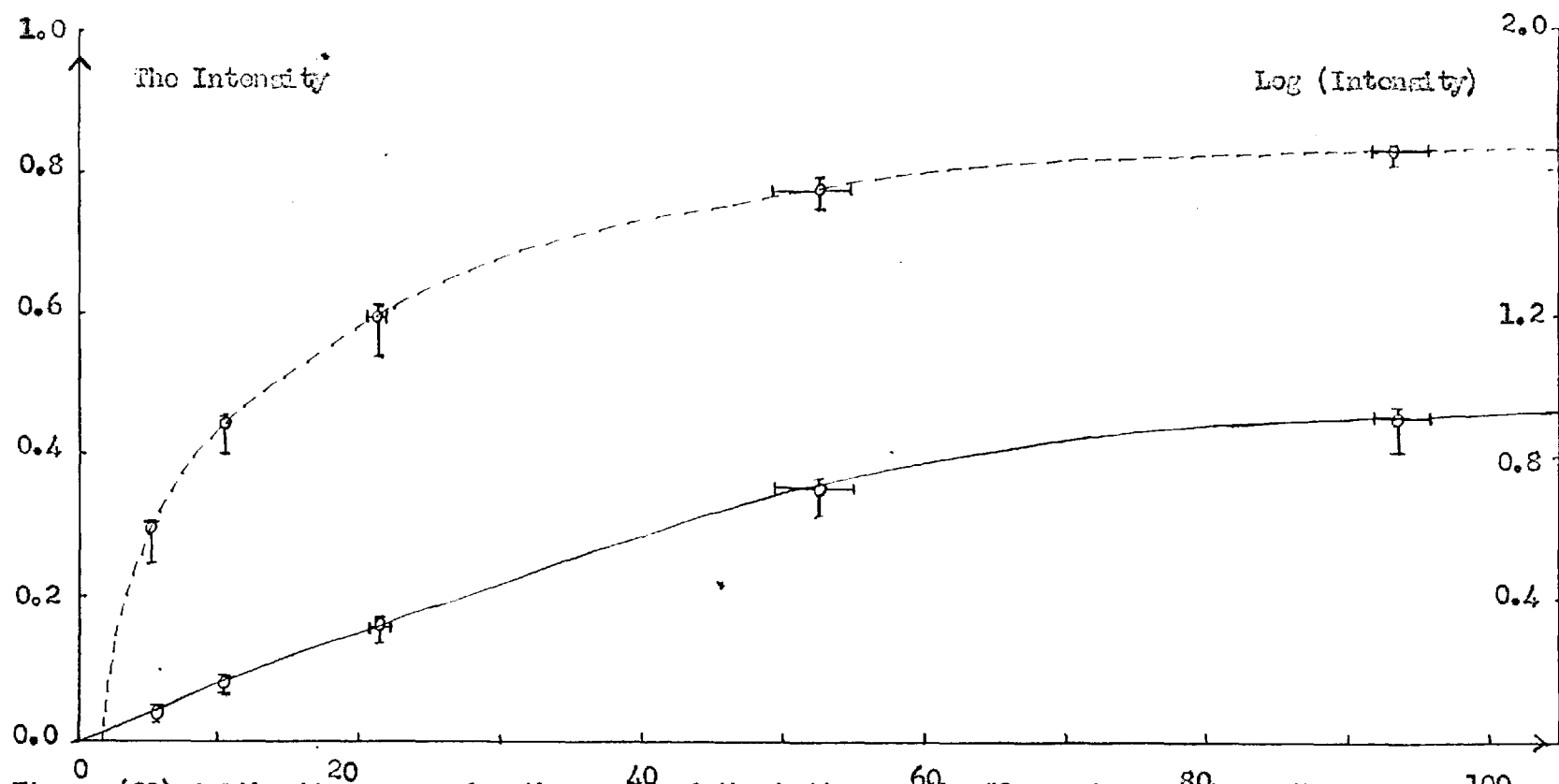


Figure (29) Calibration curves for the scale of the shutter of the Blue Primary Colour Filter. The Intensity (—). Log (Intensity) (---), —|— represents the limits of scale readings, | represents the tolerance in the neutrality of the neutral density filter.

TABLE (3) CALIBRATION OF THE SCALE OF THE RED PRIMARY FILTER.

| S   | T      | S   | T      | S   | T      | S   | T      | S   | T      |
|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|
| 1   | 0.0075 | 21  | 0.1841 | 41  | 0.4074 | 61  | 0.5623 | 81  | 0.7228 |
| 2   | 0.0135 | 22  | 0.1850 | 42  | 0.4150 | 62  | 0.5689 | 82  | 0.7295 |
| 3   | 0.0174 | 23  | 0.2042 | 43  | 0.4217 | 63  | 0.5781 | 83  | 0.7362 |
| 4   | 0.0251 | 24  | 0.2163 | 44  | 0.4315 | 64  | 0.5875 | 84  | 0.7413 |
| 5   | 0.0316 | 25  | 0.2265 | 45  | 0.4395 | 65  | 0.5943 | 85  | 0.7465 |
| 6   | 0.0377 | 26  | 0.2371 | 46  | 0.4488 | 66  | 0.6026 | 86  | 0.7534 |
| 7   | 0.0513 | 27  | 0.2483 | 47  | 0.4603 | 67  | 0.6109 | 87  | 0.7586 |
| 8   | 0.0617 | 28  | 0.2600 | 48  | 0.4656 | 68  | 0.6180 | 88  | 0.7674 |
| 9   | 0.0708 | 29  | 0.2723 | 49  | 0.4721 | 69  | 0.6281 | 89  | 0.7745 |
| 10  | 0.0766 | 30  | 0.2831 | 50  | 0.4786 | 70  | 0.6310 | 90  | 0.7798 |
| 11  | 0.0871 | 31  | 0.2985 | 51  | 0.4853 | 71  | 0.6442 | 91  | 0.7852 |
| 12  | 0.0955 | 32  | 0.3055 | 52  | 0.4943 | 72  | 0.6546 | 92  | 0.7907 |
| 13  | 0.1035 | 33  | 0.3162 | 53  | 0.5012 | 73  | 0.6109 | 93  | 0.7943 |
| 14  | 0.1135 | 34  | 0.3274 | 54  | 0.5129 | 74  | 0.6730 | 94  | 0.7962 |
| 15  | 0.1230 | 35  | 0.3388 | 55  | 0.5176 | 75  | 0.6808 | 95  | 0.7998 |
| 16  | 0.1318 | 36  | 0.3508 | 56  | 0.5260 | 76  | 0.6887 | 96  | 0.8035 |
| 17  | 0.1430 | 37  | 0.3631 | 57  | 0.5358 | 77  | 0.6950 | 97  | 0.8072 |
| 18  | 0.1531 | 38  | 0.3750 | 58  | 0.5408 | 78  | 0.7031 | 98  | 0.8110 |
| 19  | 0.1641 | 39  | 0.3846 | 59  | 0.5495 | 79  | 0.7112 | 99  | 0.8147 |
| 20  | 0.1738 | 40  | 0.3963 | 60  | 0.5559 | 80  | 0.7178 | 100 | 0.8185 |
| 101 | 0.8222 | 102 | 0.8260 | 103 | 0.8299 | 104 | 0.8337 |     |        |

TABLE (4) CALIBRATION OF THE SCALE OF THE GREEN PRIMARY FILTER

| S   | T      | S   | T      | S   | T      | S   | T      | S   | T      |
|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|
| 1   | 0.0075 | 21  | 0.2649 | 41  | 0.4764 | 61  | 0.5984 | 81  | 0.7211 |
| 2   | 0.0148 | 22  | 0.2793 | 42  | 0.4820 | 62  | 0.6026 | 82  | 0.7261 |
| 3   | 0.0251 | 23  | 0.2904 | 43  | 0.4875 | 63  | 0.6081 | 83  | 0.7311 |
| 4   | 0.0355 | 24  | 0.3041 | 44  | 0.4932 | 64  | 0.6166 | 84  | 0.7379 |
| 5   | 0.0457 | 25  | 0.3162 | 45  | 0.4989 | 65  | 0.6209 | 85  | 0.7430 |
| 6   | 0.0550 | 26  | 0.3311 | 46  | 0.5058 | 66  | 0.6281 | 86  | 0.7465 |
| 7   | 0.0676 | 27  | 0.3428 | 47  | 0.5117 | 67  | 0.6339 | 87  | 0.7499 |
| 8   | 0.0804 | 28  | 0.3573 | 48  | 0.5164 | 68  | 0.6412 | 88  | 0.7551 |
| 9   | 0.0971 | 29  | 0.3715 | 49  | 0.5236 | 69  | 0.6471 | 89  | 0.7603 |
| 10  | 0.1102 | 30  | 0.3819 | 50  | 0.5285 | 70  | 0.6577 | 90  | 0.7638 |
| 11  | 0.1259 | 31  | 0.3917 | 51  | 0.5370 | 71  | 0.6637 | 91  | 0.7656 |
| 12  | 0.1413 | 32  | 0.4037 | 52  | 0.5445 | 72  | 0.6699 | 92  | 0.7691 |
| 13  | 0.1560 | 33  | 0.4121 | 53  | 0.5521 | 73  | 0.6761 | 93  | 0.7745 |
| 14  | 0.1706 | 34  | 0.4188 | 54  | 0.5585 | 74  | 0.6823 | 94  | 0.7798 |
| 15  | 0.1820 | 35  | 0.4276 | 55  | 0.5649 | 75  | 0.6887 | 95  | 0.7871 |
| 16  | 0.1986 | 36  | 0.4365 | 56  | 0.5702 | 76  | 0.6950 | 96  | 0.7943 |
| 17  | 0.2109 | 37  | 0.4446 | 57  | 0.5754 | 77  | 0.7015 | 97  | 0.7998 |
| 18  | 0.2254 | 38  | 0.4550 | 58  | 0.5821 | 78  | 0.7080 | 98  | 0.8054 |
| 19  | 0.2371 | 39  | 0.4624 | 59  | 0.5875 | 79  | 0.7129 | 99  | 0.8091 |
| 20  | 0.2512 | 40  | 0.4688 | 60  | 0.5929 | 80  | 0.7161 | 100 | 0.8128 |
| 101 | 0.8166 | 102 | 0.8185 | 103 | 0.8204 | 104 | 0.8222 |     |        |



TABLE (5) CALIBRATION OF THE SCALE OF THE BLUE PRIMARY FILTER.

| S   | T      | S   | T      | S   | T      | S   | T      | S   | T      |
|-----|--------|-----|--------|-----|--------|-----|--------|-----|--------|
| 1   | 0.0060 | 21  | 0.1542 | 41  | 0.2884 | 61  | 0.4055 | 81  | 0.4529 |
| 2   | 0.0112 | 22  | 0.1614 | 42  | 0.2938 | 62  | 0.4083 | 82  | 0.4539 |
| 3   | 0.0191 | 23  | 0.1675 | 43  | 0.2992 | 63  | 0.4121 | 83  | 0.4550 |
| 4   | 0.0267 | 24  | 0.1754 | 44  | 0.3055 | 64  | 0.4150 | 84  | 0.4560 |
| 5   | 0.0363 | 25  | 0.1820 | 45  | 0.3112 | 65  | 0.4169 | 85  | 0.4560 |
| 6   | 0.0457 | 26  | 0.1884 | 46  | 0.3170 | 66  | 0.4207 | 86  | 0.4571 |
| 7   | 0.0537 | 27  | 0.1950 | 47  | 0.3251 | 67  | 0.4256 | 87  | 0.4571 |
| 8   | 0.0611 | 28  | 0.2018 | 48  | 0.3319 | 68  | 0.4276 | 88  | 0.4571 |
| 9   | 0.0692 | 29  | 0.2075 | 49  | 0.3388 | 69  | 0.4295 | 89  | 0.4571 |
| 10  | 0.0771 | 30  | 0.2138 | 50  | 0.3451 | 70  | 0.4325 | 90  | 0.4571 |
| 11  | 0.0843 | 31  | 0.2200 | 51  | 0.3532 | 71  | 0.4355 | 91  | 0.4571 |
| 12  | 0.0916 | 32  | 0.2280 | 52  | 0.3565 | 72  | 0.4365 | 92  | 0.4571 |
| 13  | 0.0982 | 33  | 0.2344 | 53  | 0.3656 | 73  | 0.4385 | 93  | 0.4581 |
| 14  | 0.1047 | 34  | 0.2432 | 54  | 0.3707 | 74  | 0.4406 | 94  | 0.4581 |
| 15  | 0.1122 | 35  | 0.2495 | 55  | 0.3741 | 75  | 0.4416 | 95  | 0.4581 |
| 16  | 0.1194 | 36  | 0.2559 | 56  | 0.3819 | 76  | 0.4426 | 96  | 0.4581 |
| 17  | 0.1265 | 37  | 0.2630 | 57  | 0.3873 | 77  | 0.4446 | 97  | 0.4592 |
| 18  | 0.1337 | 38  | 0.2692 | 58  | 0.3917 | 78  | 0.4467 | 98  | 0.4592 |
| 19  | 0.1410 | 39  | 0.2754 | 59  | 0.3981 | 79  | 0.4488 | 99  | 0.4592 |
| 20  | 0.1472 | 40  | 0.2818 | 60  | 0.4018 | 80  | 0.4508 | 100 | 0.4592 |
| 101 | 0.4603 | 102 | 0.4603 | 103 | 0.4603 | 104 | 0.4603 |     |        |

neutral, and all their curves are of the same shape, with their transmission factors little higher than the mean value near the red end of the spectrum and lower near the blue end. The mean transmission factor was calculated for each filter. The luminosity of the neutral density filters with respect to the three primaries used, can be calculated from these equations.

$$T_R = \frac{\int P_\lambda T_R \bar{y}_\lambda d\lambda}{\int P_\lambda R_\lambda \bar{y}_\lambda d\lambda}, \quad T_G = \frac{\int P_\lambda T_G \bar{y}_\lambda d\lambda}{\int P_\lambda G_\lambda \bar{y}_\lambda d\lambda}, \quad T_B = \frac{\int P_\lambda T_B \bar{y}_\lambda d\lambda}{\int P_\lambda B_\lambda \bar{y}_\lambda d\lambda} \quad (9)$$

for R, G and B respectively. Where  $P_\lambda$  is the spectral energy distribution of the source,  $T_\lambda$  is the transmission factor of the neutral density filter,  $R_\lambda$ ,  $G_\lambda$  and  $B_\lambda$  are the transmission factors of the red, green and blue primary filters, and  $\bar{y}_\lambda$  is the y distribution coefficient for equal energy stimulus; at wavelength  $\lambda$ .

But the differences between the values calculated from these equations for one of the neutral density filters, and the average values of its transmission factors, are 0.4% for both green and blue, and 1.0% for red which are practically insignificant.

The relation between the scale reading of the shutter of each primary colour filter and the intensity ( = transmission factor of the corresponding neutral density filter ) is plotted. The calibration curves are shown in figures (27, 28, and 29.) They are not exactly straight lines as was expected. The curve of the blue primary filter is flatter than those corresponding to red and green, which shows that the blue absorption in the optical system of the comparison patch is relatively high. Tables (3, 4 & 5) give the calibration of the scales of the primary filters in terms of intensity of stimulus, from which the final results throughout this work were calculated.

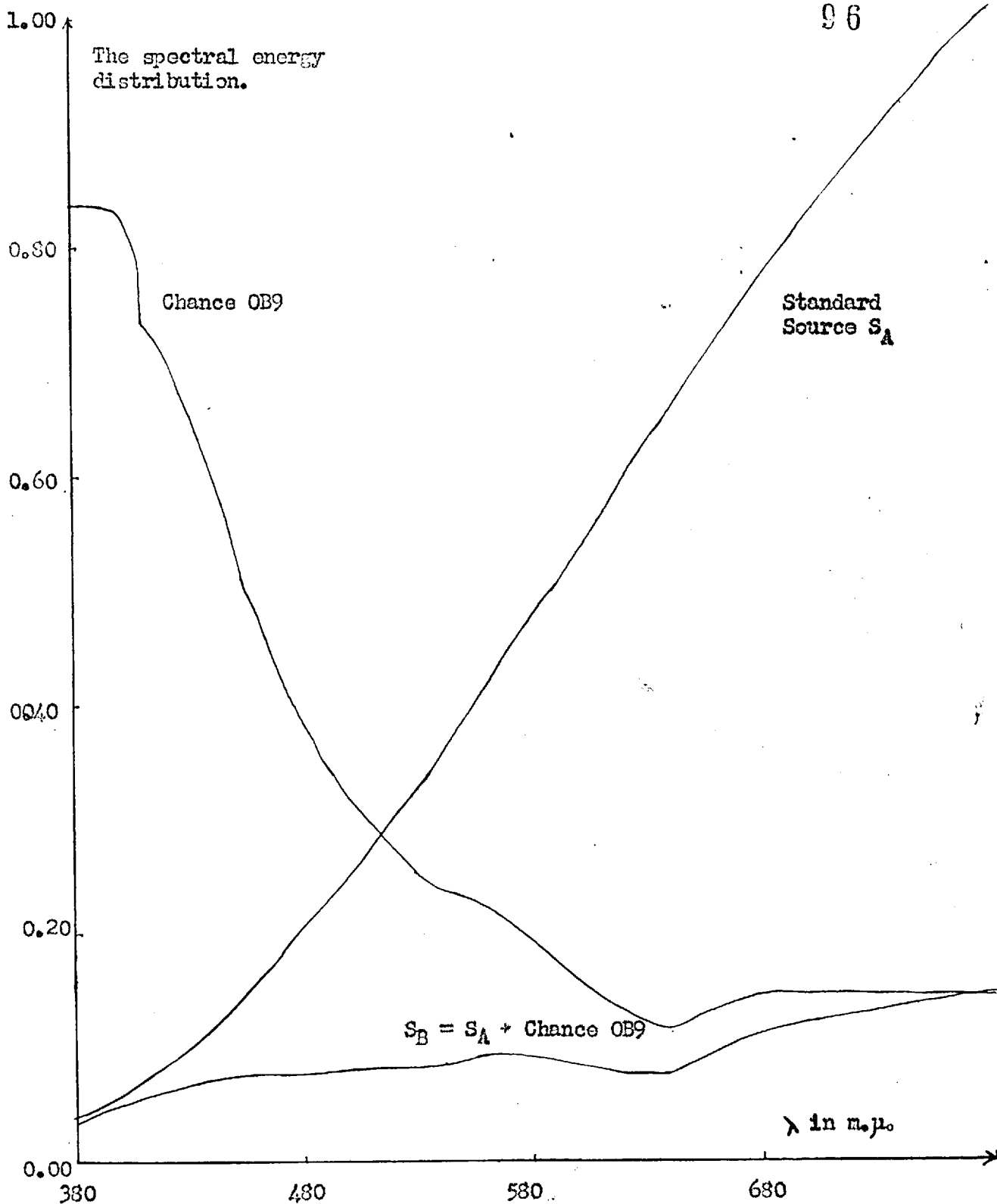


Figure (30) The spectra energy distribution curves of standard source  $S_A$ , Chance OB9 filter, and the resultant of their combination (nearly standard source  $S_B$ ).

(D) DETERMINATION OF THE WHITE POINT IN THE (RGB) SYSTEM.

In this work a chance OB9<sup>(89)</sup> filter was used to transform  $S_A$  to  $S_B$ , this being generally accepted as a white source. (Figure 30) shows the energy distribution of source  $S_A$ , the measured transmission distribution of chance OB9 filter used, and the combined energy distribution of both. Table (6) shows the chromaticity co-ordinates of the combination compared with those of the standard  $S_B$ . It is obvious that the differences between the two are so small that they can be neglected.

To determine the white point in the [R,G,B] system, the following procedure was used. Chance OB9 filter F was placed in the path of the beam of light coming from source  $S_3$  (adjusted to give  $S_A$ ) (figure 25, the combination, being the white source used. A fresh magnesium oxide surface (b) was placed at the test patch and illuminated by a beam of light coming from this white source. The reflected beam was received by the observer's right eye through an aperture (A) adjusted to allow the proper size ( $2^\circ$ ) and place of the test patch. This was matched by the correct mixture of R,G,B in the comparison patch, the process being repeated 10 times to get as accurate mean tristimulus values as possible.

Assume that the tristimulus equation of the white in [R G.B.] system is;  $w[W] = r_s [R] + g_s [G] + b_s [B]$  (10)

To render this equation or any other equation representing any match obtained by the colorimeter as :

$$c [C] = r [R] + g [G] + b [B] \quad (11)$$

into trichromatic units, the coefficients of [R], [G] and [B] in each should be divided by  $r_s$ ,  $g_s$  and  $b_s$  respectively, and each of the resulting coefficients divided by their sum. This leads to the following

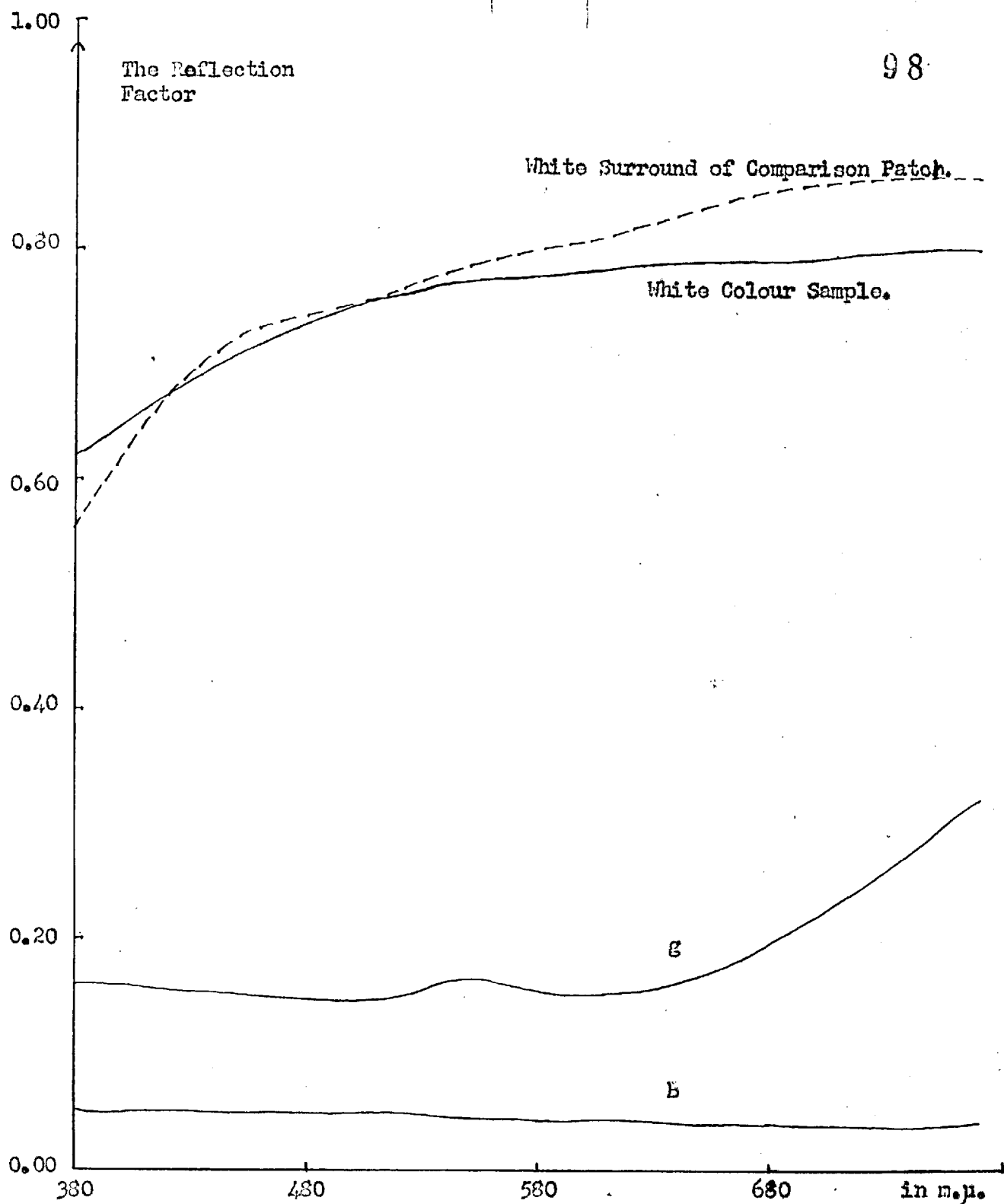


Figure (31) The Spectral reflection curves of the White Surround of the Comparison Patch, the White, Grey and Black Paper Colour Samples.

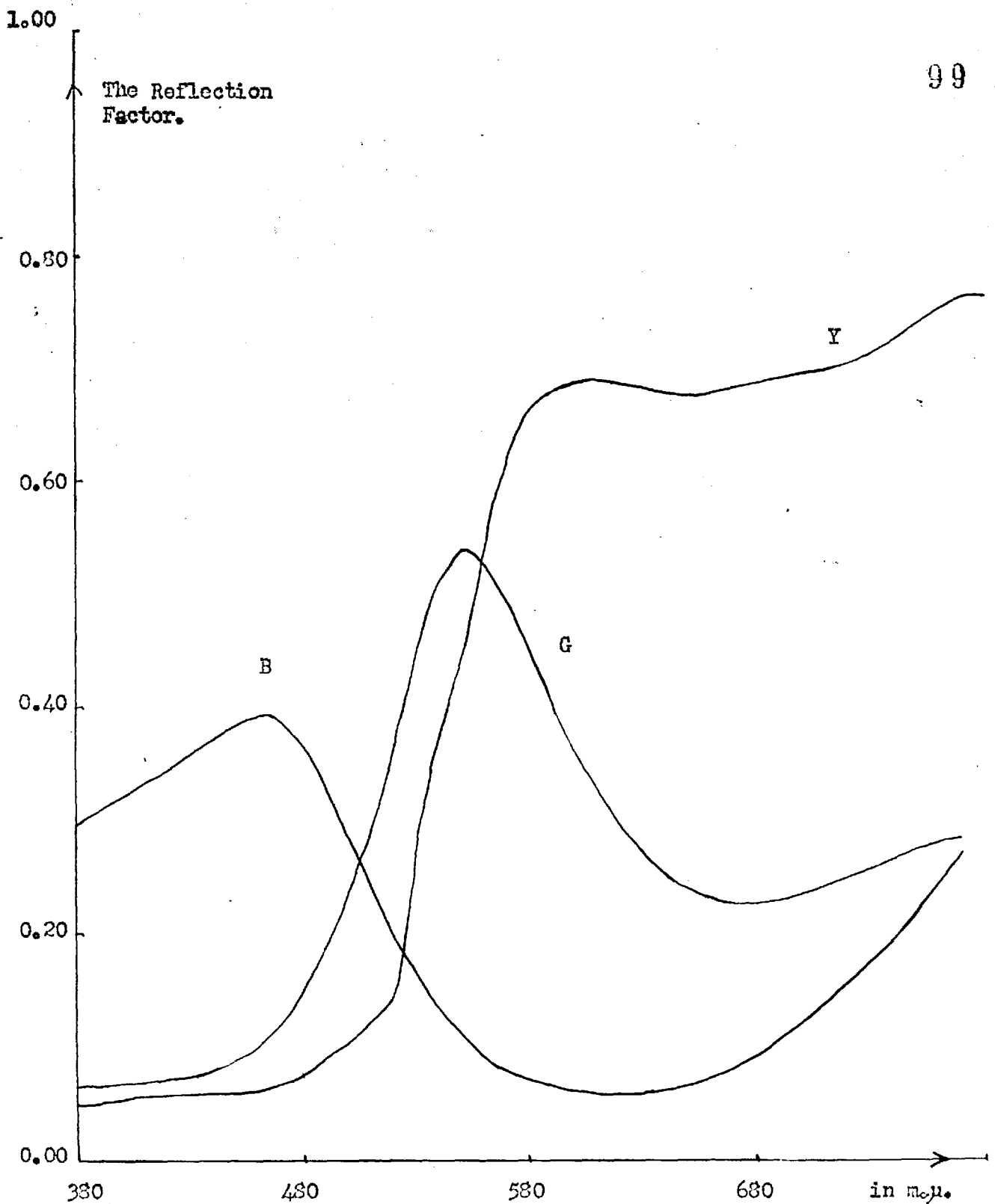


Figure (32) The Spectral reflection curves of the Blue, Green and Yellow paper colour samples.

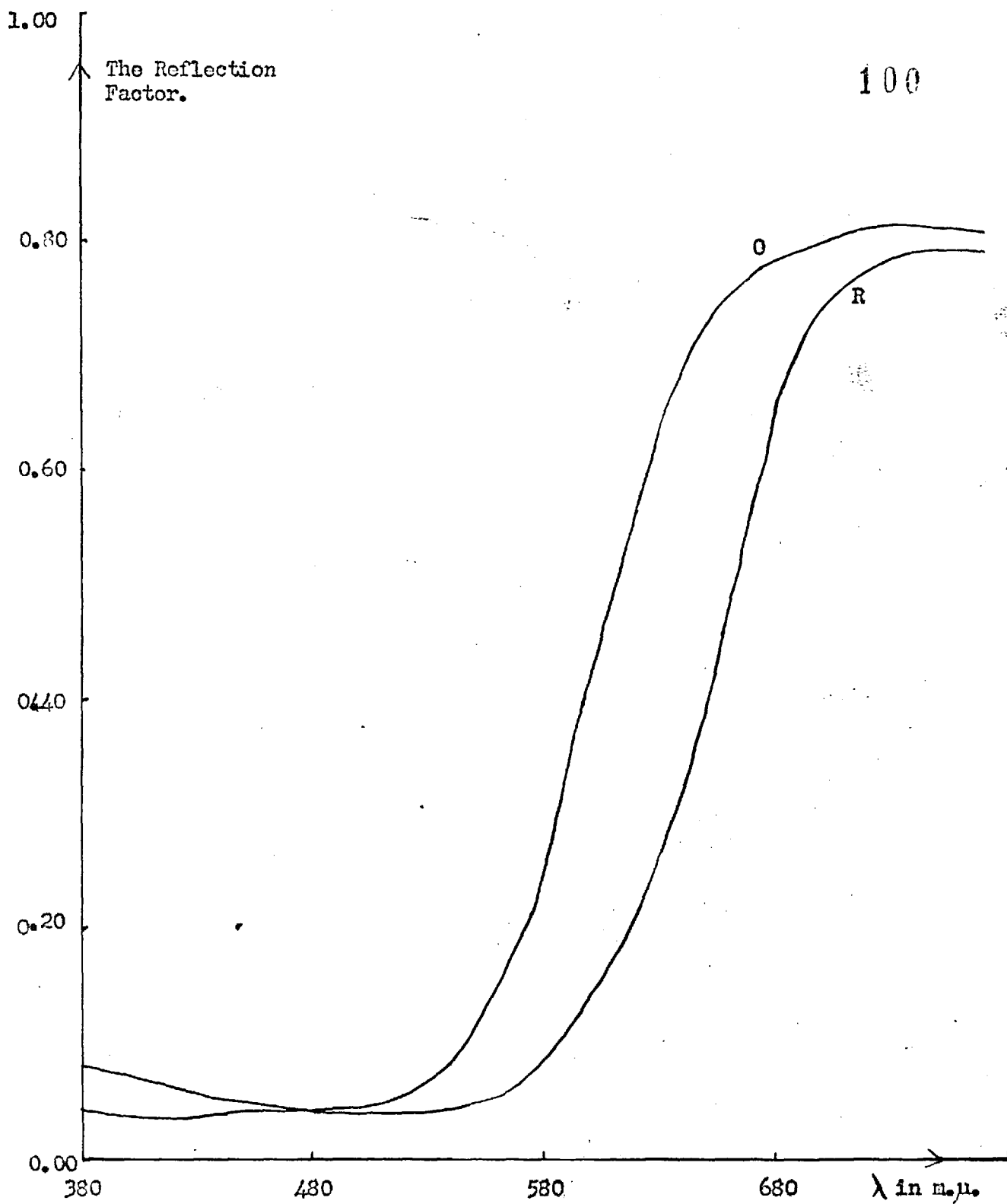


Figure (33) The Spectral reflection curves of the Orange and Red paper colour samples.

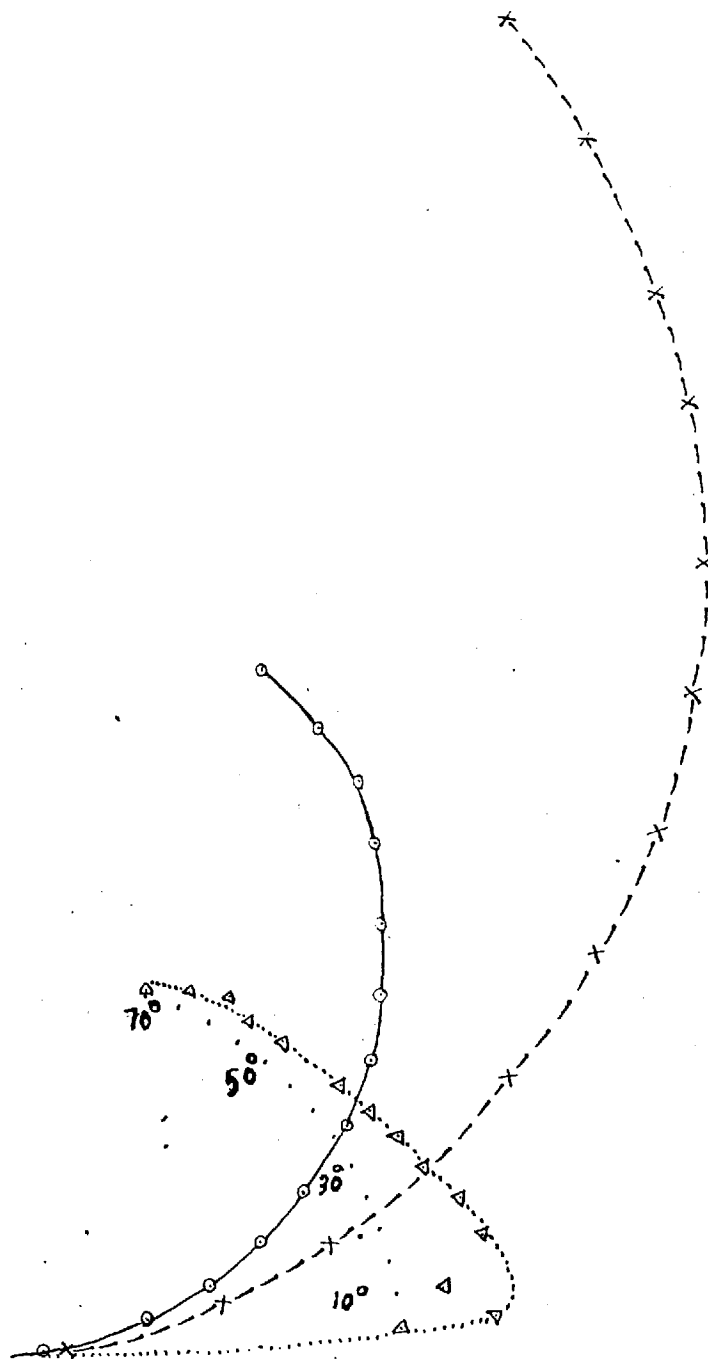


Figure (34) A half of the polar distribution curve of reflection, the green paper colour sample at  $\lambda = 580 \text{ m}\mu$ , Normal Incidence. Reflection on sample (—), Reflection on MgO (---), Reflection Factor of the Sample (....).



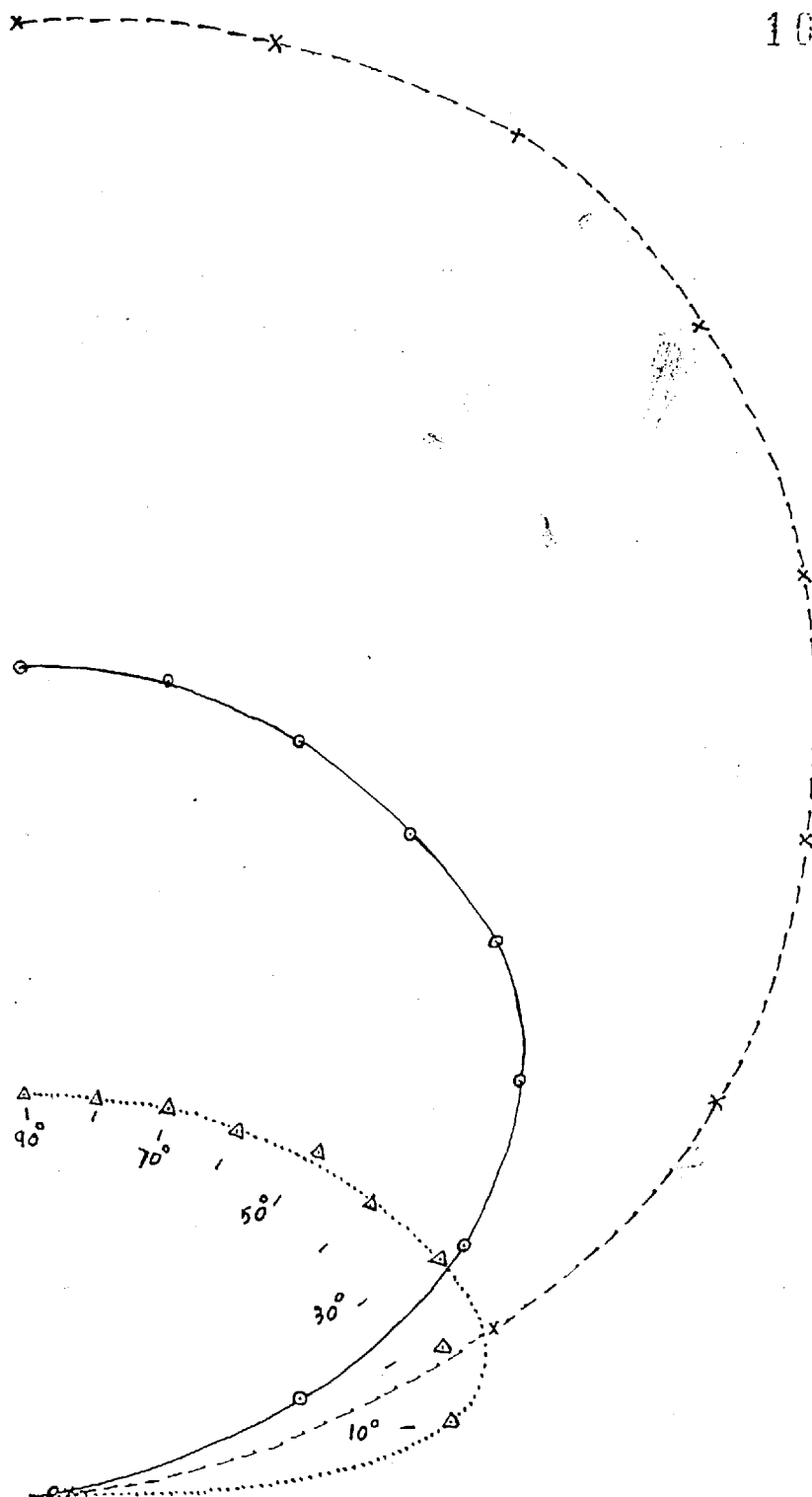


Figure (35) A half of the polar distribution curve of reflection on the Green paper colour sample at  $\lambda = 580 \text{ m.}\mu.$ , at  $45^\circ$  incidence, Reflection on sample (—), Reflection on Mg O (— — —), Reflection Factor of the sample (....).

TABLE (7) THE CHROMATICITY CO-ORDINATES FOR COLOURED PAPER SAMPLES USED AND THE WHITE SURROUND OF COMPARISON PATCH.

| SAMPLE                              | X       | Y       | Z       | X+Y+Z    | x      | y      | Z      | Y       |
|-------------------------------------|---------|---------|---------|----------|--------|--------|--------|---------|
| WHITE                               | 85.5220 | 77.6239 | 25.5320 | 188.6779 | 0.4533 | 0.4114 | 0.1353 | 0.7765  |
| YELLOW                              | 68.5173 | 53.6030 | 2.6787  | 124.7990 | 0.5490 | 0.4295 | 0.0215 | 0.5360  |
| BLUE                                | 9.3262  | 10.5520 | 12.8185 | 32.6967  | 0.2852 | 0.3227 | 0.3921 | 0.1055  |
| GREEN                               | 38.4345 | 40.6421 | 4.5243  | 83.6009  | 0.4597 | 0.4862 | 0.0541 | 0.4064  |
| GREY                                | 17.1990 | 15.6237 | 5.2716  | 38.0943  | 0.4515 | 0.4101 | 0.1384 | 0.1562  |
| RED                                 | 18.8503 | 10.9136 | 1.7481  | 31.5120  | 0.5982 | 0.3463 | 0.0555 | 0.1091  |
| ORANGE                              | 45.1067 | 26.8693 | 1.4412  | 73.4172  | 0.6144 | 0.3660 | 0.0196 | 0.2687  |
| BLACK                               | 4.7429  | 4.4535  | 1.7404  | 10.9368  | 0.4337 | 0.4072 | 0.1591 | 0.04454 |
| WHITE<br>SURROUND OF<br>COMP. PATCH | 83.4203 | 79.3875 | 25.9914 | 193.7992 | 0.4562 | 0.4096 | 0.1341 | 0.7939  |

two equations:

$$[W] \equiv 0.3333 [R] + 0.3333 [G] + 0.3333 [B] \quad (12)$$

$$[C] \equiv r' [A] + g' [G] + b' [B] \quad (13)$$

Equations (8) or (8)' can be substituted directly in equation (13) to get the tristimulus values of colour [C] in the C.I.E. system.

(E) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE COLOURED PAPER SAMPLES AND THE WHITE SURROUND OF THE COMPARISON PATCH:

The same procedure as that used for the three primary colour filters, was followed to obtain the spectrophotometric reflection characteristics and to calculate the C.I.E. tristimulus coefficients of the coloured paper samples used in this work as test colours and backgrounds, (i.e. black, grey, white, orange, yellow, green and blue) and also the white surround of the comparison patch. Figures (31,32,33) show their reflection energy distribution curves. Table (7) shows their C.I.E. specifications.

(F) THE POLAR DISTRIBUTION CURVES OF COLOURED PAPER SAMPLES USED.

Since the inclination of the test patch affects the colour contrast phenomena, the reflection on the colour samples at different angles for normal and  $45^\circ$  incidence at the wavelength of peak reflectance (for each), were measured by Wright Photoelectric Spectrophotometer, and their polar distribution curves were traced. Figures (34,35) show typical polar distribution curves for reflection on green sample at  $\lambda = 550 \text{ m}\mu$ . (compared with that of  $\text{MgO}$ ) and its reflection factor for normal and  $45^\circ$  incidence respectively. The polar distribution curves for all other

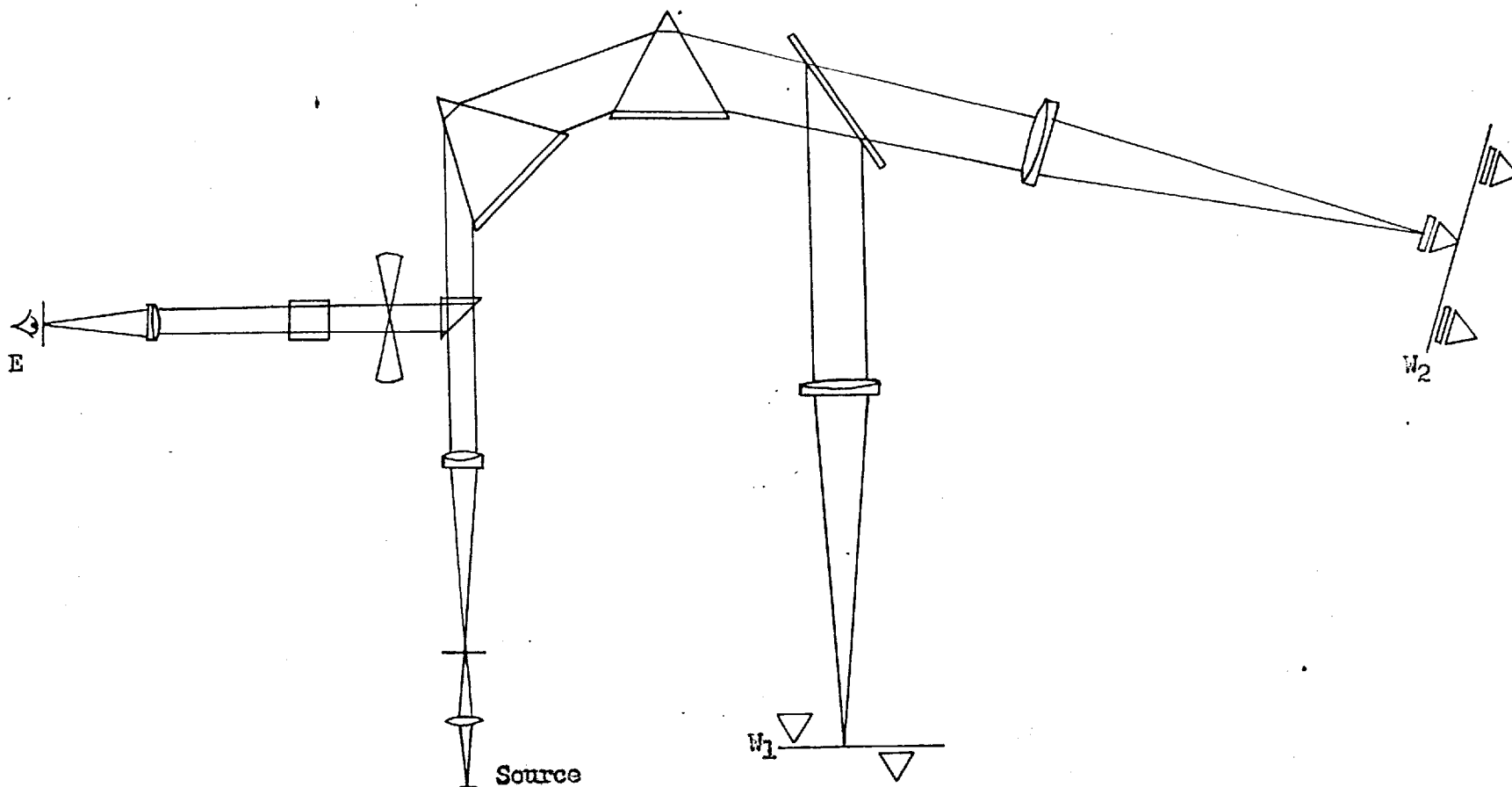


Figure (36) The Optical System of the Wright Colorimeter. (Plan View not to scale)

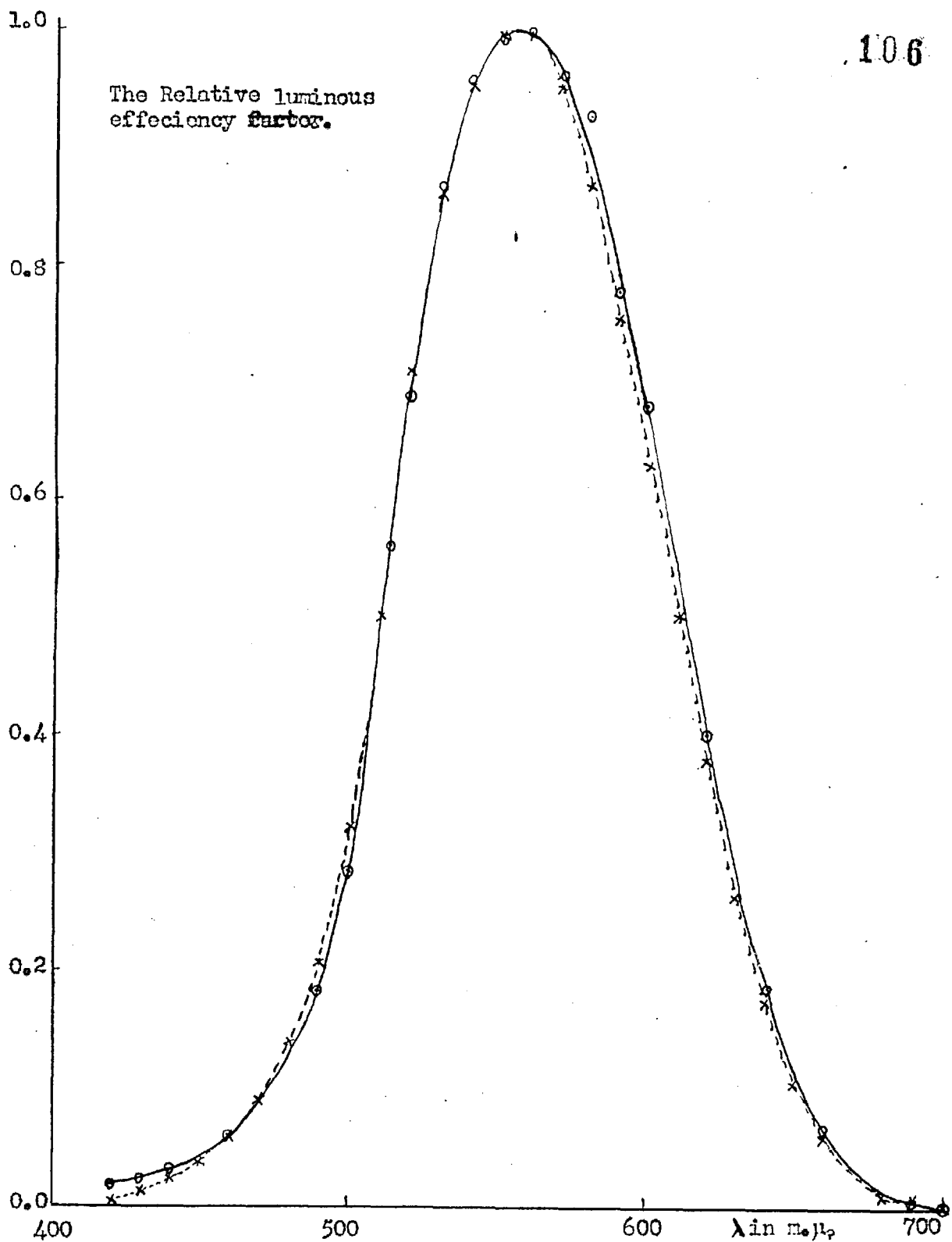


Figure (37) The Relative luminous efficiency curves of the author (—), and of the C.I.E. standard observer (---)

coloured paper samples are of exactly the same shape but differ amongst each other in magnitude. The figures show that the colour samples used are nearly perfect diffusing surfaces.

### (G) THE COLOUR VISION CHARACTERISTICS OF THE OBSERVER.

The work done using the colorimeter, being carried on by the author, it was quite important to ensure that his colour vision was normal. He made no mistakes in the Ishihara Test<sup>(47)</sup> so his colour vision characteristics were measured using Wright trichromatic Colorimeter<sup>(55)</sup> Figure (36).

#### (1) RELATIVE LUMINOUS EFFICIENCY CURVE:

The "flicker method" described by Wright,<sup>(22)</sup> was used. The intensities of various monochromatic stimuli taken from spectrum  $W_1$  (every 20 m. $\mu$ ) required to match a white source of constant intensity were measured. A rotating sector was used to enable the eye to receive alternating beams of monochromatic and white light. For matching, the two beams must be of equal brightness and in this case no flicker can be seen, as the field alternates. Figure (37) shows the relative luminosity curve of the observer compared with that of the C.I.E. standard observer. It is clear that the two curves are in good agreement, except at the blue end where the observer's curve is slightly higher.

#### (2) THE SPECTRAL TRICHROMATIC COEFFICIENTS.

These were measured in Wright's system of plotting chromaticities. Monochromatic stimuli from spectrum  $W_1$  (every 10 m. $\mu$ ) were matched with an additive mixture of three monochromatic primary stimuli (0.65, 0.53, and 0.46  $\mu$ ) from spectrum  $W_2$ . In Wright's system, instead of weighting the results by three correction factors to enable equal values of R, G and B to match a white light (as in C.I.E. system), the results were

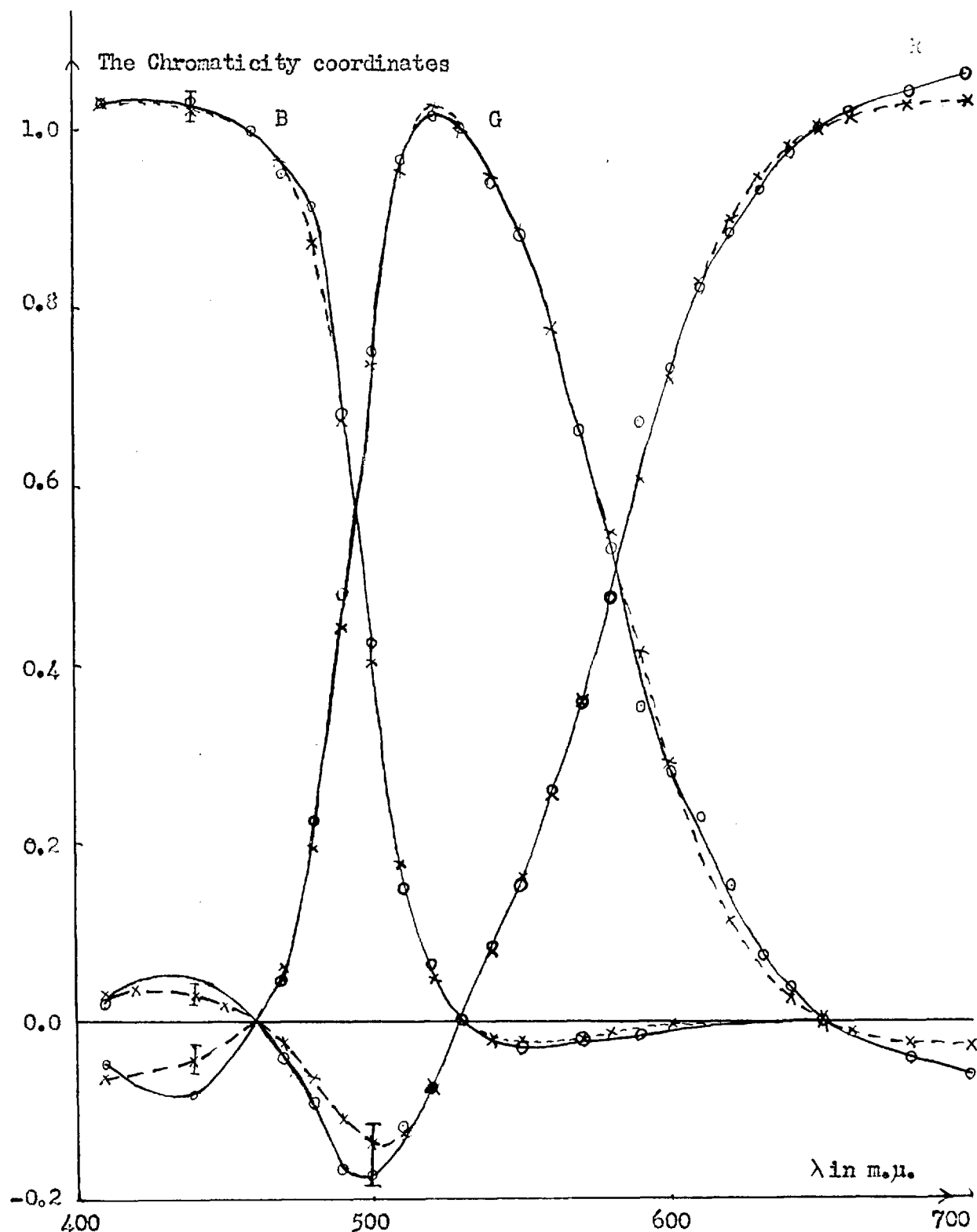


Figure (36) The Chromaticity Coordinates of the Spectrum for the author(—), and the C.I.E. standard observer (---).

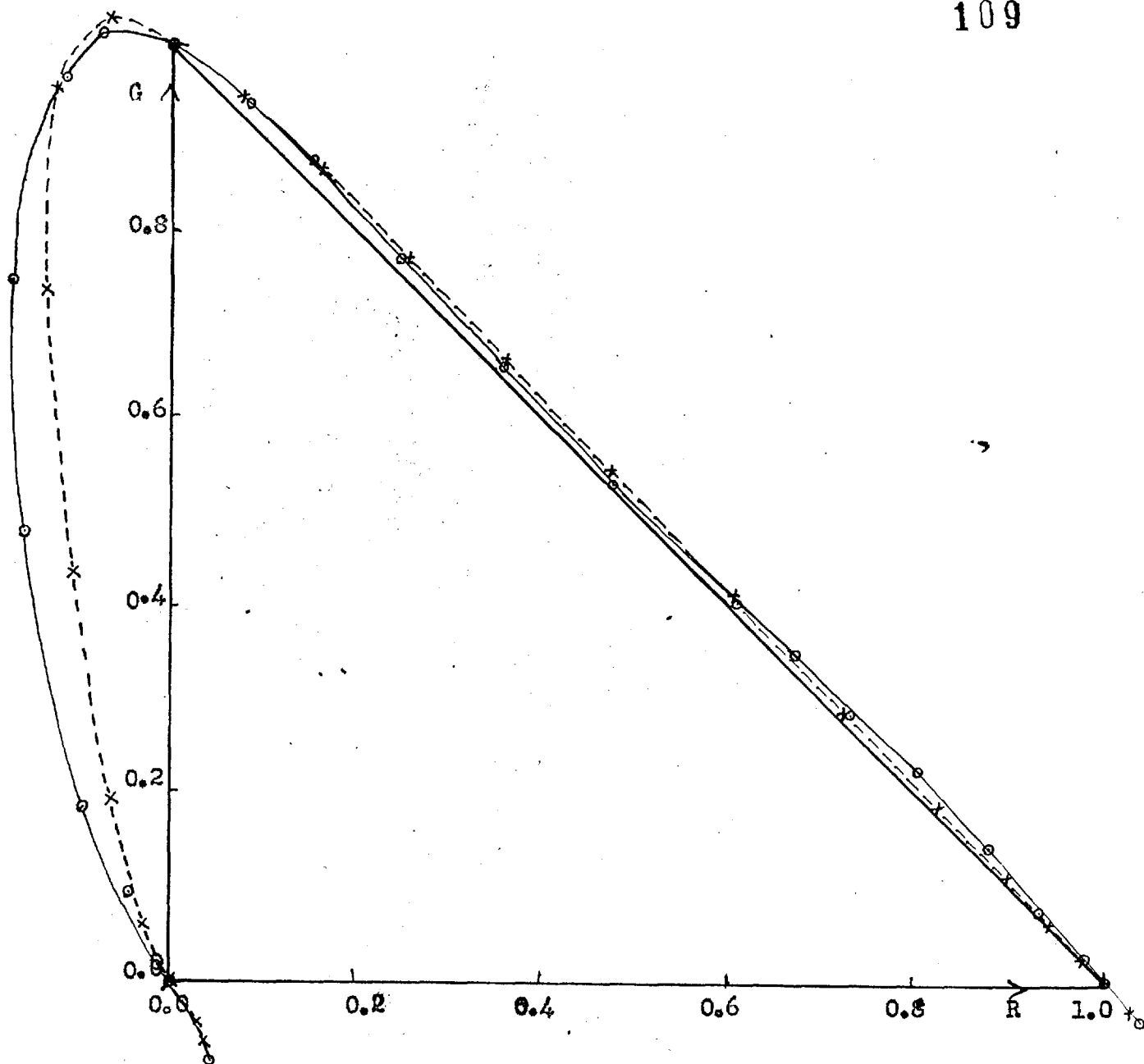


Figure (39) The Spectrum Locus in Wright's System for the author (—), and for the G.I.E. standard observer (---).



weighted by two correction factors (for Red and Blue) enabling equal values of monochromatic red ( $0.65 \mu$ ) and green ( $0.53 \mu$ ) to match monochromatic yellow ( $0.5825 \mu$ ), and equal values of monochromatic green ( $0.53 \mu$ ) and blue ( $0.46 \mu$ ) to match monochromatic blue-green ( $0.4940 \mu$ ).

Figure (38) shows the observer's curves of the spectral trichromatic coefficients compared with those of the C.I.E. standard observer. The agreement between the two systems of curves is obvious, except at the blue end of the spectrum (from  $0.40$  to  $0.50 \mu$ ) where Wright's 10 observers vary much amongst themselves (the extent of their variation is shown by I in figure (38)).

Figure(39) shows the spectrum locus (obtained from these results) of the observer compared with that of the C.I.E. standard observer. The agreement between the two loci is obvious, except at the blue end of the spectrum.

### (3) WAVELENGTH DISCRIMINATION.

The data of wavelength discrimination show the ability of the observer to distinguish between monochromatic stimuli differing in wavelength. Wright's method in measuring the just noticeable difference in wavelength discrimination was used. The two halves of the field of view in Wright colorimeter was filled with monochromatic light of the same wavelength  $\lambda$ , one half from spectrum  $W_2$  and the other from spectrum  $W_1$ . Then the roof prism in spectrum  $W_1$  is moved slightly along its slide until a difference in hue between the two halves can just be detected (both halves being maintained at the same brightness by adjusting the photometer wedge in the spectrum  $W_2$ ). The experiment was then repeated by moving the roof prism in the opposite direction. The readings were

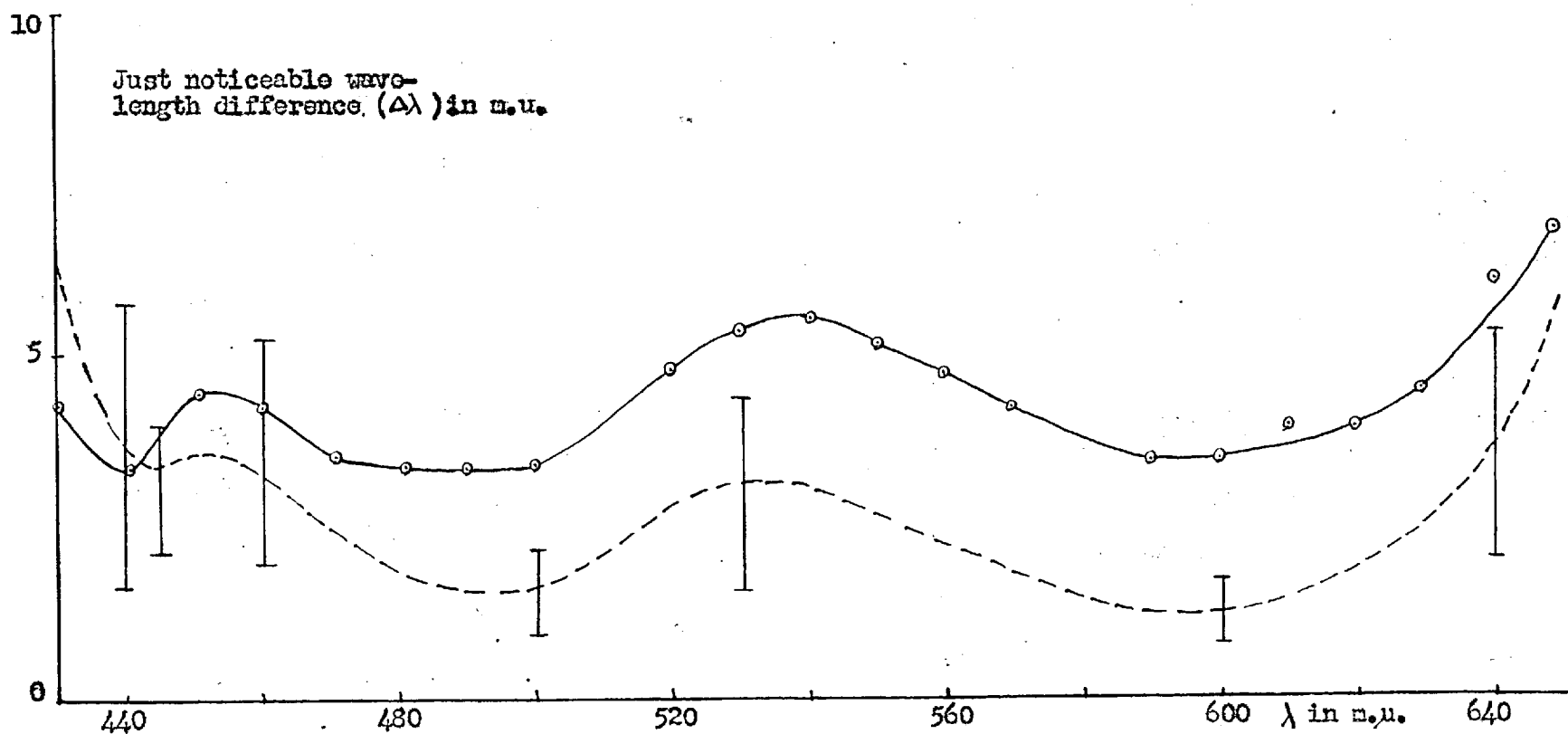
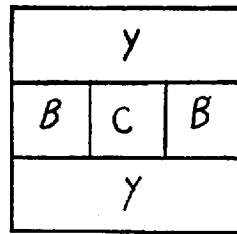


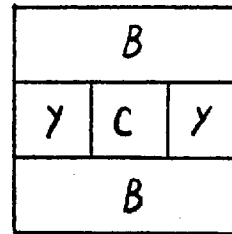
Figure (40) The wave length discrimination curves for the author (—), and the average of Wright's five observers (---).

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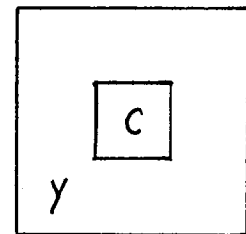
then repeated three times and an average value of the shift for both sides ( $\Delta\lambda$ ) was obtained. Figure (42) shows the wavelength discrimination of the observer compared with the mean of Wright's five observers. It is obvious that the general shape of the curves agree with the same positions of maxima and minima. Wright's observers vary very much amongst themselves, the extent of their variation is shown by I in figure (40) in the value of ( $\Delta\lambda$ ) but agree in the general shape of the curve.



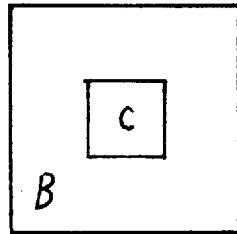
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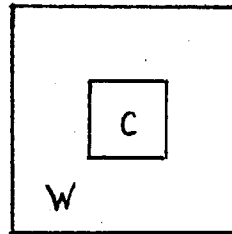
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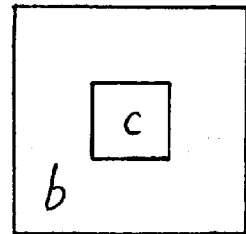
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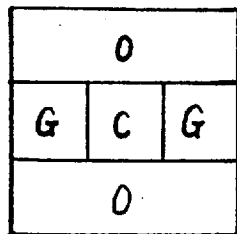
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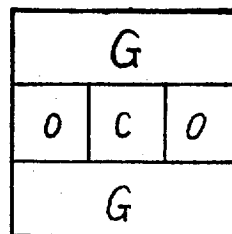
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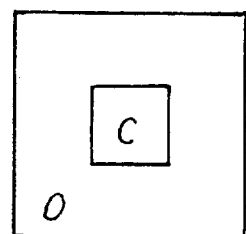
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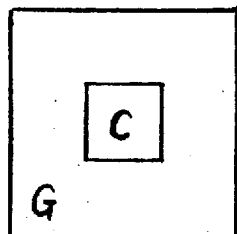
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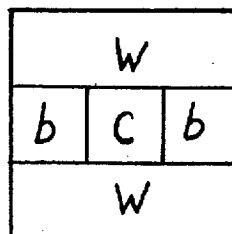
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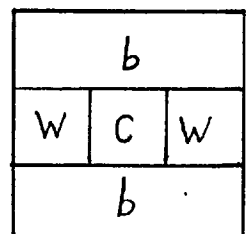
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Figure (41) The different one colour and two colour surrounds used in this investigation and the suffixes used to represent them. (C) represents any test colour, Yellow (Y), Blue (B), Orange (O), Green (G), White (W), and Black (b).

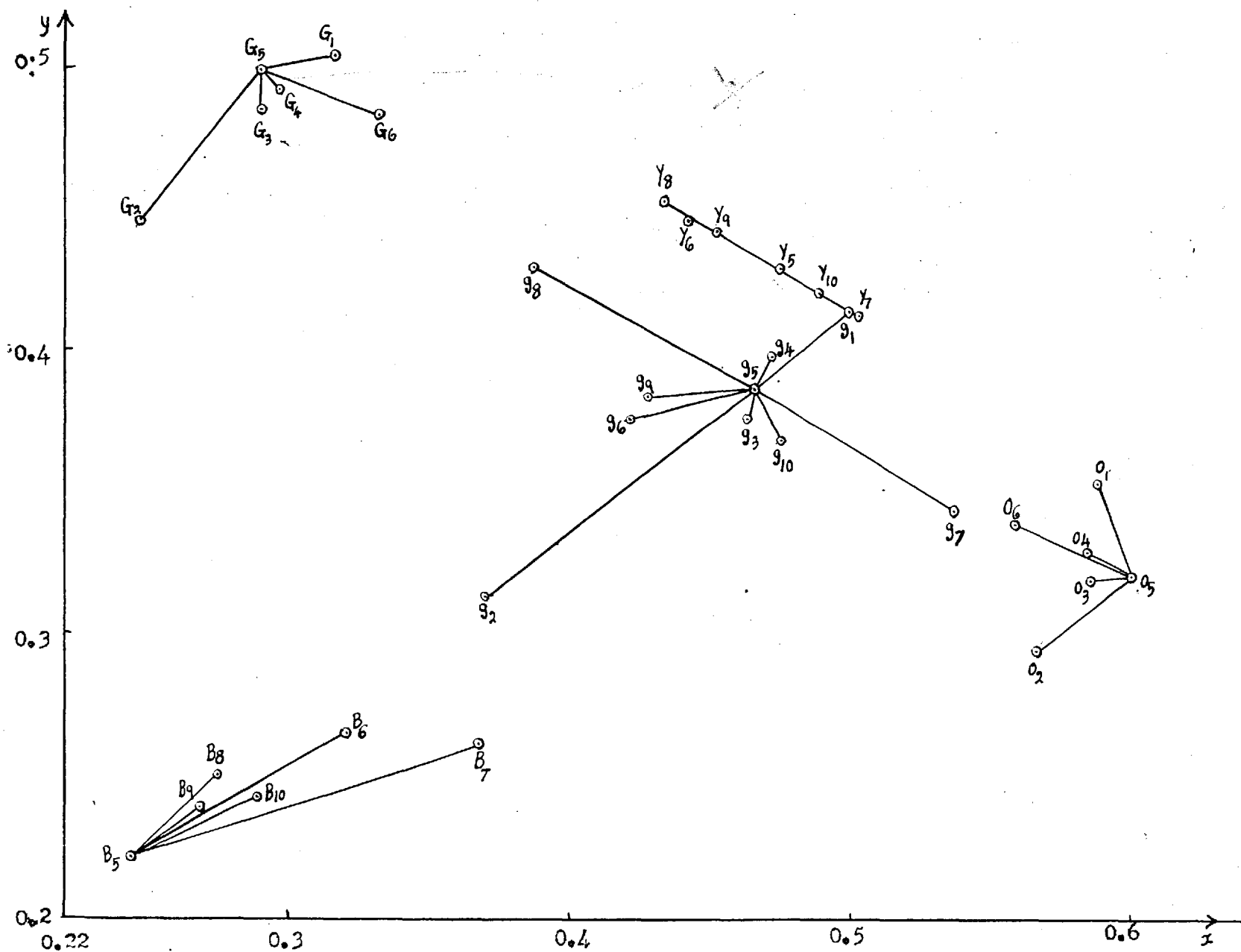


Figure (42) The chromaticities of the colour appearance of all the test colours against all the backgrounds used for the compound pattern of 15' element angle of subtense and 20° inclination.

## CHAPTER V

### THE EFFECTS OF DIFFERENT SIMPLE AND COMPOUND COLOUR SURROUNDS ON THE APPEARANCE OF DIFFERENT TEST COLOURS, AS MEASURED BY THE COLORIMETER.

The test colours used in this investigation are orange (O), yellow (Y), green (G), blue (B) and grey (g). The surrounds used are white (W), black (b), yellow (Y), blue (B), orange (O) and green (G). They are arranged in one colour and two colour surrounds, as shown in figure (41) which gives the suffixes used to represent them. The same suffixes are used to represent both the simple and compound pattern of the surround made of the same colours (figure 18).

#### (A) THE CASE OF THE COMPOUND PATTERN:

Figure (42) gives a general idea of the effects of all different colour surrounds applied to all the test colours used. This represents the case of the biggest differences in colour appearance, i.e. case of small compound pattern (element angle of subtense =  $15'$ ) at  $20^\circ$  inclination. It is clear from this figure and in all other cases mentioned later, that for all the test colours used, the point corresponding to the white surround is central with respect to the points corresponding to all other surrounds. That is why the shifts due to different surrounds are referred in this work to the case of white surround. It is clear to deduce the following general empirical rules from this figure:

Rule (1) The shifts due to two colour surrounds are bigger than those due to one colour surrounds.

Rule (2) The shifts due to one colour surrounds are generally away from that colour. This is obvious in the case of yellow and grey samples. In the cases of orange and green test colours on yellow and blue surrounds, it can be seen that the point corresponding to yellow surround is shifted

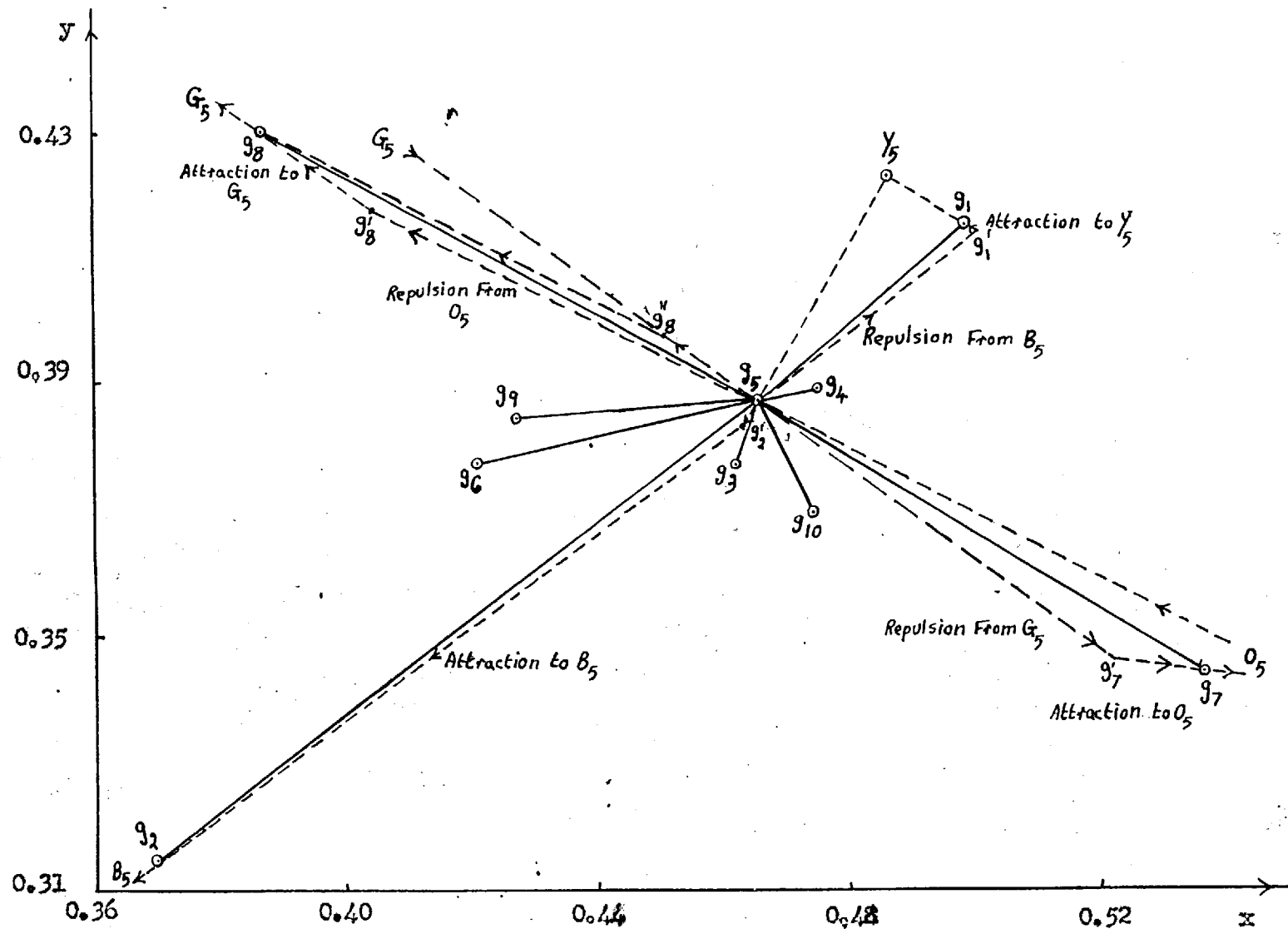


Figure (43) The chromaticities of the appearance of the Grey Test Colour against all the backgrounds used for the compound pattern of 15' element angle of subtense and 20° inclination.

away from the yellow further than that corresponding to the blue surround and vice-versa. The same thing applies for the case of blue test colour on orange and green surrounds.

Rule (3): The shifts due to two colour surrounds are generally away from the colour of the stripe on which the test colour is mounted and towards that of the other two side stripes. The first rule can be seen as a direct corollary to this third rule. In the case of one colour surround, if we imagine that this surround is divided into stripes of the same colour, then the effect of the stripes on which the test colour is mounted is that of repulsion, and that of the other stripes is that of attraction. Since both the attraction and repulsion is due to the same colour of the surround, then the resultant effect due to this colour surround is reduced. While in the case of the two colour surrounds that are located on the chromaticity chart in two opposite directions relative to the test colour, the combined effect is enhanced.

Rule (4) The shifts due to black surround are generally towards desaturation.

For more details, figures (43-47) inclusive, show on a larger scale, the cases of grey, orange, yellow, green and blue test colours respectively for the same conditions shown in figure (42). A brief account of the changes in colour appearance due to different surrounds in the cases of these test colours will now be given.

(I) THE GREY TEST COLOUR: Figure (43)

The grey test colour shows the most striking colour contrast effects, because it appears rather dark neutral on a white surround, brighter neutral on a black surround, yellow, blue, orange and green on the other surrounds. These apparent colours are much more saturated for the two



colour surrounds than for the one colour surrounds. The four empirical rules just mentioned before, are obvious in this case and can be described as follows:

(1) The shifts  $g_5 g_1, g_5 g_2, g_5 g_7$  and  $g_5 g_8$  due to two colour surrounds are bigger than shifts  $g_5 g_4, g_5 g_3, g_5 g_{10}$  and  $g_5 g_9$  due to one colour surrounds respectively. That is why the apparent colours in the case of two colour surrounds look more saturated than those due to one colour surrounds.

(2) The shifts caused by one colour surrounds e.g. due to yellow ( $g_5 g_3$ ), blue ( $g_5 g_4$ ), orange ( $g_5 g_9$ ) and green ( $g_5 g_{10}$ ) are away from yellow ( $Y_5$ ), blue ( $B_5$ ), orange ( $O_5$ ) and green ( $G_5$ ) respectively.

(3) The shifts due to two colour surrounds are generally away from the colour of the stripe on which the test colour is mounted and towards the other colour. For the two colour surrounds 1, 2, 7 and 8 (shown in figure (43)); it can be noticed that: the shift  $g_5 g_1$  is away from blue ( $B_5$ ) and towards yellow ( $Y_5$ );  $g_5 g_2$  is away from yellow and towards blue,  $g_5 g_7$  is away from green ( $G_5$ ) and towards orange ( $O_5$ ), and  $g_5 g_8$  is away from orange and towards green. It may be argued that once the shift is away from the blue or the green, then, automatically, it will be towards the yellow or the orange respectively, and vice-versa, since the yellow and blue are in the opposite sides of the grey and so the green and orange. This is not what is meant by the third rule which can be illustrated geometrically from figure (43) by the following example:

Taking the case of orange green surround (8) i.e. the point  $g_8$ : assume we join  $O_5 g_5$  and extend it to meet the extension of  $G_5 g_8$  at point  $g'_8$ . The effect of this two colour surround on the appearance of

grey on white surround ( $g_5$ ) can be analysed into two components:

(a)  $g_5 g_8'$  which is a shift away from the orange (i.e. repulsion from orange)

(b)  $g_8' g_8$  which is a shift towards the green (i.e. attraction to the green).

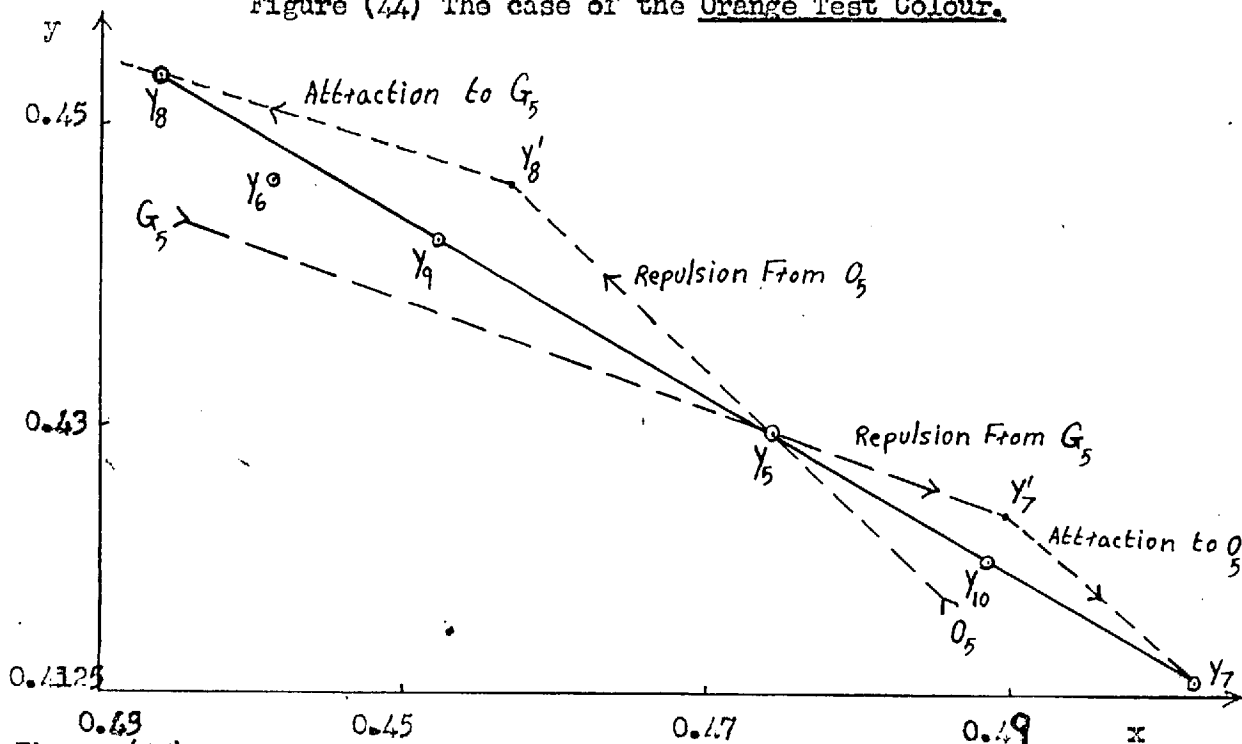
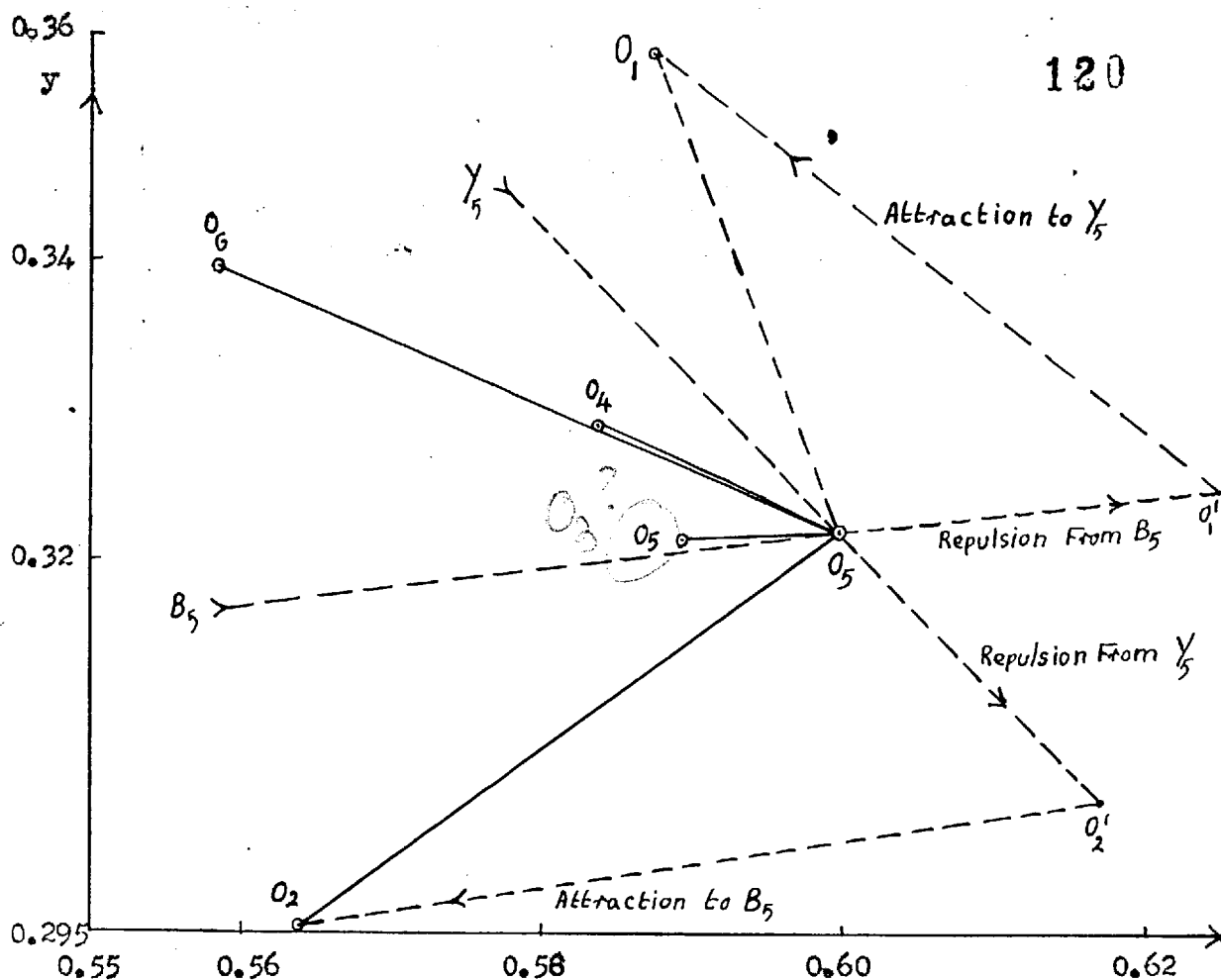
The same result can be obtained by joining  $G_5 g_5$ , which meets the line  $O_5 g_8$  at point  $g_8''$ . In this case the effect of the surround will be an attraction to the green represented by shift  $g_5 g_8''$  and a repulsion from the orange represented by shift  $g_8'' g_8$ . The same analysis applies for the other three cases of two colour surrounds as shown in figure (43).

It is noticed also that in the blue yellow surrounds, the effects of blue are much bigger than that of the yellow in both cases of attraction and repulsion ( $g_2 g_2' > g_2 g_5$  and  $g_5 g_1' > g_1' g_1$ ). This may be due to the fact that the grey on white surround ( $g_5$ ) is nearer to the yellow ( $Y_5$ ) than to the blue ( $B_5$ ) in the chromaticity chart (figure 42). In the case of orange green surrounds, the repulsive shift is bigger than the attractive one whether it is due to orange or green ( $g_5 g_8' > g_8' g_8$  and  $g_5 g_7' > g_7' g_7$ ). This may be due to the fact that the grey on white surround ( $g_5$ ) is nearly at equal distance from orange ( $O_5$ ) and green ( $G_5$ ) on white surrounds.

This may indicate that there are two factors affecting the magnitude of the change in the appearance due to colour contrast caused by two colours:

(a) The distance between the test and the surround colours in the chromaticity chart. (i.e. the difference between their chromaticities).

(b) The situation of the surrounding colour: whether it is in the same horizontal band as the test colour or on the two sides of that band.



It is difficult at this stage of the work to decide which of these two factors is more effective than the other. Nevertheless, there are two other possible factors which may be playing a major role in the overall colour contrast effects; namely:

(c) The relative brightness of the surrounding colours w.r.t. that of the test colour.

(d) The relative areas of the surrounding colours w.r.t. that of the test colour.

With these four possible factors it becomes more difficult to give any definite judgement about the actual colour contrast effects from just looking at the chromaticity chart (for some relation between the magnitude and direction of the shifts corresponding to different colour surrounds, and the relative locations of these surrounding colours w.r.t. the test colours). This graphical analysis gives no more than a general and qualitative idea about these effects. A quantitative analysis of the results must be done to help the study of these effects. This will be given in simple linear relations in Chapter IX as a simplification of this complicated phenomena of colour contrast.

(4) The shift due to black surround ( $g_5 g_6$ ) is away from yellow and red, in other words towards neutrality i.e. towards desaturation. The shift in this case is bigger than shifts due to other one colour surrounds.

#### II ORANGE TEST COLOUR: Figure (44)

In this case the four empirical rules mentioned before can be seen clearly illustrated in figure (44), with one difference related to the second rule: For the yellow and blue surrounds, the shifts  $O_5 O_3$  and  $O_5 O_4$  are not away from yellow and blue (respectively) in the direct

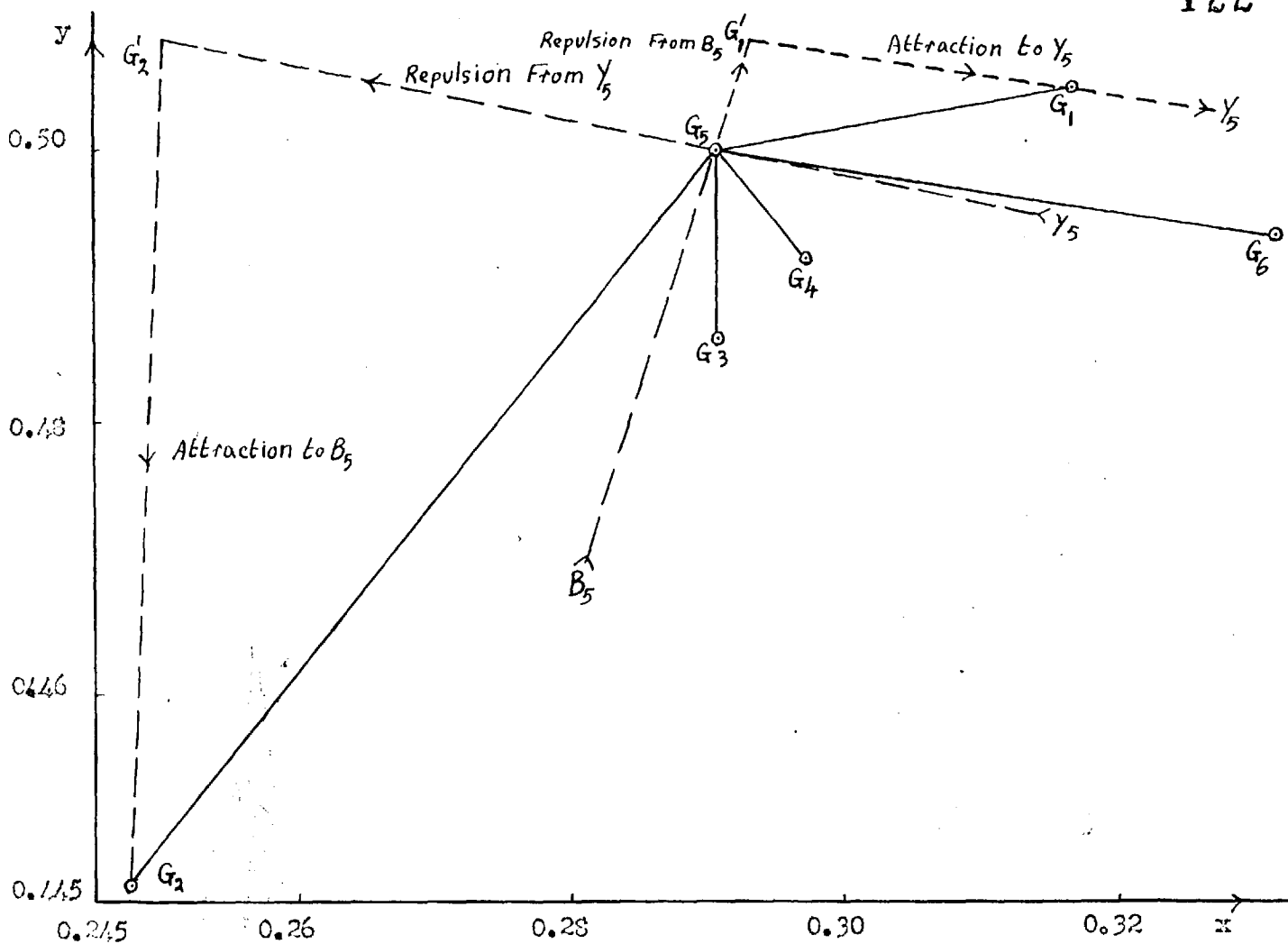


Figure (46) The case of The Green Test Colour.

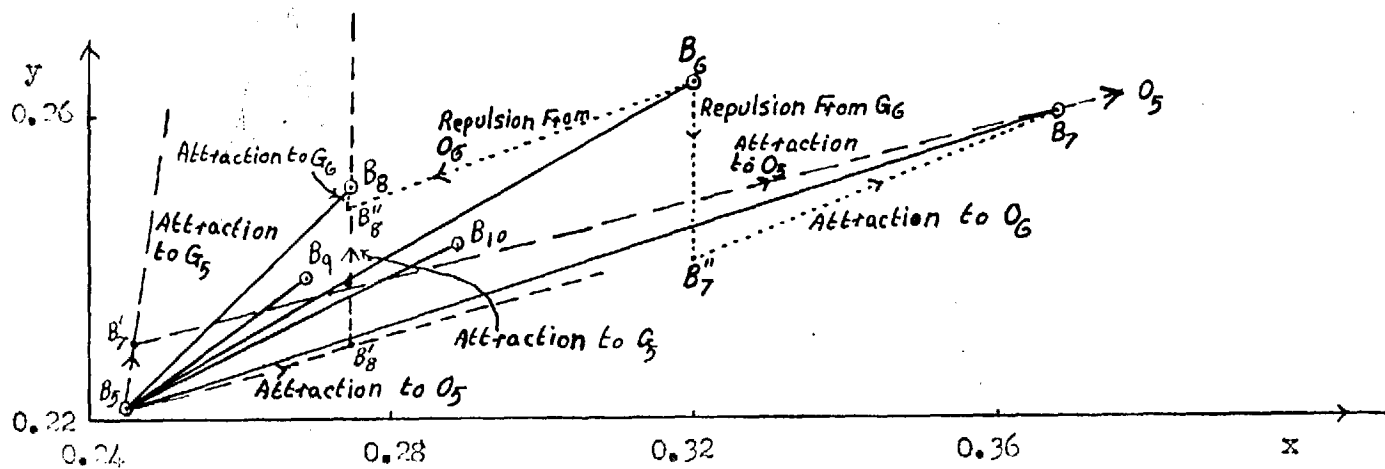


Figure (47) The case of the Blue Test Colour.

sense, but shift  $O_5 O_3$  is further than  $O_5 O_4$  from yellow and hence  $O_5 O_4$  is further than  $O_5 O_3$  from blue. The repulsive shift due to one colour surround can be seen directly if the shifts are referred to the case of orange on black surround i.e.  $O_6$  ( $O_6 O_3$  is away from  $Y_6$  and  $O_6 O_4$  is more or less away from  $b_6$ )

In the case of the yellow blue surrounds, the attractive shift is bigger than the repulsive shift, whether it is due to yellow or blue ( $O_1 O_1 > O_5 O_1$  and  $O_2 O_2 > O_5 O_2$ ).

. THE YELLOW TEST COLOUR: figure (45)

The shifts in this case lie in a straight line because red and green primaries only (no blue) were needed to match the appearance of the yellow against all its different backgrounds. (The shift  $Y_5 Y_6$  lies outside this straight line because  $Y_6$ , being the brightest, was the result of a match made without using filter  $F_4$  in the path of R,G,B mixture while this filter was used in the cases of all other surrounds).

The four rules mentioned before apply directly for the case of the yellow test colour, as shown in figure (35). The attractive and repulsive shifts due to orange and green are nearly equal in the two cases of orange green surrounds 7 and 8 (i.e.  $Y_5 Y_8 \approx Y_3 Y_8$  and  $Y_5 Y_7 \approx Y_7 Y_7$ ). This may be due to a balance in the effects of the four factors mentioned in the case of grey test colour. The shift due to black surround  $Y_5 Y_6$  is away from the monochromatic yellow ( $\lambda = 590 \text{ m}\mu$ )

. , THE BLUE TEST COLOUR: figure (47)

Rules (1) and (4) only apply directly in this case as seen in figure (7): The shifts  $B_5 B_9$  and  $B_5 B_{10}$  due to one colour surround are smaller than the shifts  $B_5 B_8$  and  $B_5 B_7$  due to two colour surrounds and

the shift  $B_5 B_6$  due to black surround is towards desaturation.

Rule (2) (i.e. repulsive shift due to one colour surround) applies indirectly i.e. shift  $B_5 B_9$  (due to orange surround) is further than shift  $B_5 B_{10}$  (due to green surround) from the orange and vice-versa. This rule applies directly if these shifts are referred to case of blue on black surround (shift  $B_6 B_9$  is away from orange  $O_6$  and shift  $B_6 B_{10}$  is away from  $G_6$ )

Rule (3) does not apply at all, if the shifts are referred to the case of blue on white surround since the two shifts due to orange and green in the two cases of orange green surrounds (7 & 8) are attractive. But if the shifts are referred to the case of blue on black surround rule (3) applies (as seen in the dotted line). The shifts due to orange are bigger than shifts due to green whether they are repulsive or attractive.

The success of the application of the four general empirical rules in the case of the blue test colour, when referring the shifts to the case of black surround and the failure of the same analysis when the shifts were referred to the case of white surround, may be due to the fact that the blue colour used is dark, and it looks even darker when seen against white surround. The brighter the colour, the greater intensity of the primaries used for matching and hence the more accurate the results will be. Also the intensity of the blue depends largely on the density of macular yellow pigment of the eye and hence the latter affects the accuracy of measurement.

# V THE GREEN TEST COLOUR: (Figure 46)

This case (as shown in figure 46) is similar to the case of orange test colour. It is clear that the four empirical rules apply. The repulsive shifts due to yellow and blue surrounds are indirect (shift  $G_5 G_3$  is further than shift  $G_5 G_4$  from yellow, and hence  $G_5 G_4$  is further than  $G_5 G_3$  from blue). Also their repulsive shifts can be seen directly if the shifts are referred to case of green on black surround ( $G_6$ ) instead of white surround  $G_5$  (shift  $G_6 G_3$  is away from yellow  $Y_6$  and shift  $G_6 G_4$  is more or less away from blue  $b_6$ ). Also the case of yellow blue surrounds, the attractive shift is bigger than the repulsive one whether it is due to yellow or blue ( $G_1'G_1 \quad G_5 G_1'$  and  $G_2'G_2 \quad G_5 G_2'$ )

## (B) THE CASE OF SIMPLE PATTERN:

The case of the compound pattern was studied before the case of



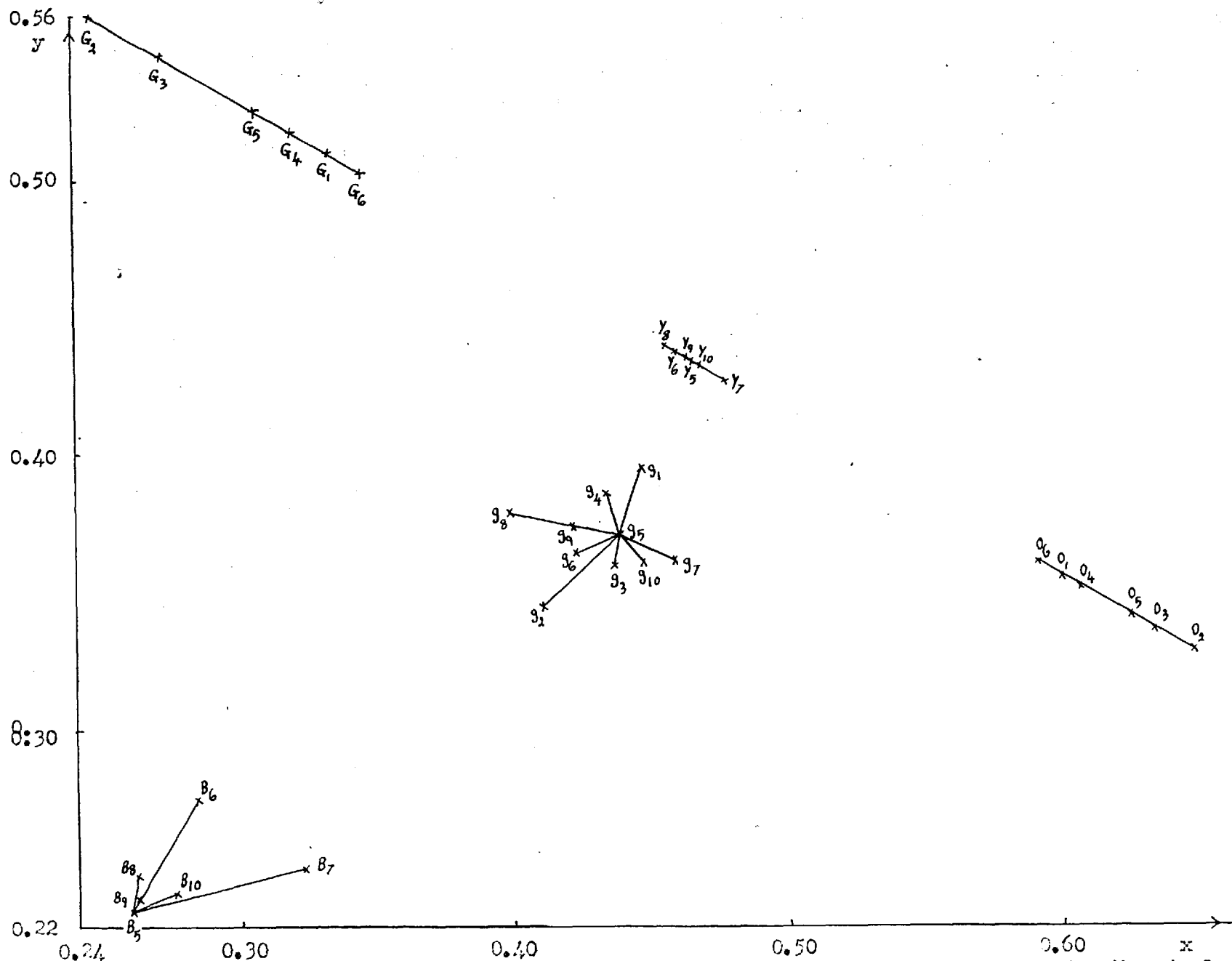


Figure (43) The effect of different surrounds on the appearance of the test colours used, for the simple pattern, 15' element angle of subtense.

the simple pattern because: (1) It represents the biggest effect of colour contrast since it was measured for a small angle of subtense ( $15'$  for the element square) and at an inclination  $= 20^{\circ}$ . The bigger the effect the more obvious the analysis will be.

(2) In the case of simple pattern for orange, and green test colours, red and green primaries only (no blue) were needed to match their appearance on any of the different surrounds used (which is not the case for orange and green test colours in the compound pattern). This being the case, all the points in the chromaticity chart corresponding to these test colours against their backgrounds lie on the straight line joining the two points corresponding to R. And G primaries. Therefore the analysis in this case of the simple pattern will be more limited than in the case of the compound pattern (as will be seen later).

Figure (48) shows the effect of different surrounds on the appearance of all the test colours used in this investigation for simple pattern of element of angle of subtense  $15'$ , lying in a vertical plane. It is obvious that for all the test colours, the point corresponding to the white surround is central with respect to the points corresponding to all other surrounds. This case will be studied now in the light of the four empirical rules mentioned before:

The first rule: (namely the shifts due to two colour surrounds are bigger than those due to one colour surround) applies in this case for all the test colours.

The second rule: (namely the shifts due to one colour surrounds are generally away from that colour) applies directly for the grey and yellow test colours, and for the yellow surround of the orange and green

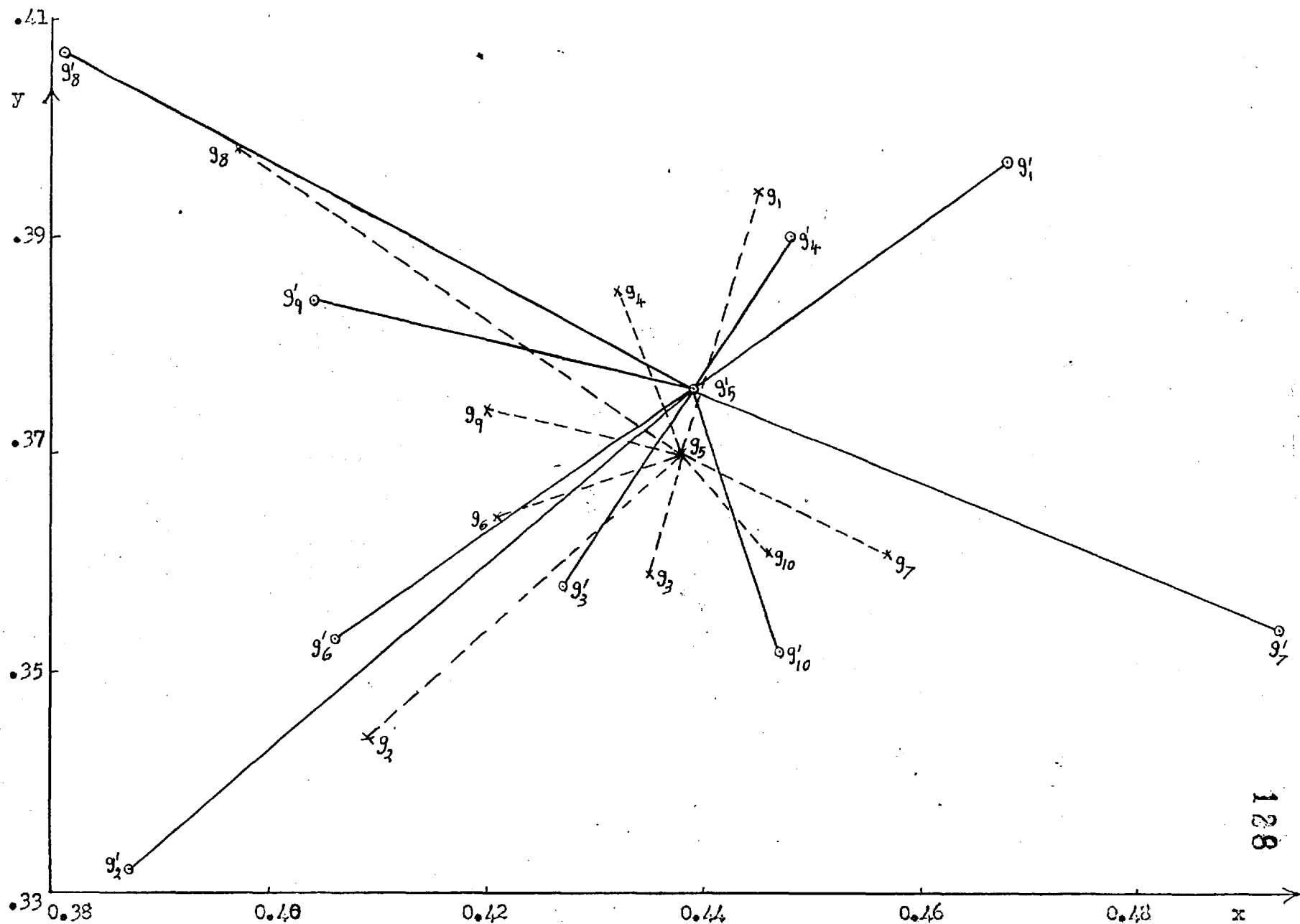


Figure (19) The effect of the pattern on the Grey Test Colour, the compound pattern (—), and the simple pattern (---).

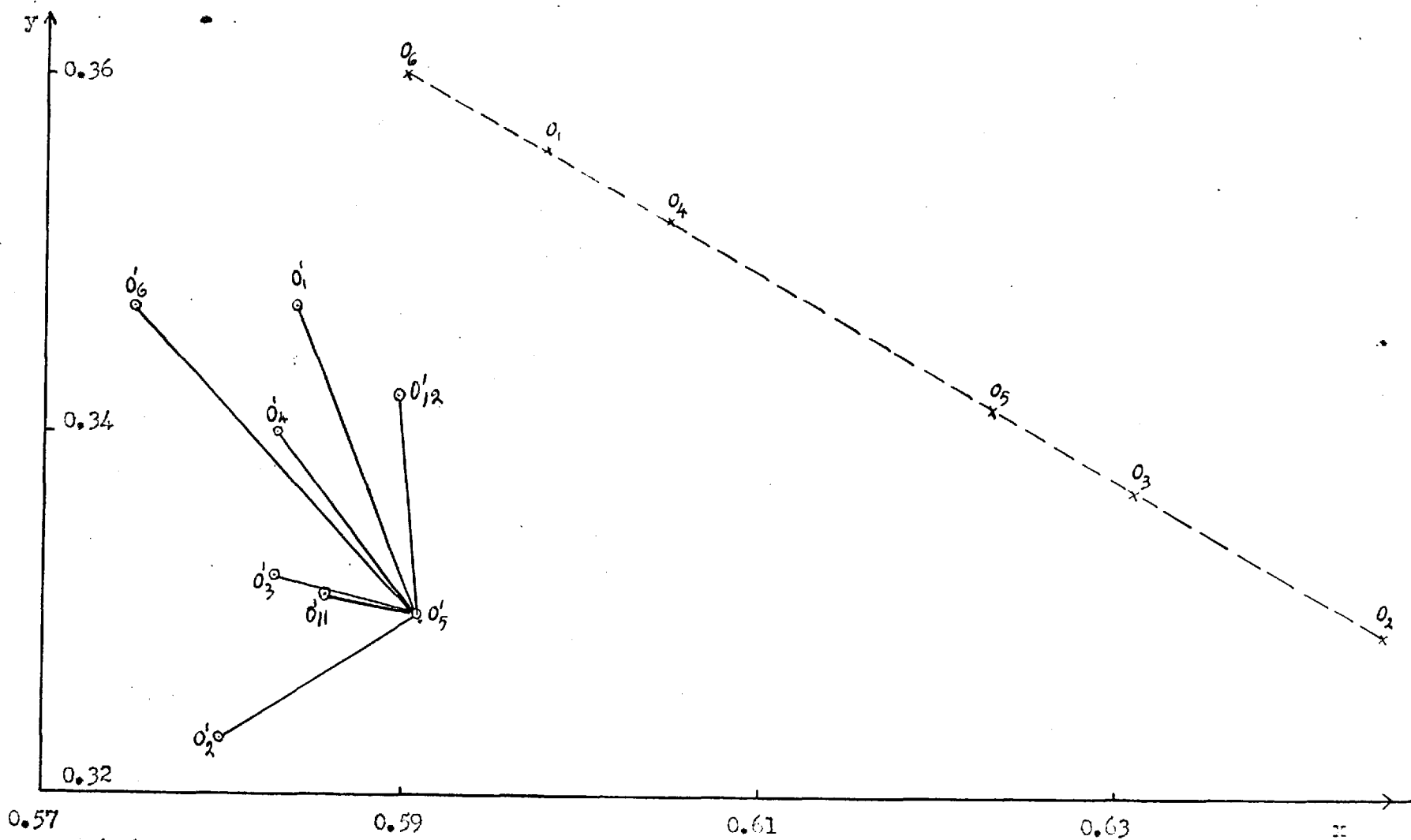


Figure (50) The effect of the pattern on the Orange Test Colour, the compound pattern (—), and the simple pattern (---).

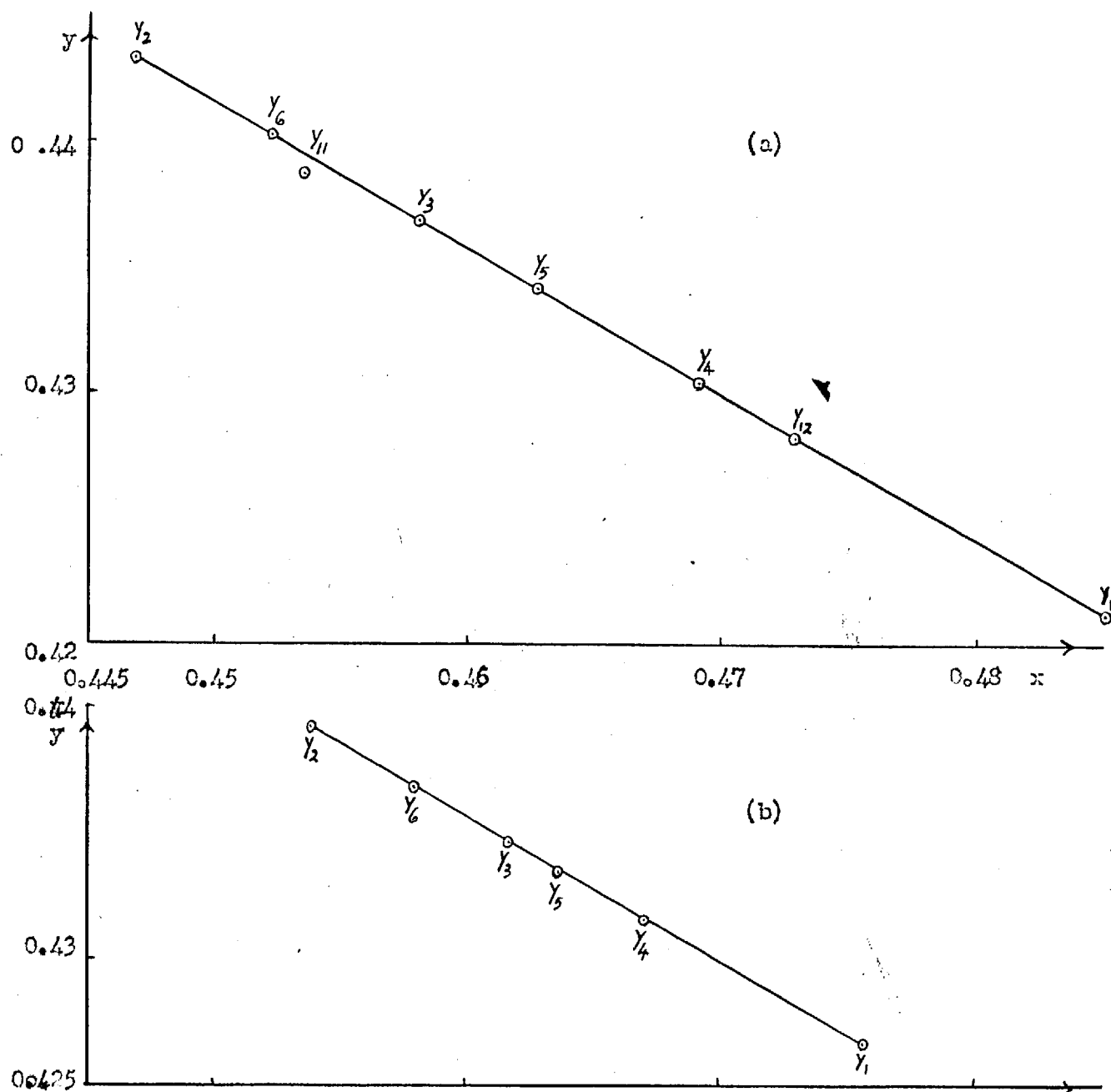


Figure (51) The effect of the pattern on the Yellow Test Colour, the compound pattern (a), and the simple pattern (b).

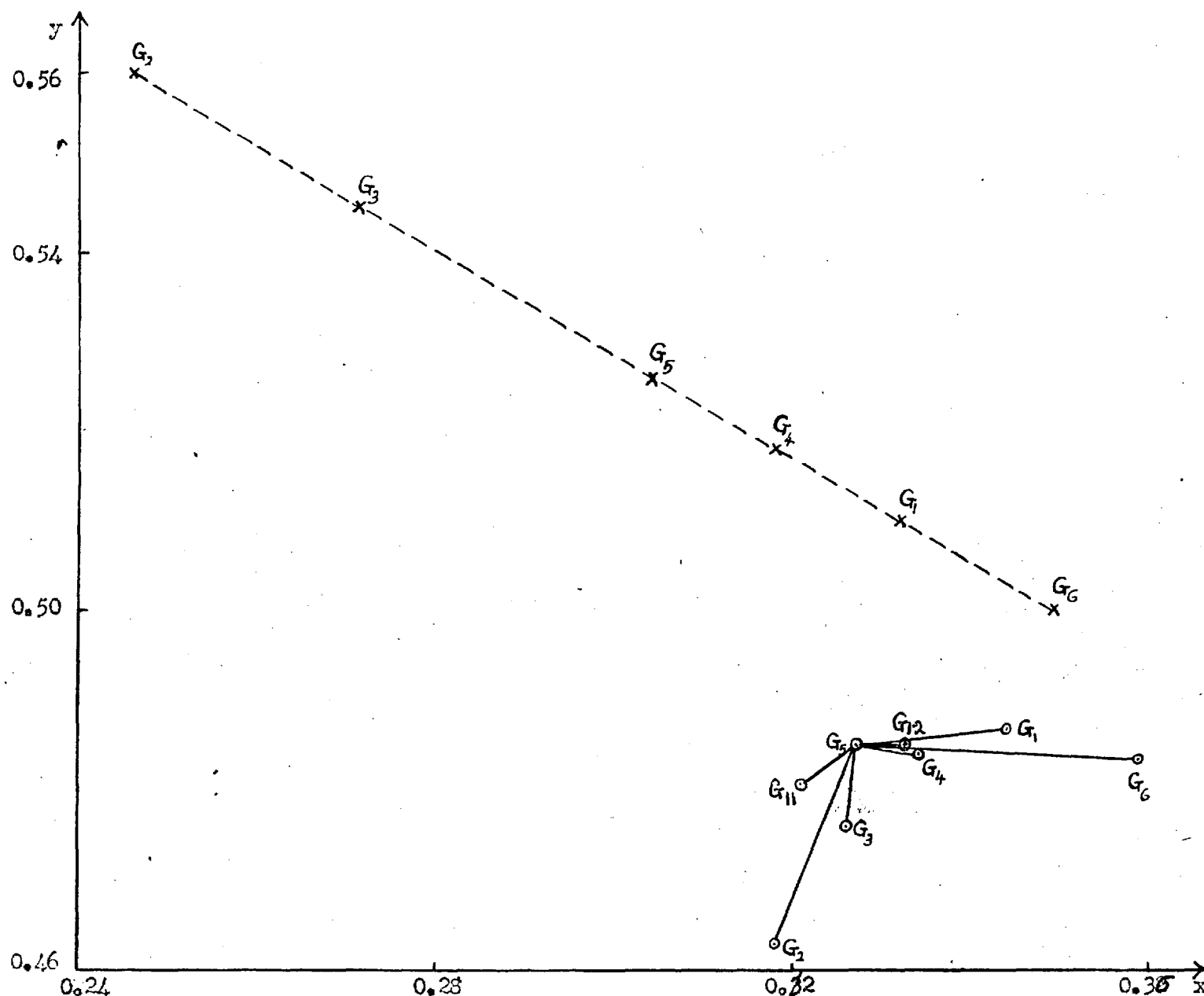


Figure (52) The effect of the pattern on the Green Test Colour, the compound pattern (—), the simple pattern (— — —);

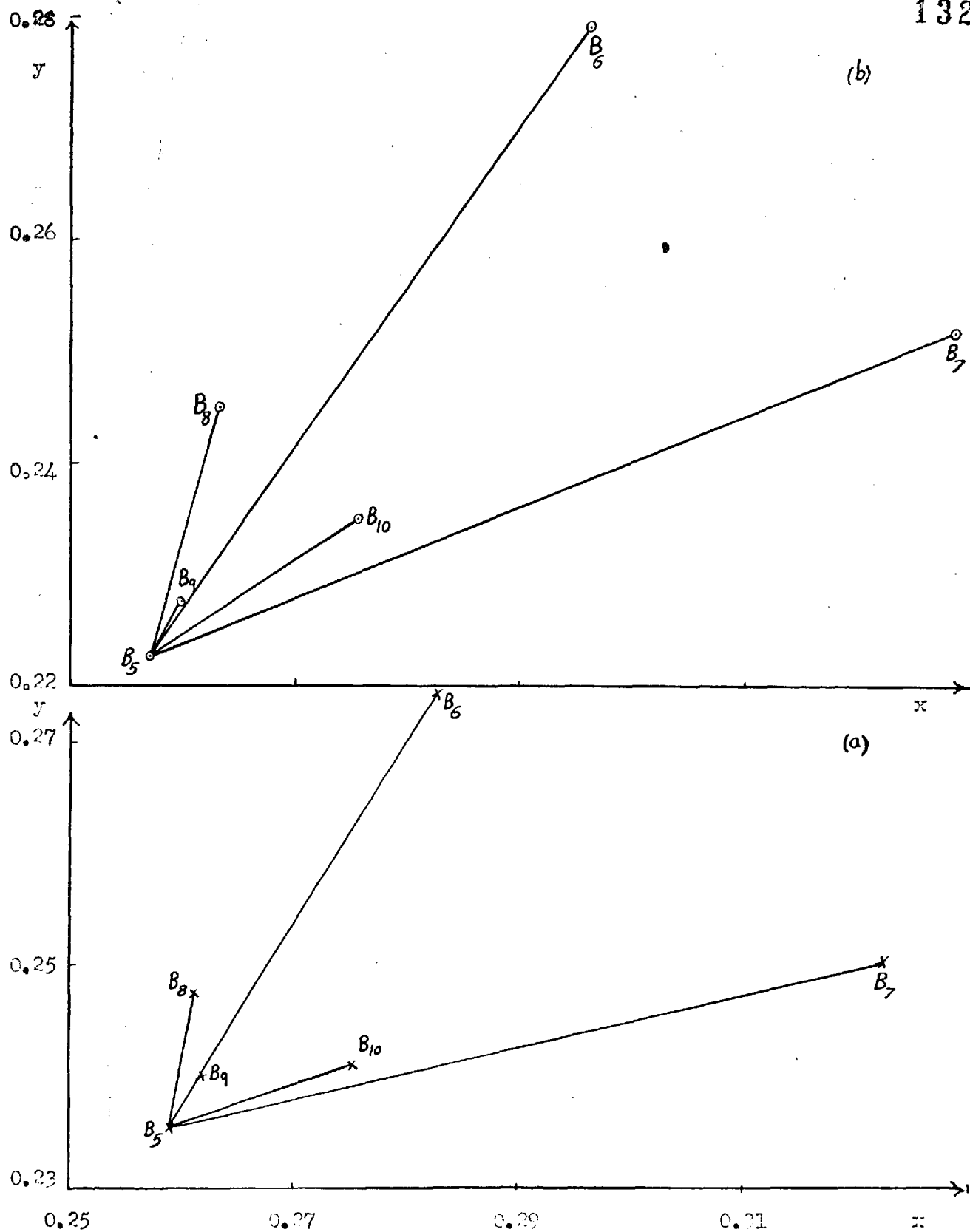


Figure (53) The effect of the pattern on the Blue Vest Colour, the compound pattern (b), and the simple pattern (a).

test colours, and indirectly for the blue test colour (in the same way as mentioned in the case of compound pattern (see page 124). But for the blue surrounds of the orange and green ( $O_4$  and  $G_4$ ), the shifts are towards the yellow (and not away from the blue) since there is no blue component in the matching beam.

The third rule: (namely the shifts due to two colour surrounds are generally away from the colour of the stripe on which the test colour is mounted and towards that of the other two side stripes), applies directly for the grey test colour and indirectly for the blue test colour (in the same way as mentioned in the case of the compound pattern (see page 124). As for the orange, yellow and green test colours, since all their points lie on the same straight line, then this rule does not apply directly. It shows itself in the first rule as mentioned before in the explanatory note related to rule 3 (see page 17).

The fourth rule: (namely the shifts due to black surround are towards desaturation) applies directly for the cases of blue and grey test colours and indirectly as shifts on the straight line (R) (G) away from the red and green ends of the chart and away from 0.59 u for the cases of orange, green and yellow test colours respectively.

#### (C) THE EFFECT OF THE PATTERN OF THE TEST PATCH:

For comparison, figure (49-53) inclusive, show the cases of the simple and compound patterns, for grey, orange, yellow, green and blue test colours respectively, for the same experimental conditions (element angle of subtense =  $15'$  and vertical test patch).

FOR THE ORANGE AND GREEN TEST COLOURS: figures (50&52)

The following points can be seen clearly:



(a) In the case of the simple pattern and for all the surrounds used, the orange and green look more saturated than in the case of compound surround.

(b) The shifts in the simple pattern are bigger than in the case of the compound pattern.

(c) The whole set of the points for the simple pattern, with respect to that for the compound pattern, is displaced towards the red end of the chromaticity chart for the orange test colour and towards the green end for the green test colour.

(d) In the case of the simple pattern, most of the effect of the different surrounds appears in the form of change in hue and very little change in saturation (if any) occurs, while on the case of the compound pattern, the effect is divided between the change in hue (which is less than in the first case) and change in saturation ( which is much more than in the first case).

A possible explanation for these effects is as follows:

The eye sees the whole pattern paying special attention to the test colour i.e. the whole pattern is imaged on the fovea of the retina, with a trial to match the appearance of the test colour. So, in the case of the compound pattern, a summation of the effects of the surrounding colours on the test colour is taking place (possibly mixing of the colours, as will be explained in Chapter VIII) and this is greater than in the case of a simple pattern which causes this desaturation and the reduction of the apparent differences in hue. --

FOR THE YELLOW TEST COLOUR: figure (51)

(a) The shifts due to different surrounds are larger in the case of the compound pattern than in the case of simple pattern.

(2) There is no tendency for the whole set of points to be displaced either way to the red or to the green.

This may be due to (a) the location of the yellow test colour in the chromaticity chart being nearly midway in between the locations of the orange and green (of the surround) and at the same time (b) the yellow test colour can be built by a mixture of the orange and green (the actual surrounds in this case).

FOR THE BLUE TEST COLOUR figure (53)

(1) The shifts due to different surrounds are bigger in the case of the compound pattern than in the case of the simple pattern.

(2) The reference point ( $B_5$ ) corresponding to the white surround being practically unchanged from one case to the other, the blue test colour on the other surrounds appears in the compound pattern less saturated than in the case of simple pattern. This is the same result as in the case of orange and green test colours.

FOR THE GREY TEST COLOUR figure (49)

(1) The shifts due to different surrounds are bigger in the case of compound pattern than in the case of simple pattern.

(2) The reference point ( $g_5$ ) corresponding to the white surround being changed little in the two cases, the grey in all other surrounds looks more saturated in the compound pattern than in the case of the simple pattern. This may be due to the fact that the grey, being originally nearly neutral, then the more the mixing effect due to the compound pattern the more saturated the apparent colour appears.

(D) THE EFFECTS OF DIFFERENT COLOUR SURROUNDS ON THE APPARENT BRIGHTNESS OF THE TEST COLOURS: In this work, no attempt was made to

TABLE(8) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE ORANGE TEST COLOUR AGAINST ALL BACKGROUNDS, AND FOR ALL VIEWING CONDITIONS USED.

| SURROUND  | (1)  |      |      | (2)  |      |      | (3)  |      |      | (4)  |      |      | (5)  |      |      | (6)  |      |      |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| I         | .590 | .360 | 3.72 | .615 | .346 | 3.42 | .609 | .349 | 2.83 | .594 | .358 | 3.83 | .599 | .355 | 2.04 | .584 | .364 | 4.00 |
| II        | .593 | .359 | 3.13 | .624 | .341 | 3.19 | .617 | .345 | 3.13 | .595 | .358 | 3.64 | .610 | .349 | 1.63 | .581 | .366 | 3.97 |
| III       | .594 | .358 | 3.36 | .630 | .337 | 3.22 | .626 | .339 | 3.09 | .600 | .355 | 3.71 | .614 | .347 | 2.24 | .582 | .365 | 3.83 |
| IV        | .598 | .356 | 2.79 | .645 | .329 | 1.92 | .631 | .337 | 2.05 | .605 | .352 | 3.52 | .623 | .341 | 1.30 | .590 | .360 | 3.75 |
| V         | .638 | .333 | 1.04 | .665 | .318 | 0.95 | .661 | .320 | 0.80 | .646 | .328 | 1.12 | .657 | .322 | 0.49 | .625 | .341 | 1.15 |
| VI        | .636 | .335 | 0.80 | .671 | .314 | 0.80 | .657 | .322 | 0.68 | .644 | .330 | 0.86 | .648 | .327 | 0.31 | .625 | .341 | 0.80 |
| VII       | .634 | .335 | 0.85 | .687 | .304 | 0.72 | .666 | .316 | 0.85 | .643 | .330 | 1.03 | .655 | .324 | 0.62 | .621 | .343 | 1.02 |
| VIII      | .616 | .346 | 3.22 | .644 | .329 | 3.07 | .636 | .334 | 2.78 | .625 | .340 | 3.40 | .630 | .337 | 2.51 | .602 | .354 | 3.70 |
| IX        | .618 | .344 | 3.28 | .650 | .326 | 3.04 | .634 | .335 | 2.76 | .623 | .341 | 3.44 | .629 | .338 | 2.34 | .603 | .353 | 3.65 |
| X         | .664 | .318 | 3.17 | .708 | .292 | 3.10 | .696 | .299 | 2.62 | .675 | .311 | 3.51 | .688 | .304 | 2.11 | .641 | .311 | 3.69 |
| XI        | .660 | .320 | 1.08 | .692 | .301 | 0.96 | .683 | .307 | 0.97 | .670 | .314 | 1.05 | .675 | .312 | 0.96 | .649 | .327 | 1.06 |
| XII       | .658 | .321 | 1.04 | .696 | .299 | 0.92 | .687 | .304 | 0.94 | .662 | .319 | 1.08 | .679 | .309 | 0.68 | .644 | .330 | 1.08 |
| XIII      | .664 | .318 | 1.02 | .708 | .292 | 0.89 | .696 | .299 | 0.86 | .675 | .311 | 1.02 | .688 | .304 | 0.58 | .641 | .331 | 1.05 |
| XIV       | .584 | .347 | 2.80 | .580 | .323 | 2.14 | .583 | .332 | 2.22 | .583 | .340 | 3.55 | .591 | .330 | 1.34 | .575 | .347 | 3.89 |
| XV        | .615 | .337 | 0.86 | .606 | .302 | 0.96 | .623 | .315 | 0.67 | .618 | .323 | 1.07 | .641 | .314 | 0.23 | .599 | .340 | 1.16 |
| XVI       | .600 | .344 | 0.64 | .587 | .314 | 0.48 | .599 | .323 | 0.41 | .594 | .334 | 0.79 | .605 | .321 | 0.31 | .580 | .336 | 0.60 |
| XVII      | .587 | .354 | 2.99 | .564 | .296 | 3.11 | .589 | .321 | 2.77 | .584 | .329 | 3.47 | .600 | .322 | 2.04 | .558 | .340 | 3.99 |
| XVIII     | .563 | .361 | 1.42 | .568 | .303 | 0.98 |      |      |      |      |      |      | .580 | .324 | 1.26 |      |      |      |
| XIX       | .576 | .340 | 1.27 | .544 | .271 | 0.83 |      |      |      |      |      |      | .582 | .299 | 1.07 |      |      |      |
| XX        | .564 | .364 | 1.41 | .556 | .331 | 1.07 |      |      |      |      |      |      | .582 | .299 | 1.07 |      |      |      |

TABLE (9) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE GREEN TEST COLOUR AGAINST ALL BACKGROUNDS, AND FOR ALL THE VIEWING CONDITIONS USED.

| SURROUND  | (1)  |      |      | (2)  |      |      | (3)  |      |      | (4)  |      |       | (5)  |      |      | (6)  |      |       |
|-----------|------|------|------|------|------|------|------|------|------|------|------|-------|------|------|------|------|------|-------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y     | x    | y    | Y    | x    | y    | Y     |
| I         | .360 | .494 | 5.04 | .334 | .509 | 5.64 | .337 | .507 | 2.95 | .348 | .501 | 6.93  | .344 | .503 | 2.49 | .366 | .490 | 3.92  |
| II        | .353 | .495 | 3.82 | .309 | .523 | 4.82 | .320 | .517 | 2.40 | .350 | .500 | 6.43  | .345 | .503 | 2.01 | .365 | .491 | 7.92  |
| III       | .338 | .506 | 3.72 | .278 | .541 | 3.90 | 2.96 | .531 | 3.07 | .330 | .511 | 5.70  | .318 | .518 | 2.40 | .357 | .495 | 7.27  |
| IV        | .332 | .510 | 3.39 | .246 | .560 | 4.61 | .271 | .545 | 2.27 | .318 | .518 | 4.94  | .305 | .526 | 1.92 | .349 | .500 | 6.81  |
| I'        | .377 | .484 | 9.27 | .360 | .493 | 9.37 | .363 | .492 | 7.29 | .372 | .487 | 10.87 | .369 | .489 | 6.68 | .383 | .481 | 11.59 |
| II'       | .376 | .484 | 8.32 | .348 | .500 | 8.13 | .365 | .491 | 5.78 | .373 | .486 | 9.36  | .372 | .487 | 4.83 | .379 | .481 | 11.41 |
| III'      | .365 | .491 | 7.70 | .325 | .514 | 7.65 | .345 | .503 | 7.56 | .357 | .495 | 9.02  | .353 | .498 | 5.09 | .370 | .488 | 10.97 |
| V         | .311 | .525 | 1.12 | .274 | .548 | 1.26 | .287 | .538 | 0.66 | .306 | .528 | 1.81  | .298 | .533 | 0.44 | .329 | .515 | 2.21  |
| VI        | .317 | .522 | 0.76 | .259 | .556 | 1.47 | .265 | .553 | 0.40 | .298 | .533 | 1.42  | .272 | .549 | 0.41 | .333 | .513 | 2.19  |
| X         | .354 | .500 | 2.75 | .318 | .521 | 3.31 | .321 | .520 | 2.75 | .351 | .502 | 4.52  | .334 | .512 | 2.25 | .366 | .493 | 4.75  |
| XIII      | .309 | .527 | 1.35 | .244 | .565 | 1.64 | .250 | .561 | 1.44 | .298 | .533 | 2.12  | .268 | .551 | 1.43 | .334 | .512 | 3.21  |
| XIV       | .344 | .487 | 4.06 | .318 | .463 | 2.30 | .326 | .476 | 2.66 | .334 | .484 | 4.35  | .327 | .485 | 2.68 | .359 | .483 | 5.27  |
| XV        | .332 | .495 | 1.69 | .256 | .450 | 0.65 | .293 | .489 | 0.42 | .302 | .495 | 0.80  | .300 | .501 | 0.77 | .341 | .490 | 1.63  |
| XVI       | .330 | .502 | 2.05 | .289 | .445 | 1.64 | .313 | .482 | 1.52 | .321 | .490 | 2.37  | .314 | .494 | 1.31 | .347 | .482 | 2.25  |
| XVII      | .316 | .505 | 4.98 | .248 | .446 | 4.67 | .290 | .486 | 2.59 | .298 | .492 | 4.96  | .290 | .500 | 2.71 | .331 | .494 | 4.88  |
| XVIII     | .353 | .493 | 2.84 | .281 | .466 | 1.78 |      |      |      |      |      |       | .328 | .496 | 2.16 |      |      |       |
| XIX       | .340 | .468 | 1.77 | .249 | .446 | 1.47 |      |      |      |      |      |       | .290 | .484 | 0.81 |      |      |       |
| XX        | .335 | .436 | 2.25 | .304 | .408 | 1.25 |      |      |      |      |      |       | .290 | .484 | 0.81 |      |      |       |

**TABLE (10) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE YELLOW TEST COLOUR AGAINST ALL THE BACKGROUNDS, AND FOR ALL THE VIEWING CONDITIONS USED.**

| SURROUND  | (7)  |      |      | (8)  |      |      | (9)  |      |      | (10) |      |      | (5)  |      |      | (6)  |      |      |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| I         | .461 | .435 | 6.88 | .448 | .443 | 7.44 | .451 | .441 | 7.29 | .458 | .438 | 7.20 | .453 | .440 | 5.18 | .449 | .442 | 7.50 |
| III       | .470 | .430 | 6.61 | .456 | .438 | 7.11 | .459 | .436 | 6.95 | .465 | .433 | 6.90 | .462 | .434 | 4.91 | .458 | .437 | 7.19 |
| IV        | .475 | .427 | 6.26 | .454 | .439 | 7.14 | .462 | .435 | 6.76 | .467 | .432 | 6.81 | .464 | .433 | 4.80 | .458 | .437 | 7.15 |
| X         | .469 | .433 | 6.58 | .436 | .452 | 7.85 | .444 | .448 | 7.16 | .463 | .436 | 6.88 | .456 | .440 | 6.03 | .437 | .449 | 8.05 |
| XIV       | .485 | .421 | 5.97 | .447 | .443 | 7.42 | .458 | .437 | 6.90 | .463 | .434 | 6.76 | .463 | .434 | 4.83 | .452 | .440 | 7.38 |
| XV        | .537 | .393 | 1.75 | .461 | .437 | 2.32 | .484 | .424 | 1.98 | .469 | .431 | 1.88 | .491 | .419 | 1.34 | .467 | .434 | 2.34 |
| XVI       | .512 | .406 | 1.33 | .471 | .430 | 1.72 | .481 | .423 | 1.68 | .500 | .414 | 1.46 | .489 | .419 | 1.03 | .473 | .428 | 1.73 |
| XVII      | .502 | .413 | 5.57 | .434 | .453 | 7.64 | .452 | .443 | 7.23 | .488 | .421 | 6.14 | .474 | .430 | 4.51 | .441 | .446 | 7.85 |
| XVIII     | .489 | .421 | 2.12 | .451 | .443 | 2.40 |      |      |      |      |      |      | .471 | .431 | 1.79 |      |      |      |
| XIX       | .525 | .400 | 1.75 | .449 | .445 | 1.35 |      |      |      |      |      |      | .497 | .416 | 1.54 |      |      |      |
| XX        | .504 | .412 | 1.94 | .483 | .425 | 1.56 |      |      |      |      |      |      | .497 | .416 | 1.54 |      |      |      |

**TABLE (11) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE BLUE TEST COLOUR AGAINST ALL THE BACKGROUNDS, AND FOR ALL THE VIEWING CONDITIONS USED.**

| SURROUND  | (7)  |      |      | (8)  |      |      | (9)  |      |      | (10) |      |      | (5)  |      |      | (6)  |      |      |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | x    |
| I         | .287 | .252 | 0.37 | .275 | .257 | 0.39 | .276 | .253 | 0.31 | .279 | .253 | 0.41 | .275 | .251 | 0.26 | .289 | .266 | 1.68 |
| III       | .304 | .244 | 0.36 | .267 | .245 | 0.35 | .273 | .242 | 0.32 | .283 | .245 | 0.30 | .271 | .241 | 0.15 | .294 | .265 | 0.95 |
| IV        | .322 | .250 | 0.34 | .261 | .247 | 0.26 | .262 | .240 | 0.23 | .275 | .241 | 0.29 | .259 | .235 | 0.14 | .283 | .274 | 0.90 |
| X         | .312 | .251 | 0.40 | .280 | .251 | 0.52 | .269 | .245 | 0.38 | .280 | .243 | 0.39 | .253 | .234 | 0.35 | .283 | .252 | 1.01 |
| XIV       | .329 | .251 | .45  | .263 | .245 | 0.40 | .260 | .227 | 0.42 | .276 | .235 | 0.32 | .257 | .223 | 0.23 | .296 | .279 | 2.07 |
| (XIV)     | .336 | .267 | 1.00 | .273 | .258 | 1.57 | .272 | .244 | 0.60 | .282 | .253 | 0.53 | .270 | .240 | 0.34 | .298 | .302 | 2.73 |
| XVI       | .349 | .286 | 0.27 | .278 | .290 | 0.18 | .263 | .248 | 0.12 | .283 | .262 | 0.12 | .254 | .236 | 0.12 | .300 | .305 | 0.70 |
| XVII      | .361 | .261 | 0.40 | .275 | .250 | 0.54 | .269 | .239 | 0.46 | .289 | .243 | 0.32 | .245 | .222 | 0.21 | .321 | .265 | 0.61 |
| XVIII     | .337 | .255 | 0.19 | .254 | .240 | 0.15 |      |      |      |      |      |      | .261 | .230 | 0.11 |      |      |      |
| XIX       | .370 | .277 | 0.10 | .262 | .250 | 0.13 |      |      |      |      |      |      | .222 | .200 | 0.05 |      |      |      |
| XX        | .321 | .258 | .21  | .277 | .258 | 0.24 |      |      |      |      |      |      | .222 | .200 | 0.05 |      |      |      |

TABLE (12) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE GREY TEST COLOUR AGAINST SOME BACKGROUNDS, AND FOR ALL THE VIEWING CONDITIONS USED.

| SURROUND  | (1)  |      |      | (2)  |      |      | (3)  |      |      | (4)  |      |      | (5)  |      |      | (6)  |      |      |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| I         | .458 | .386 | 1.39 | .426 | .367 | .79  | .439 | .369 | 0.64 | .451 | .386 | 1.59 | .451 | .379 | .44  | .428 | .374 | 1.77 |
| IV        | .445 | .394 | 1.26 | .409 | .344 | 0.95 | .435 | .359 | 0.42 | .432 | .385 | 1.05 | .438 | .370 | 0.21 | .421 | .364 | 1.10 |
| X         | .447 | .407 | 1.24 | .411 | .355 | 0.89 | .438 | .367 | 0.64 | .468 | .394 | 1.08 | .456 | .391 | 0.37 | .423 | .374 | 1.62 |
| XIV       | .449 | .416 | 2.28 | .387 | .364 | 2.78 | .426 | .388 | 1.27 | .427 | .401 | 2.27 | .425 | .395 | 0.93 | .397 | .388 | 2.64 |
| XV        | .468 | .397 | 1.49 | .387 | .332 | 0.93 | .427 | .358 | 0.55 | .448 | .390 | 1.41 | .439 | .376 | 0.23 | .406 | .353 | 1.26 |
| XVI       | .458 | .399 | 1.52 | .370 | .331 | 1.46 | .429 | .359 | 0.75 | .432 | .389 | 1.56 | .425 | .377 | 0.36 | .391 | .369 | 2.65 |
| XVII      | .499 | .415 | 0.65 | .370 | .314 | 0.77 | .463 | .377 | 0.51 | .472 | .399 | 0.80 | .466 | .387 | 0.49 | .422 | .378 | 1.25 |
| XVIII     | .463 | .415 | 1.35 | .377 | .312 | 0.39 |      |      |      |      |      |      | .441 | .392 | 0.41 |      |      |      |
| XIX       | .469 | .411 | 1.32 | .315 | .268 | 0.42 |      |      |      |      |      |      | .439 | .391 | 0.36 |      |      |      |
| XX        | .483 | .396 | 0.74 | .425 | .361 | 0.43 |      |      |      |      |      |      | .439 | .391 | 0.36 |      |      |      |

TABLE (12) THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE GREY TEST COLOUR AGAINST OTHER  
(Contd.) BACKGROUNDS, AND FOR ALL THE VIEWING CONDITIONS USED.

| SURROUND  | (7)  |      |      | (8)  |      |      | (9)  |      |      | (10) |      |      | (5)  |      |      | (6)  |      |      |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| CONDITION | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| I         | .450 | .361 | 0.85 | .427 | .385 | 0.76 | .443 | .376 | 0.55 | .443 | .370 | 0.65 | .451 | .379 | 0.44 | .428 | .374 | 1.77 |
| IV        | .457 | .361 | 0.77 | .397 | .398 | 0.60 | .420 | .374 | 0.56 | .446 | .361 | 0.60 | .438 | .370 | 0.21 | .421 | .364 | 1.10 |
| X         | .435 | .349 | 0.25 | .414 | .380 | 1.05 | .435 | .378 | 0.95 | .447 | .368 | 0.99 | .456 | .391 | 0.37 | .423 | .374 | 1.62 |
| XIV       | .448 | .382 | 1.80 | .381 | .411 | 1.54 | .403 | .399 | 2.35 | .433 | .385 | 1.64 | .425 | .395 | 0.93 | .397 | .388 | 2.64 |
| XV        | .493 | .354 | 0.94 | .381 | .407 | 0.80 | .404 | .384 | 0.91 | .447 | .352 | 0.73 | .439 | .376 | 0.23 | .406 | .353 | 1.26 |
| XVI       | .462 | .364 | 1.20 | .375 | .397 | 0.78 | .401 | .374 | 1.05 | .442 | .356 | 1.07 | .425 | .377 | 0.36 | .391 | .369 | 2.65 |
| XVII      | .536 | .344 | 0.60 | .387 | .430 | 0.73 | .428 | .384 | 0.84 | .475 | .369 | 0.73 | .466 | .387 | 0.49 | .422 | .378 | 1.25 |
| XVIII     | .449 | .369 | .24  | .428 | .456 | 0.36 |      |      |      |      |      |      | .441 | .392 | 0.41 |      |      |      |
| XIX       | .501 | .253 | 0.14 | .381 | .484 | 0.27 |      |      |      |      |      |      | .439 | .391 | 0.36 |      |      |      |
| XX        | .459 | .357 | 0.24 | .446 | .452 | 0.36 |      |      |      |      |      |      | .439 | .391 | 0.36 |      |      |      |



TABLE (12) Cont'd. THE C.I.E. TRISTIMULUS SPECIFICATION OF THE APPEARANCE OF THE ORANGE, GREEN AND YELLOW TEST COLOURS ON WHITE, BLACK AND WHITE BLACK SURROUNDS.

| SURROUND    | (5)  |      |      | (6)  |      |      | (11) |      |      | (12) |      |      |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|
| TEST COLOUR | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| Orange      | .591 | .330 | 1.34 | .575 | .347 | 3.09 | .586 | .331 | 2.79 | .590 | .342 | 0.92 |
| Green       | .327 | .485 | 2.66 | .359 | .483 | 5.27 | .321 | .480 | 3.02 | .333 | .485 | 2.17 |
| Yellow      | .463 | .434 | 4.83 | .452 | .440 | 7.33 | .457 | .437 | 5.51 | .476 | .427 | 3.79 |

The Viewing conditions in Tables (8-12) inclusive:

- (a) I, II, III, IV, for vertical simple pattern of element angles of subtense:  $2^\circ$ ,  $1^\circ$ ,  $30'$  and  $15'$  respectively, for bright surround of comparison patch.
- (b) V, VI, VII for vertical simple pattern of element angles of subtense:  $2^\circ$ ,  $1^\circ$  and  $30'$ , respectively for dark surround of comparison patch.
- (c) VIII, IX, X for simple pattern,  $2^\circ$  element angle of subtense at inclinations  $40^\circ$ ,  $20^\circ$ ,  $5^\circ$  respectively for bright surround of comparison patch.
- (d) XI, XII, XIII for simple pattern,  $2^\circ$  element angle of subtense at inclinations,  $40^\circ$ ,  $20^\circ$  and  $5^\circ$  respectively for dark surround of comparison patch.
- (e) XIV, XV, XVI for vertical compound pattern of  $15'$  element angle of subtense for bright and dark surrounds of comparison patch and lower luminance of the whole test patch.
- (f) XVII for compound pattern of  $15'$  element angle of subtense at an inclination  $20^\circ$ , for bright surround of comparison patch.
- (g) XVIII, XIX for the chart at an element angle of subtense  $12'$  and  $6'$  respectively for bright surround of comparison patch (horizontal stripes).
- (h) XX for the chart at an angle of subtense  $6'$  and for vertical stripes.

construct a scale of subjective brightness, but the sum of the fractional luminances of the three primary colours used in the matches were taken as a relative measure of the apparent brightness of the test colours against their different backgrounds. This, in itself, is sound for comparison in the different cases, although the numbers shown have no absolute significance, as have those related to a well established scale. Hopkinson, (114) has developed two such scales of subjective brightness based on: (1) equal steps of contrast, (2) Direct numerical estimation. Nevertheless the work in this field is not yet complete and more investigations are still in progress.

Adjusting the comparison patch to be of the same apparent brightness as that of the test colour in its surround, is very difficult (as shown in Chapter III) for the following two main reasons:

- (1) The separation of the test and the comparison patches.
- (2) The different conditions of the test patch.

It can be safely claimed that adjusting the comparison patch to match the chromaticity of the test colour, which in itself is difficult, is easier and more accurate than its final adjustment to match the brightness also. This lead to very few cases of discrepancies in the following general analysis of the results and these departures can be ignored.

From the results shown in tables (8-12) inclusive, the following general conclusions for all the test colours in all different conditions used, can be seen:

- (1) The white surround (5) makes them appear the darkest with respect to all other surrounds.
- (2) The black surround (6) makes them appear the brightest with respect to all other surrounds.

(3) The blue surround (4) makes them look brighter than in the case of the yellow surround (3).

(4) The surround (1) makes them look brighter than in the case of the surround (2).

(5) The orange surround (9) makes them look brighter than in the case of the green surround (10).

(6) The surround (8) makes them look brighter than in the case of surround (7)

Bearing in mind, that the blue is darker than the yellow and the orange is darker than the green (as shown in Table 7), these conclusions may lead to the following two general empirical rules.

Rule (5) For the one colour backgrounds: the darker the surround, the brighter the test colour appears. This is clear from the experience of our everyday life.

Rule (6) For the two colour backgrounds: The test colour seems to be related in brightness to the brightness of the stripe on which it is mounted. (Since the conclusions (4 & 6) are direct applications of rules (5 & 6).

#### (E) BLACK-WHITE SURROUNDS:

Compound black-white surrounds (11) and (12) figure (41) were studied for the orange, yellow and green test colour, for element angle of subtense 15' in the vertical plane, and the changes in chromaticity and apparent brightness are shown in Table (12) and figures (50-52) inclusive. Black and white being nearly neutral and differ only in their reflectance factor, it was expected that these surrounds would affect only the brightness and saturation of the test colour, but its hue also was

affected.

Rule (6) (namely, the test colour is related in brightness to the brightness of the stripe on which it is mounted) and Rule (5) (namely, the darker the surround, the brighter the test colour appears), apply in the present two cases. In general the brightness of the test colour in surround (11) ~~lies~~ in between those in surrounds (5) and (6) and the brightness in the case of surround (12) is smaller than that of surround (5) (with one exception, the case of orange in surround (12)), whose brightness lies in between those in surround (5) and (6) also).

Rule (1) (namely, the shifts due to two colour surrounds are bigger than those due to one colour surround,) and Rule (2) (namely the shifts due to two colour surrounds are generally away from the colour of the stripe on which the test colour is mounted and towards that of the two side stripes), do not apply in the present two cases. This is not a surprising result since the black and white used are nearly of the same chromaticity (Table 7) and the point corresponding to the white surround is taken as reference of shifts. The results can be looked at from another angle, namely the shift due to total black surround is bigger than that due to partial black and white surround.

#### (F) THE SIGNIFICANCE OF THE SHIFTS DUE TO DIFFERENT SURROUNDS.

The appearance of each test colour on any surround as shown in the results throughout this work is calculated from the average of four settings of the three controlling knobs. The final results of each of these settings were calculated for all the test colours and surrounds used, in the case of the compound pattern of 15' element angle of subtense and 20° inclination. The spreading in these results is shown numerically in

**TABLE (13) THE SPREAD OF THE RESULTS CORRESPONDING TO THE FOUR SETTINGS OBTAINED FOR EACH POINT TOGETHER WITH THE AVERAGE RESULTS, FOR ALL TEST COLOURS AGAINST THEIR BACKGROUNDS FOR COMPOUND PATTERN OF 15° ELEMENT ANGLE OF SUBTENSE AND 20° INCLINATION.**

| SURROUND    |    | (1)  |      |      | (2)  |      |      | (3)  |      |      | (4)  |      |      | (5)  |      |      | (6)  |      |      |
|-------------|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| TEST COLOUR |    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| Orange      | 1. | .584 | .355 | 2.99 | .565 | .296 | 3.16 | .589 | .322 | 2.87 | .586 | .329 | 3.45 | .595 | .324 | 2.06 | .558 | .340 | 2.96 |
|             | 2. | .587 | .355 | 3.07 | .561 | .296 | 3.12 | .591 | .320 | 2.83 | .583 | .329 | 3.51 | .599 | .321 | 2.03 | .556 | .341 | 3.99 |
|             | 3. | .588 | .355 | 2.97 | .566 | .300 | 3.09 | .590 | .320 | 2.74 | .579 | .330 | 3.54 | .600 | .323 | 2.02 | .560 | .339 | 3.98 |
|             | 4. | .591 | .352 | 2.94 | .566 | .294 | 3.07 | .592 | .323 | 2.84 | .582 | .328 | 3.48 | .600 | .322 | 2.06 | .553 | .343 | 4.04 |
|             | M  | .587 | .354 | 2.99 | .564 | .296 | 3.11 | .589 | .321 | 2.77 | .584 | .329 | 3.47 | .600 | .322 | 2.04 | .558 | .340 | 3.99 |
| Green       | 1. | .310 | .509 | 5.04 | .246 | .443 | 4.65 | .292 | .430 | 2.47 | .291 | .497 | 5.00 | .290 | .501 | 2.77 | .332 | .493 | 4.75 |
|             | 2. | .313 | .508 | 4.96 | .249 | .447 | 4.74 | .285 | .489 | 2.32 | .295 | .491 | 5.19 | .290 | .500 | 2.66 | .334 | .493 | 5.05 |
|             | 3. | .315 | .507 | 4.97 | .246 | .450 | 4.61 | .291 | .486 | 2.58 | .298 | .491 | 4.90 | .292 | .499 | 2.68 | .329 | .495 | 4.83 |
|             | 4. | .319 | .503 | 4.95 | .249 | .446 | 4.62 | .294 | .489 | 2.59 | .297 | .495 | 4.94 | .289 | .502 | 2.79 | .330 | .494 | 5.19 |
|             | M  | .316 | .505 | 4.98 | .248 | .446 | 4.67 | .290 | .486 | 2.59 | .298 | .492 | 4.96 | .290 | .500 | 2.71 | .331 | .494 | 4.88 |
| Grey        | 1. | .497 | .416 | 0.64 | .368 | .307 | .78  | .466 | .376 | .52  | .473 | .397 | .79  | .471 | .388 | .49  | .422 | .373 | 1.23 |
|             | 2. | .505 | .412 | 0.68 | .374 | .316 | .73  | .463 | .372 | .51  | .470 | .401 | .80  | .465 | .384 | .48  | .423 | .375 | 1.23 |
|             | 3. | .499 | .414 | 0.66 | .371 | .309 | .74  | .464 | .381 | .51  | .472 | .399 | .80  | .468 | .388 | .48  | .418 | .376 | 1.28 |
|             | 4. | .499 | .415 | 0.63 | .379 | .318 | .79  | .458 | .380 | .51  | .471 | .399 | .80  | .466 | .385 | .48  | .420 | .378 | 1.28 |
|             | M  | .499 | .415 | 0.65 | .370 | .314 | 0.77 | .463 | .377 | 0.51 | .472 | .399 | 0.80 | .466 | .387 | 0.49 | .422 | .378 | 1.25 |

TABLE (13) Cont'd.

| SURROUND    |    | (7)  |      |      | (8)  |      |      | (9)  |      |      | (10) |      |      | (5)  |      |      | (6)  |      |      |
|-------------|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| TEST COLOUR |    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    | x    | y    | Y    |
| Yellow      | 1. | .504 | .412 | 5.55 | .432 | .454 | 7.63 | .451 | .444 | 7.31 | .484 | .424 | 6.24 | .475 | .429 | 4.43 | .443 | .446 | 7.79 |
|             | 2. | .504 | .412 | 5.49 | .435 | .453 | 7.63 | .455 | .441 | 7.13 | .492 | .419 | 6.02 | .479 | .426 | 4.41 | .440 | .447 | 7.18 |
|             | 3. | .499 | .415 | 5.66 | .434 | .454 | 7.65 | .451 | .443 | 7.33 | .486 | .423 | 6.25 | .474 | .430 | 4.48 | .441 | .447 | 7.86 |
|             | 4. | .501 | .414 | 5.58 | .436 | .452 | 7.71 | .453 | .442 | 7.14 | .488 | .422 | 6.15 | .475 | .429 | 4.53 | .441 | .447 | 7.38 |
|             | H  | .502 | .413 | 5.57 | .434 | .453 | 7.64 | .452 | .443 | 7.23 | .488 | .421 | 6.14 | .474 | .430 | 4.51 | .441 | .446 | 7.85 |
| Blue        | 1. | .363 | .259 | 0.40 | .277 | .250 | 0.54 | .268 | .240 | 0.48 | .286 | .242 | 0.32 | .244 | .222 | 0.20 | .323 | .268 | 0.62 |
|             | 2. | .370 | .260 | 0.39 | .274 | .248 | 0.52 | .273 | .239 | 0.44 | .289 | .243 | 0.34 | .245 | .218 | 0.21 | .325 | .267 | 0.60 |
|             | 3. | .362 | .260 | 0.40 | .278 | .252 | 0.53 | .271 | .237 | 0.48 | .288 | .239 | 0.32 | .247 | .221 | 0.20 | .320 | .264 | 0.59 |
|             | 4. | .368 | .260 | 0.42 | .272 | .251 | 0.56 | .268 | .239 | 0.46 | .287 | .243 | 0.32 | .244 | .223 | 0.21 | .321 | .264 | 0.62 |
|             | H  | .368 | .261 | 0.40 | .275 | .250 | 0.54 | .269 | .239 | 0.46 | .289 | .243 | 0.32 | .245 | .222 | 0.21 | .321 | .265 | 0.61 |
| Grey        | 1. | .536 | .348 | 0.62 | .387 | .431 | 0.71 | .424 | .387 | 0.82 | .474 | .370 | 0.74 | .471 | .388 | 0.49 | .422 | .373 | 1.23 |
|             | 2. | .538 | .345 | 0.60 | .387 | .429 | 0.72 | .428 | .388 | 0.84 | .474 | .366 | 0.73 | .465 | .384 | 0.48 | .423 | .375 | 1.23 |
|             | 3. | .540 | .341 | 0.62 | .387 | .427 | 0.73 | .429 | .382 | 0.86 | .471 | .371 | 0.73 | .468 | .388 | 0.48 | .418 | .376 | 1.23 |
|             | 4. | .540 | .343 | 0.59 | .388 | .429 | 0.74 | .426 | .384 | 0.83 | .476 | .368 | 0.74 | .466 | .385 | 0.48 | .420 | .378 | 1.23 |
|             | H  | .536 | .344 | 0.60 | .387 | .430 | 0.73 | .428 | .384 | 0.84 | .475 | .369 | 0.73 | .466 | .387 | 0.49 | .422 | .373 | 1.25 |

Tables (13) and graphically in figures (98-102) inclusive. These tables and graphs show that the individual results are fairly consistent with the differences from the average results varying for different test colours according to (1) their luminance and (2) the non-uniform spacing of the C.I.E. chromaticity chart. <sup>(77,79)</sup> (The differences in the chromaticity co-ordinates (x and y), range from 0 to  $\pm 0.004$  and in the relative luminance (Y) ranges from 0 to  $\pm 4\%$  with very few exceptions).

The graphs show also that the shifts due to different surrounds are significant compared with this spreading.

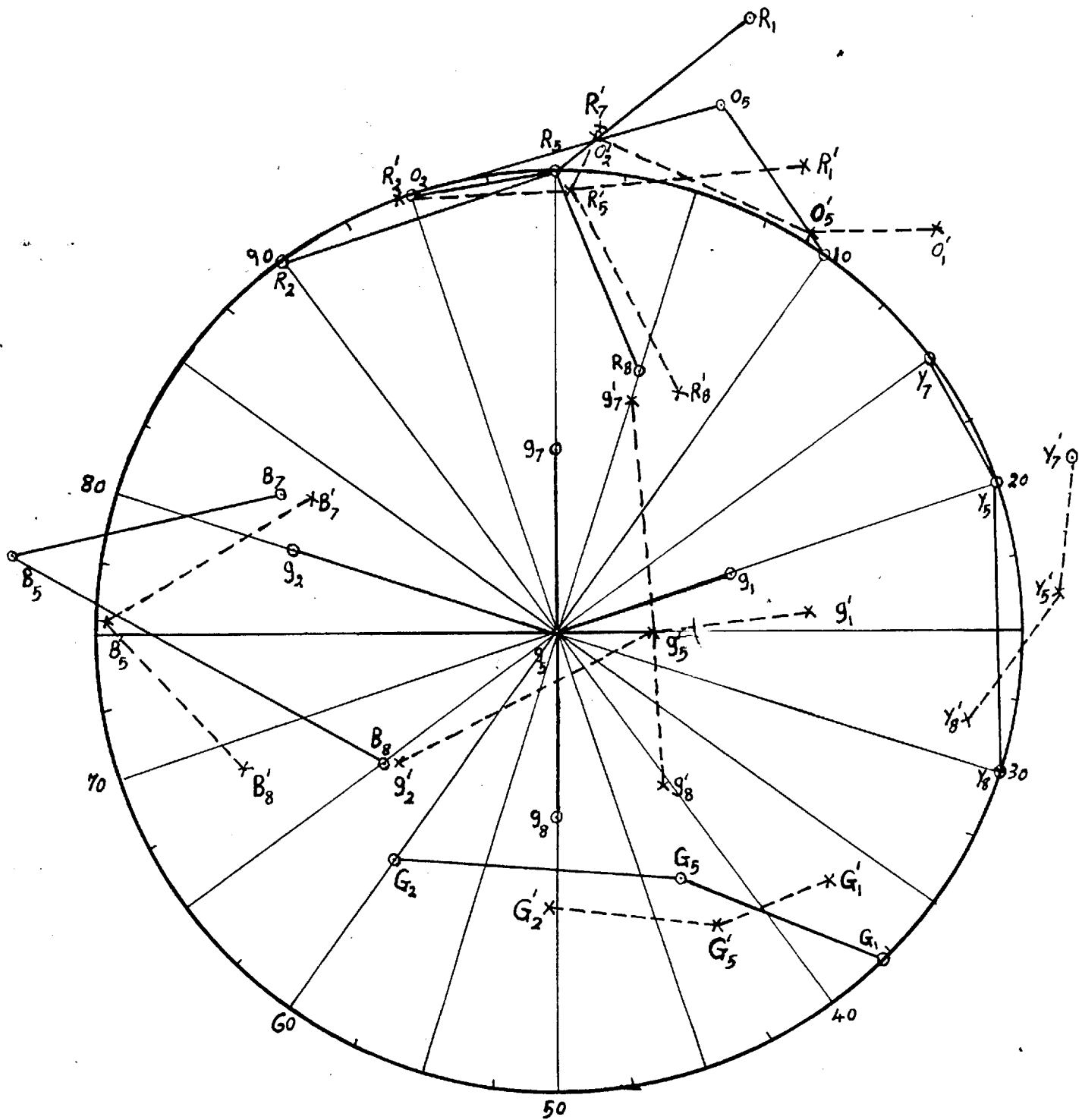


Figure (54) The Hue Chart showing the ~~average~~ results of the observers(- - -) and the results of the author (—), for the charts at 6' element angle of subtense, compared with the samples of the Munsell Book of Color.



## CHAPTER VI.

### COLOUR CONTRAST AS STUDIED BY DIFFERENT OBSERVERS USING THE MUNSELL BOOK OF COLOR.

In this method, two charts as shown in Plates (1a & 2a), with the complex pattern of test colours on two colour surrounds, were used. From the previous analysis of the results, obtained by using the colorimeter, these are the two conditions giving, (1) The bigger shifts corresponding to larger changes in colour appearance due to different surrounds, and (2) the changes in appearance occur in hue, chroma and value.

In the first method, using the colorimeter, source  $S_A$  was used to illuminate the test patch and the surround of the comparison patch. This enabled the study of the colour contrast phenomena under a standard illuminant ( $S_A$  i.e. the tungsten light which is widely used in our everyday life) with an eye adapted to the same illuminant.

In the present method, natural daylight was used to illuminate both the chart and the Munsell Book of Color, since the Munsell coloured chips were calibrated in daylight (Source C). This enables a study of the Colour Contrast Phenomena as they occur in nature during daytime i.e. in the same conditions of illumination and viewing (adaptation of the eye).

Each of the observers, carrying out the long procedure described in Chapter III was fairly consistent in his results.

Figure (54) shows the average results of the different observers (11 observers for the first chart and 8 observers for the second chart), plotted on a hue chart (hue circle with chroma represented by the distance from its centre) for all the test colours used (red (R), orange (O), yellow (Y), green (G), blue (B) and grey (g)), for an element angle of

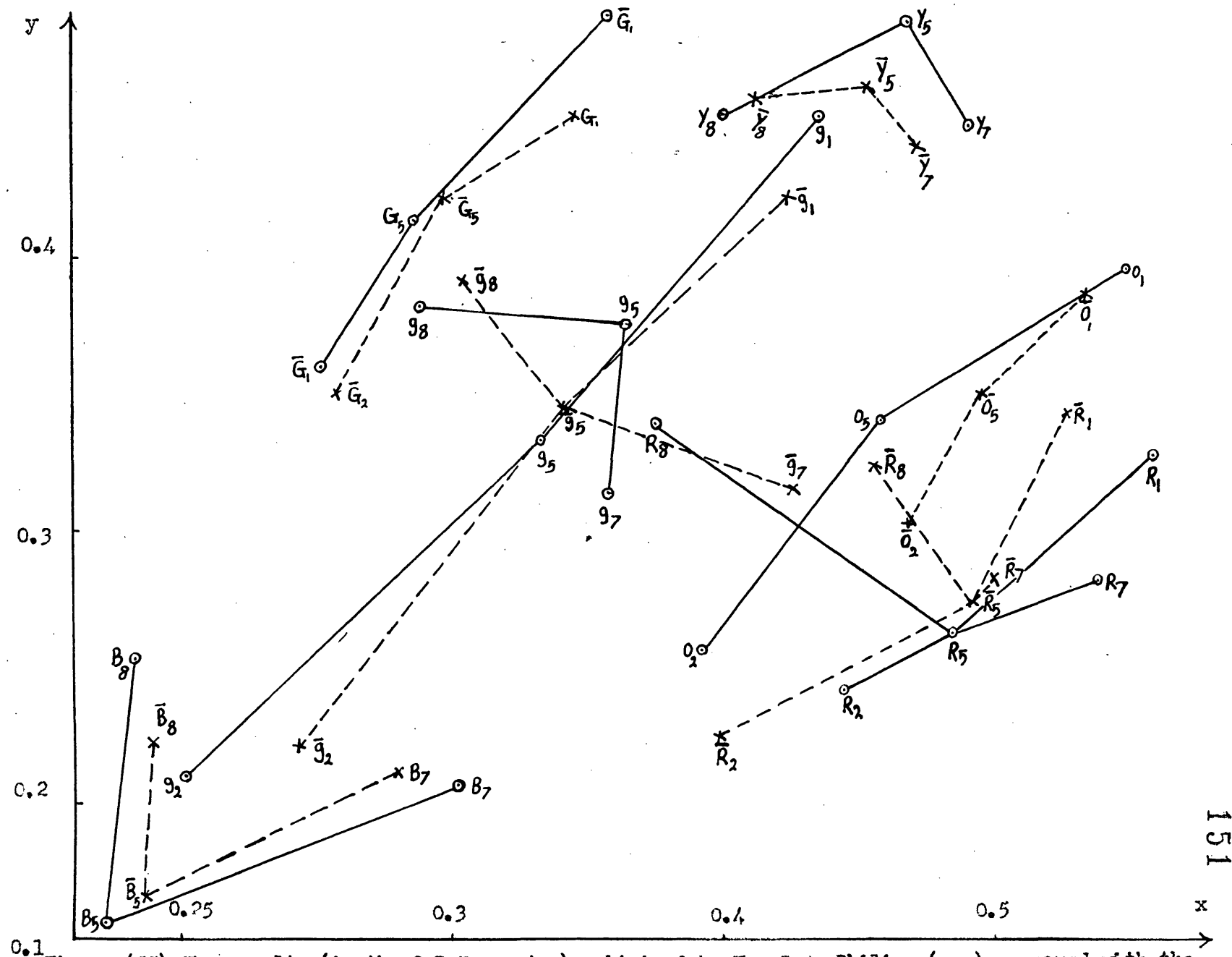


Figure (55) The results (in the C.I.E. system), obtained by Mr. D.H. Philips (—) compared with the average results, for the two charts at 6' angle of subtense. (---)

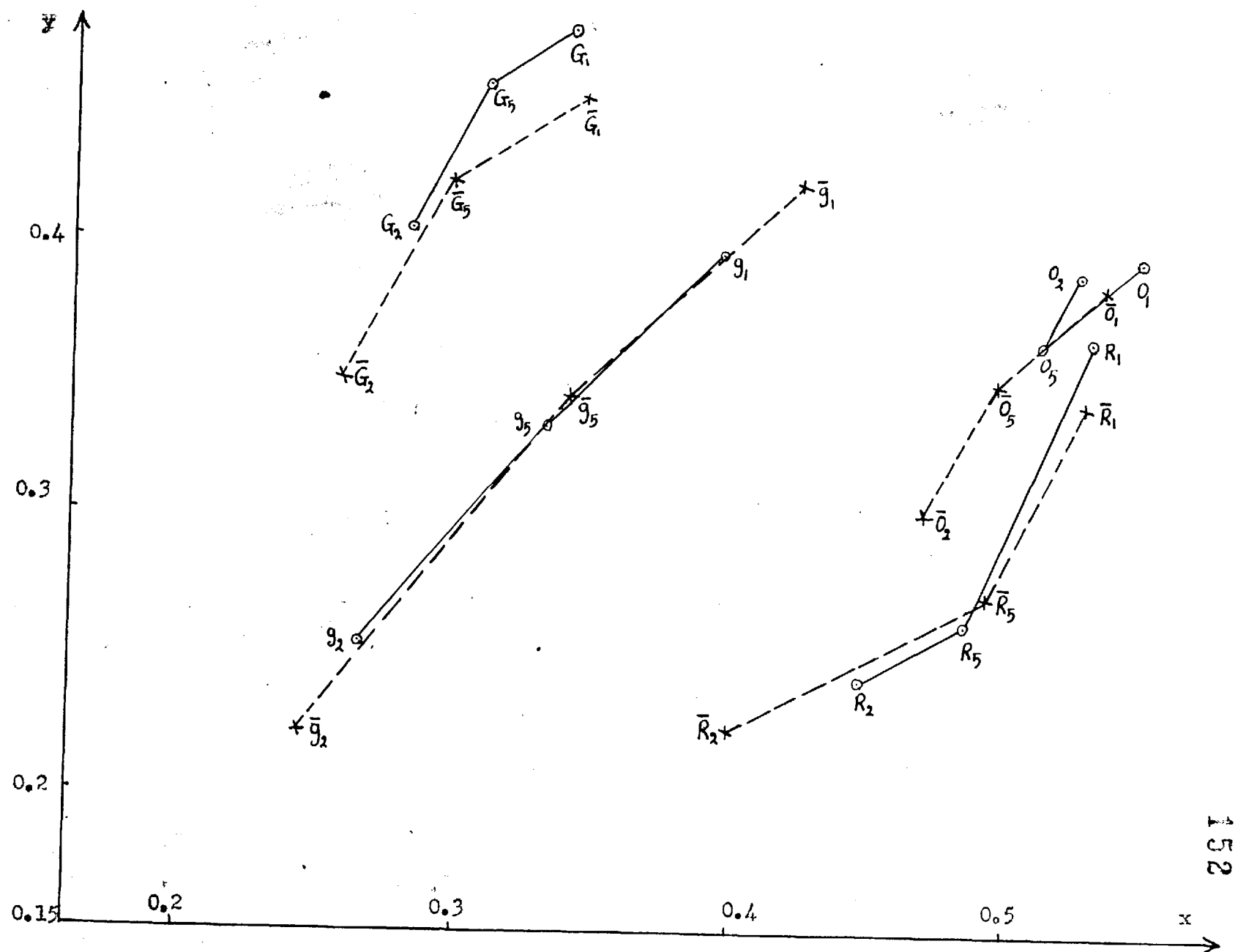


Figure (56) The results (in the C.I.E. system), obtained by Mr. K.H. Ruddock (—) compared with the average results (---), for the first chart at 6' element angle of subtense.

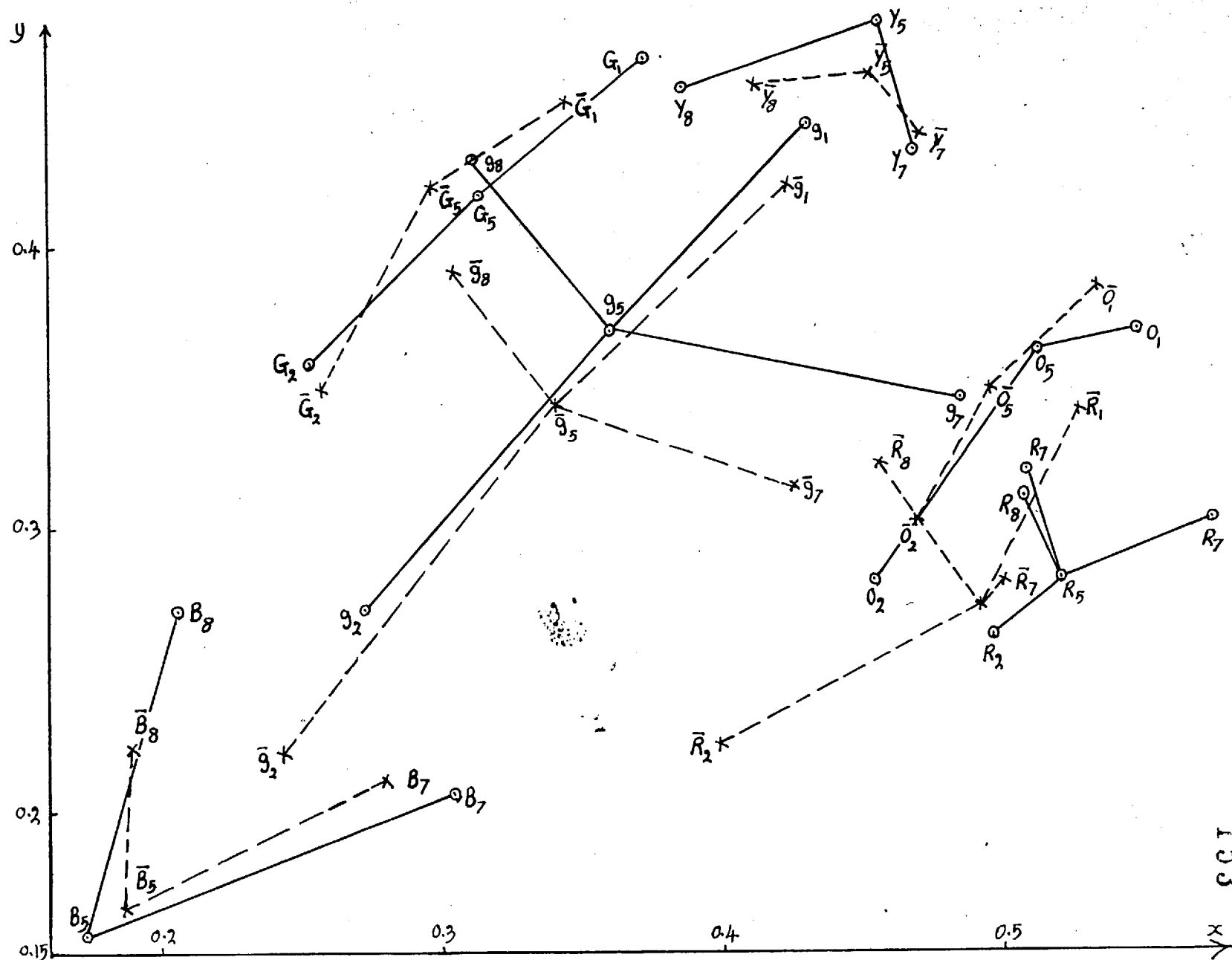


Figure (57) The results (in the C.I.M. system), obtained by Mr. P.R. Bunkall (—), compared with the average results (---), for the two charts at 6' element angle of subtense.

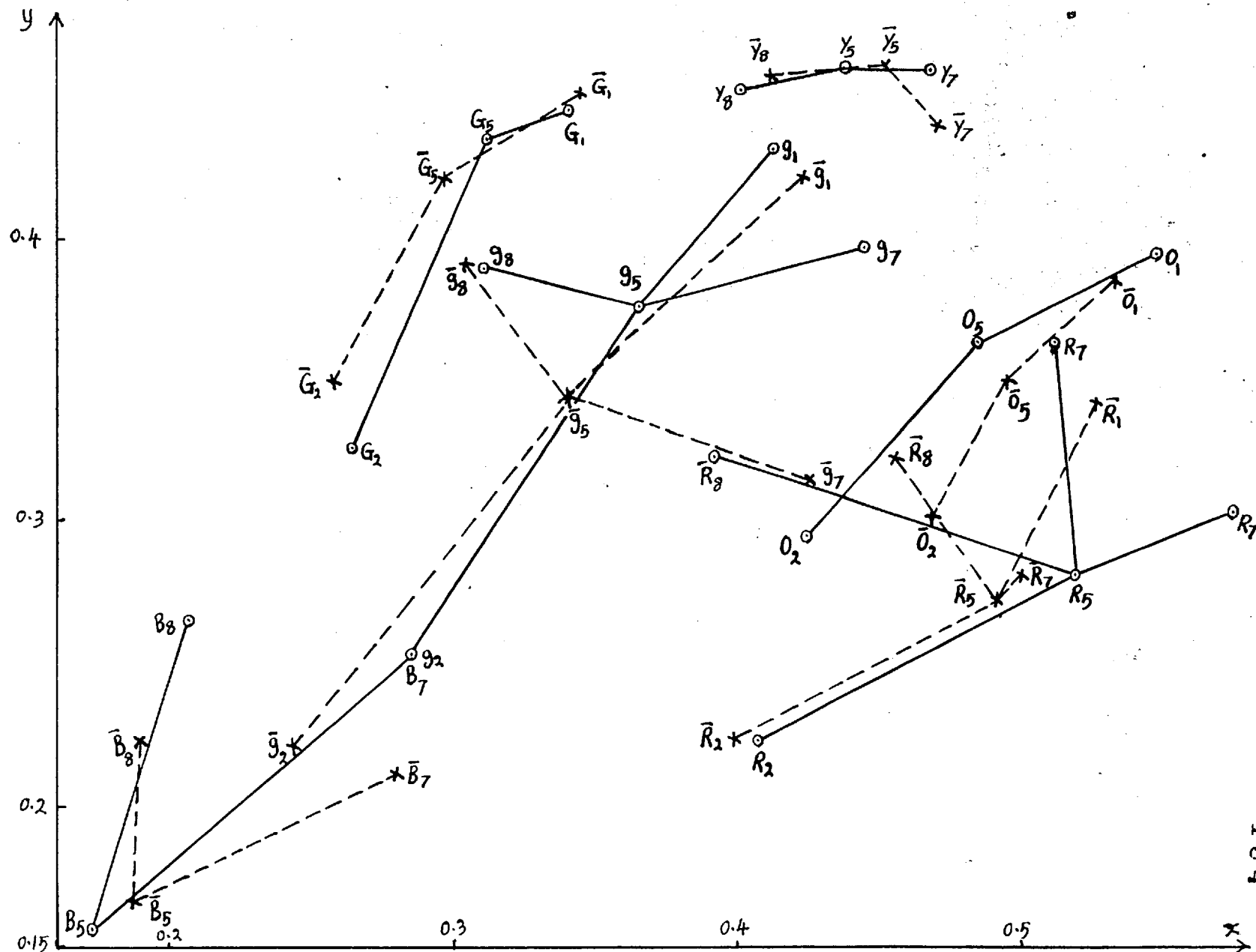


Figure (53) The results, obtained by Mr. R.A. Hargreaves (—), compared with the average results (---), For the two charts at 6' element angle of subtense.



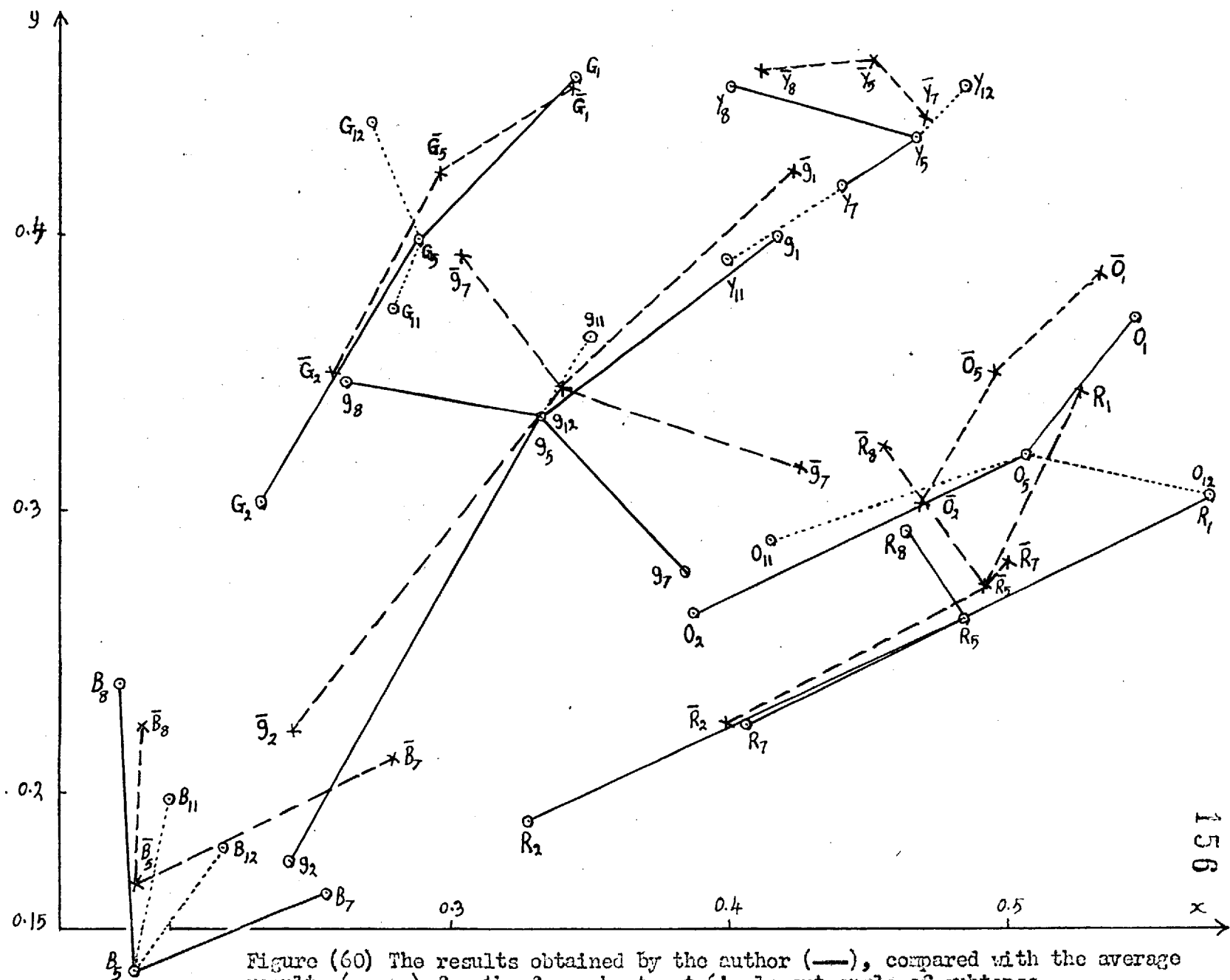


Figure (60) The results obtained by the author (—), compared with the average results (---), for the four charts at 6' element angle of subtense.

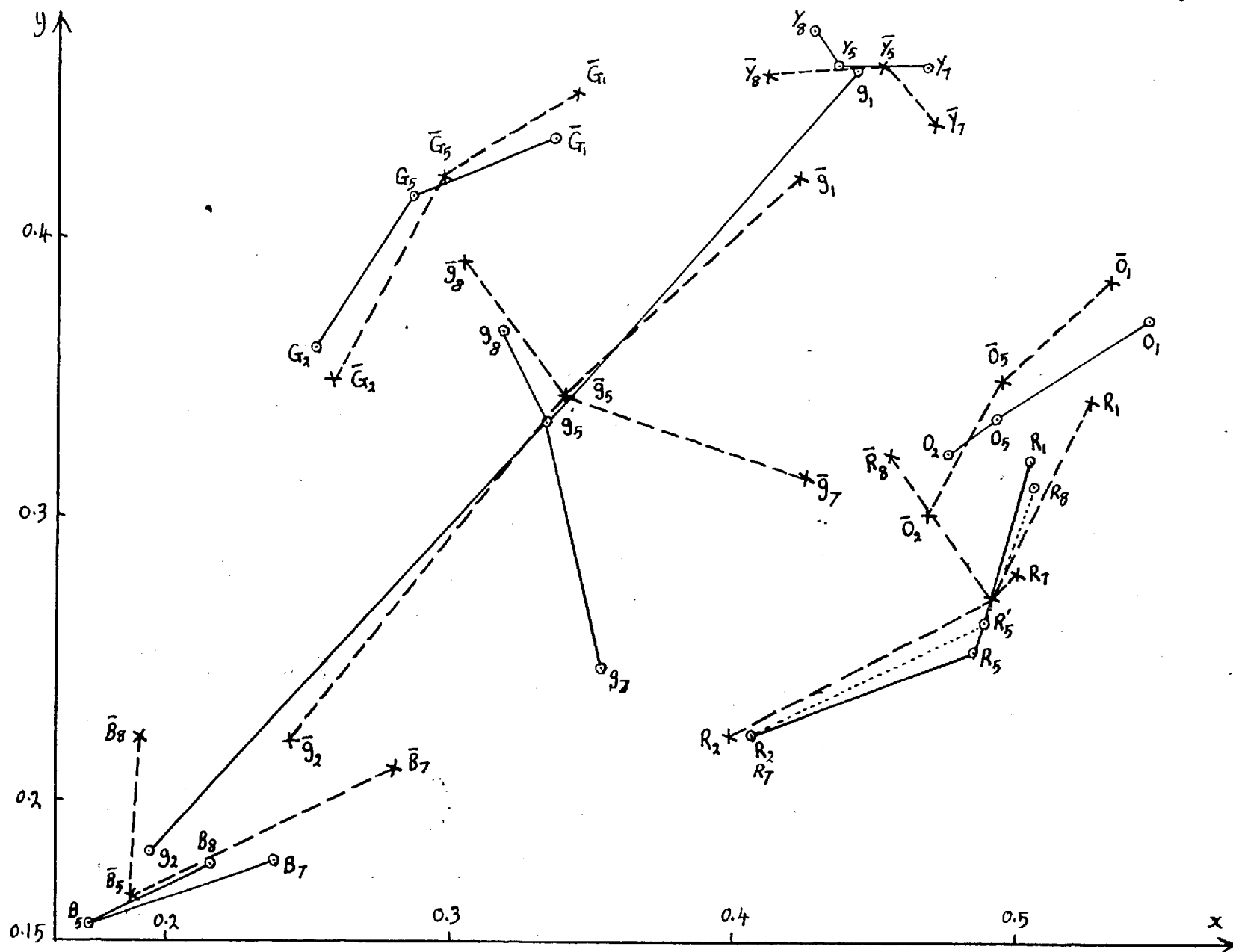


Figure (61) The results obtained by Mr. W. H. Kitchen (—), compared with the average results (---) for the two charts at 6' element angle of subtense.



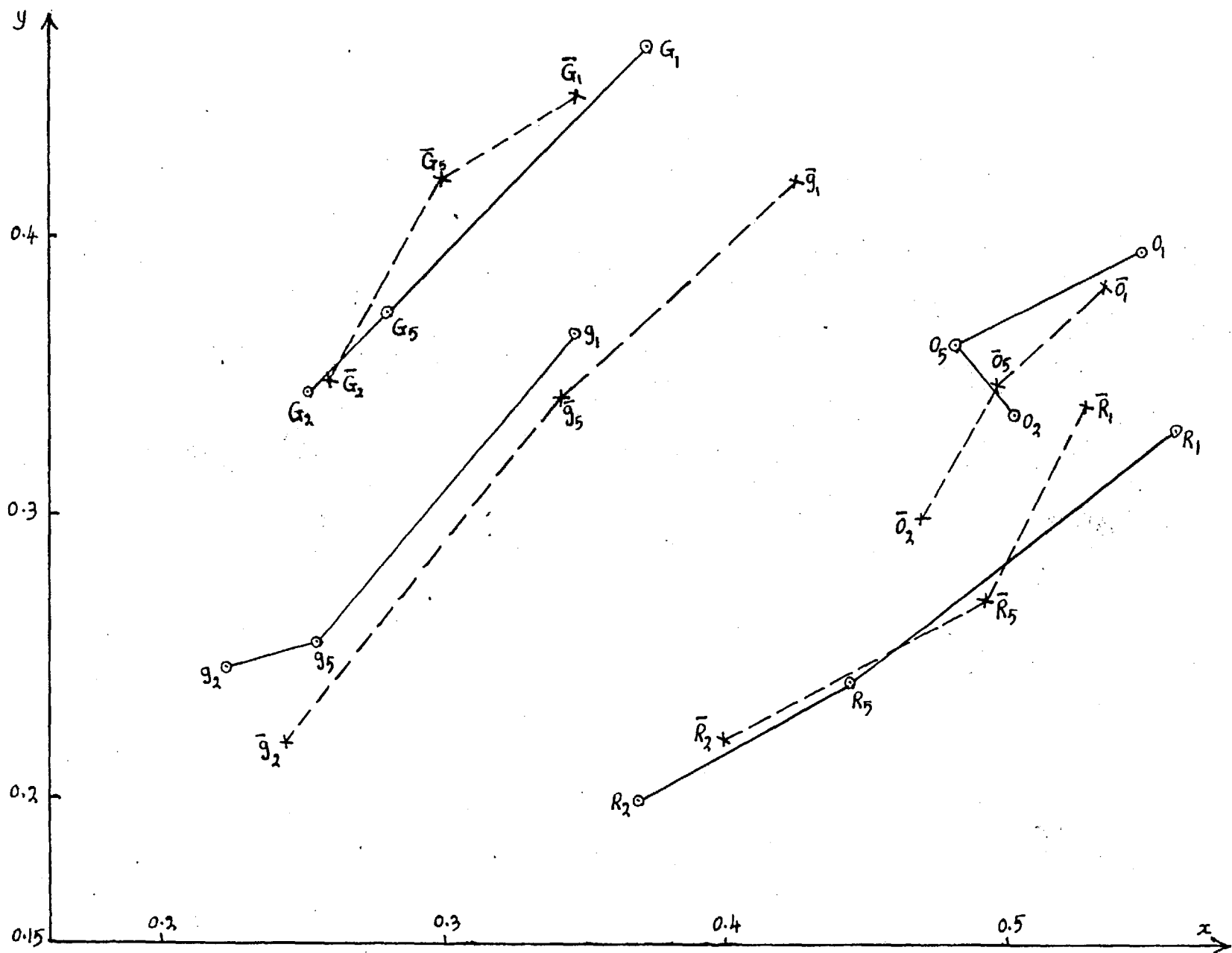


Figure (62) The results obtained by Mrs. J. Birch, compared with the average results (---), for the First chart at 6' element angle of subtense. (—).

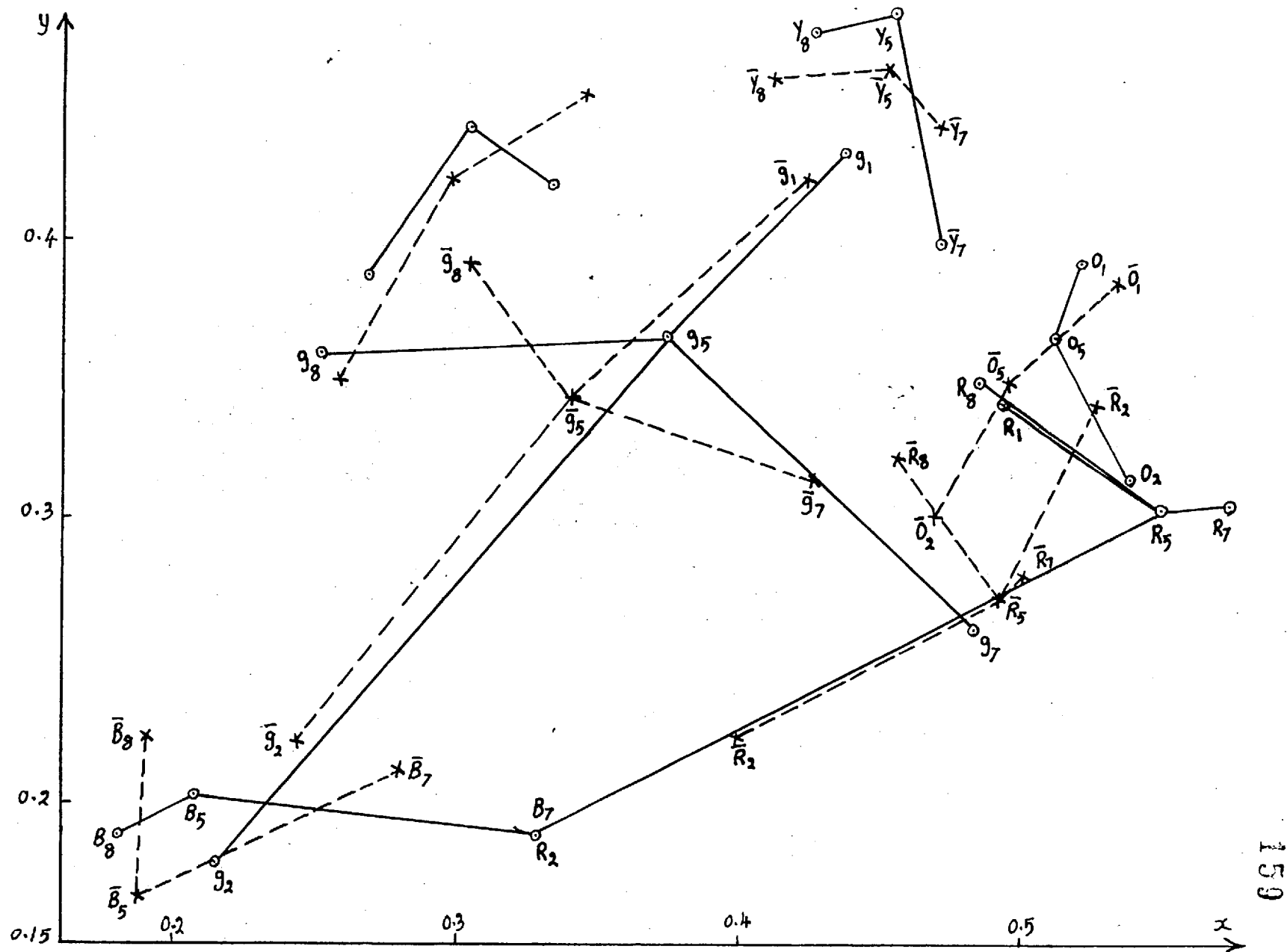


Figure (63) The results obtained by Mr. I. Nimeroff (—), compared with the average results (---) for the two charts, at 6' element angle of subtense.

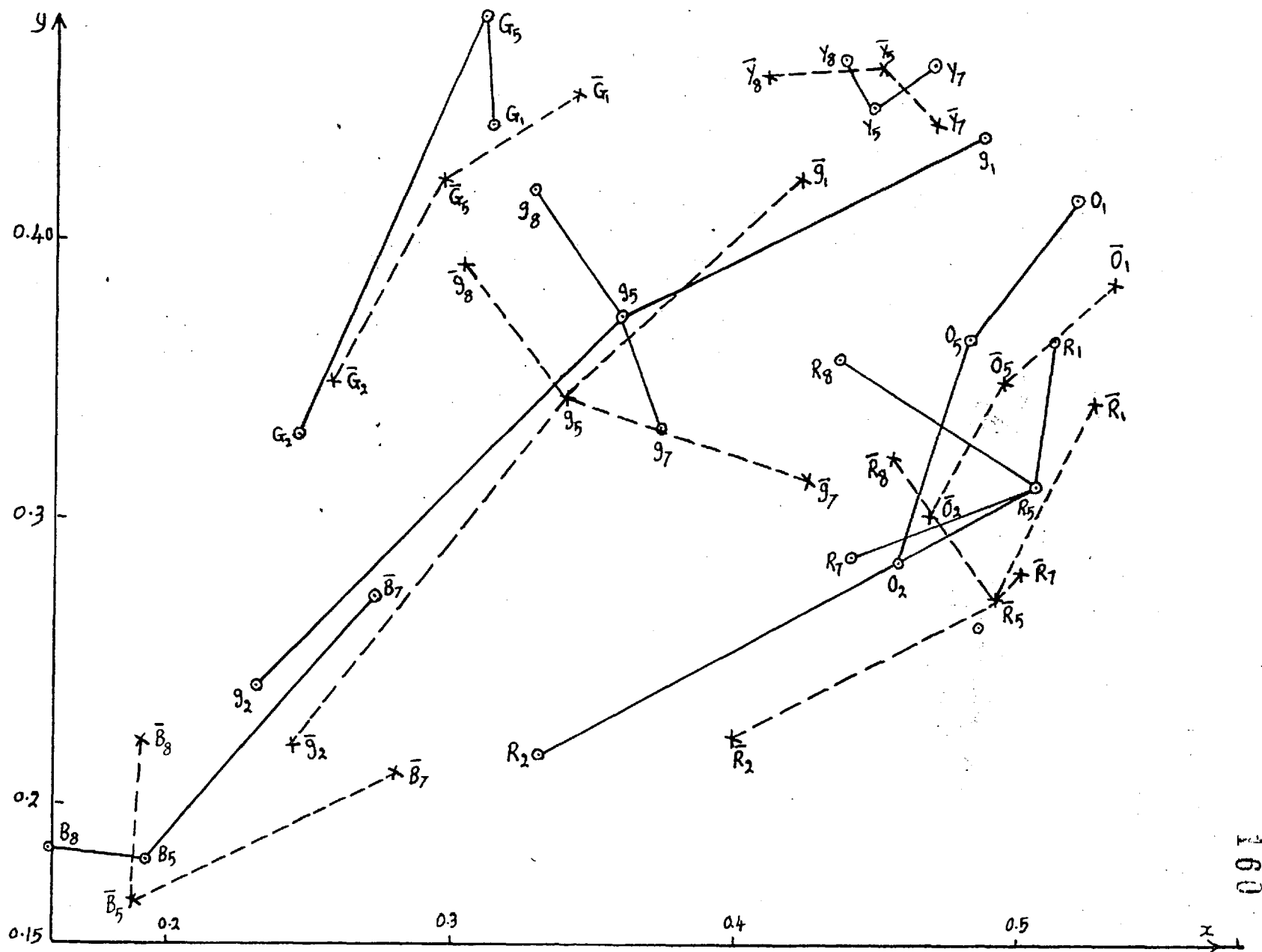


Figure (64) The results obtained by Mr. P. Charoenkul (—), compared with the average results (---) for the two charts, at 6' element angle of subtense.

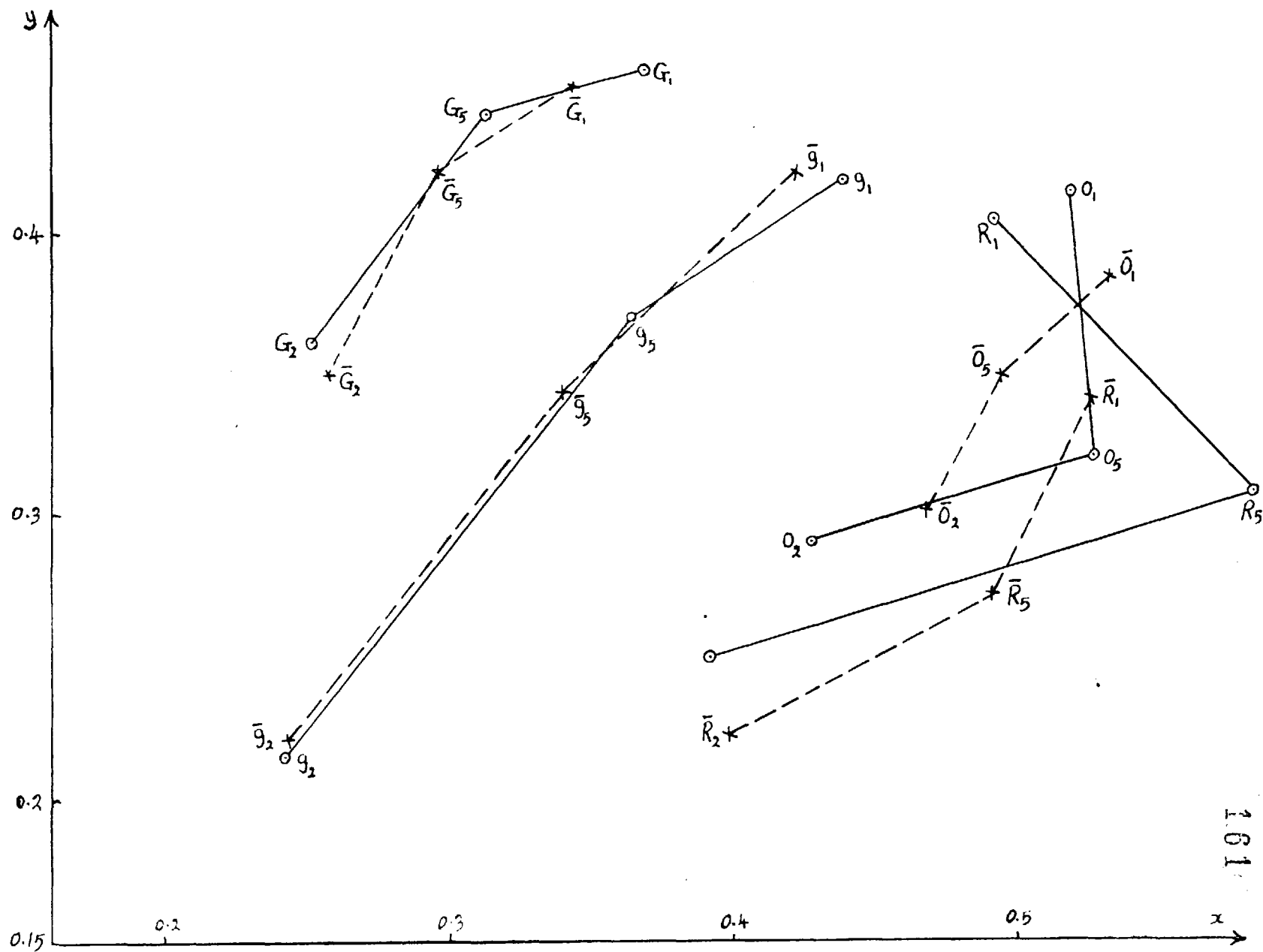


Figure (65) The results obtained by Dr. I. S. R. Ishak (—), compared with the average results (---), for the first chart, at 61 element angle of subtense.

subtense = 6' (The angle of subtense of the square of test colour on the white surround = 12'). The third general empirical rule (namely the shifts due to two colour surrounds are generally away from the colour of the stripe on which the test colour is mounted, and towards that of the other two side stripes), applies also in this case with one exception, the case of blue on surround(8). This method, being limited to the case of compound pattern with two colour surround, can not show the other three empirical rules.

Figure (54), also shows the results obtained by the author compared with the average results of all the observers plotted on a hue chart. The following can be seen from this figure:

(1) The general directions of the shifts due to different surrounds are nearly the same in the two cases.

(2) In general, the magnitudes of the shifts obtained by the author are bigger than the average shifts obtained by all the observers. This may show that the author is more sensitive to colour contrast than the average observer, (most of the observers are not accustomed to the colour matching technique using the Munsell Book of Color).

The results are then transformed from the Munsell system of hue (H) value (V) and chroma (C) into the C.I.E. system of the trichromatic coordinates (x) and (y) and luminance factor (Y), and are plotted in the chromaticity chart. The figures (55-65) inclusive, show the results obtained by each observer compared with the average results for all observers. Also the results are summed up in one graph for each test colour, as shown in figures (66-71) inclusive. It can be concluded from all these figures that:

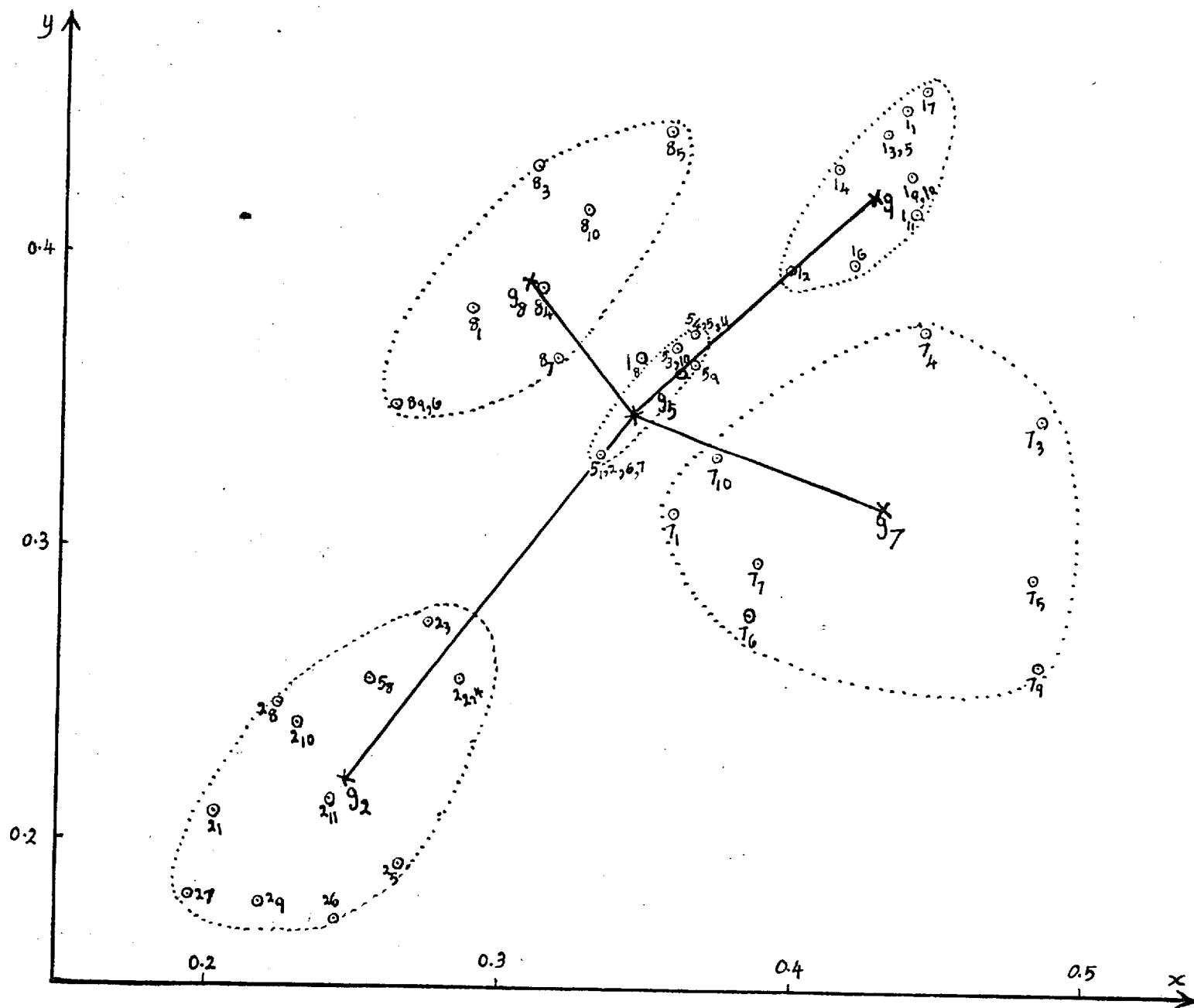


Figure (66) The results of all observers and their average, for the Grey Test Colour.

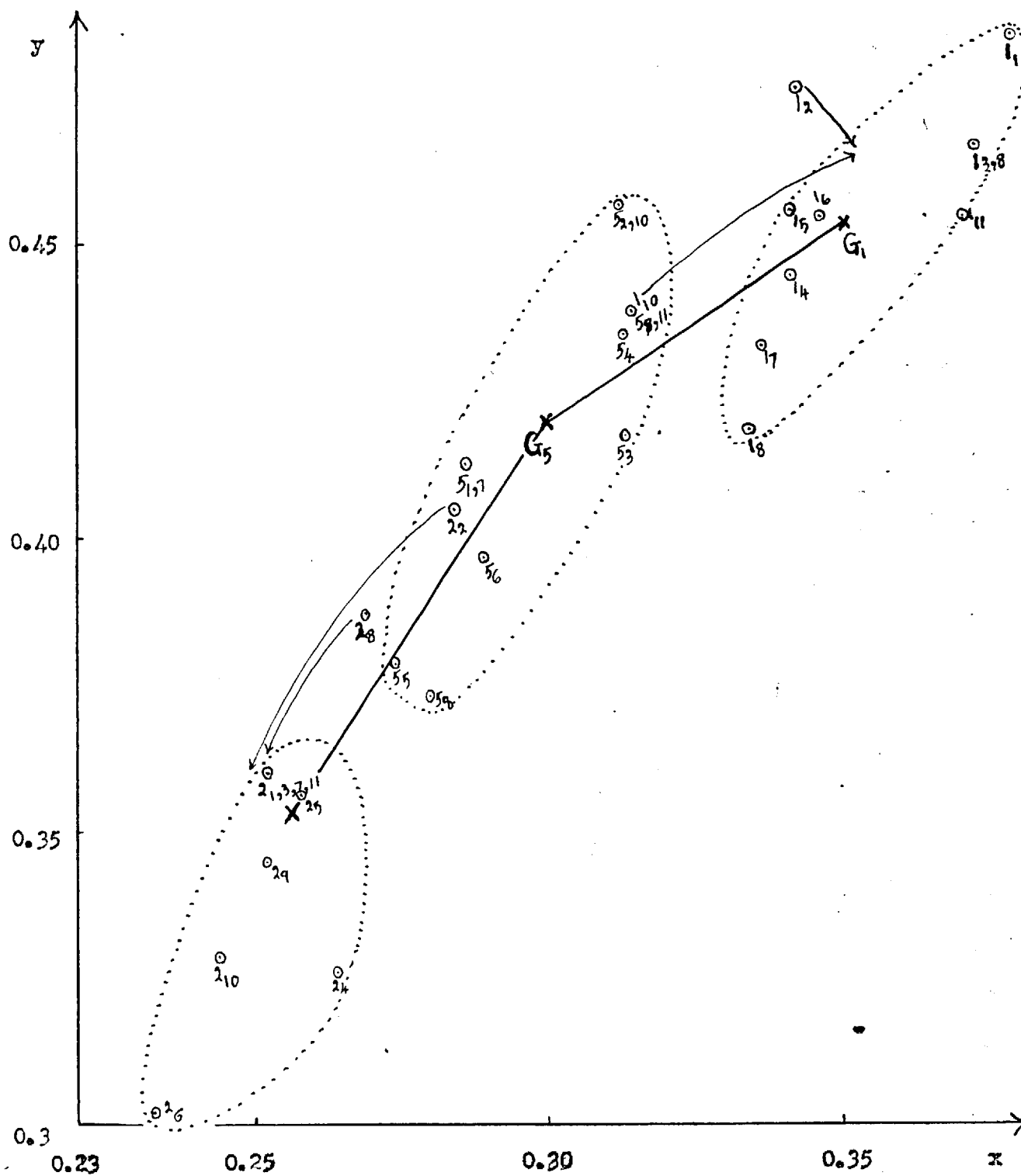
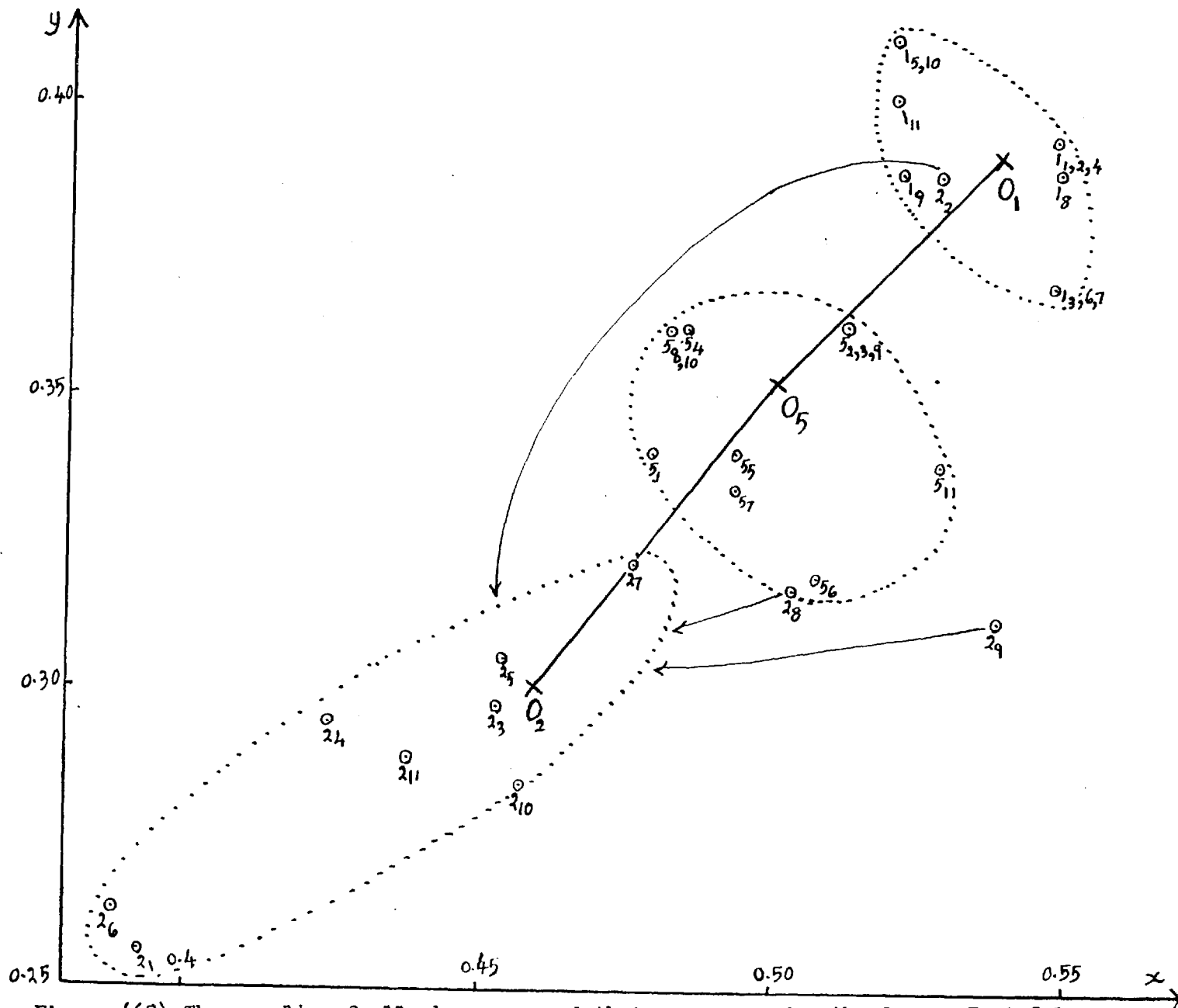
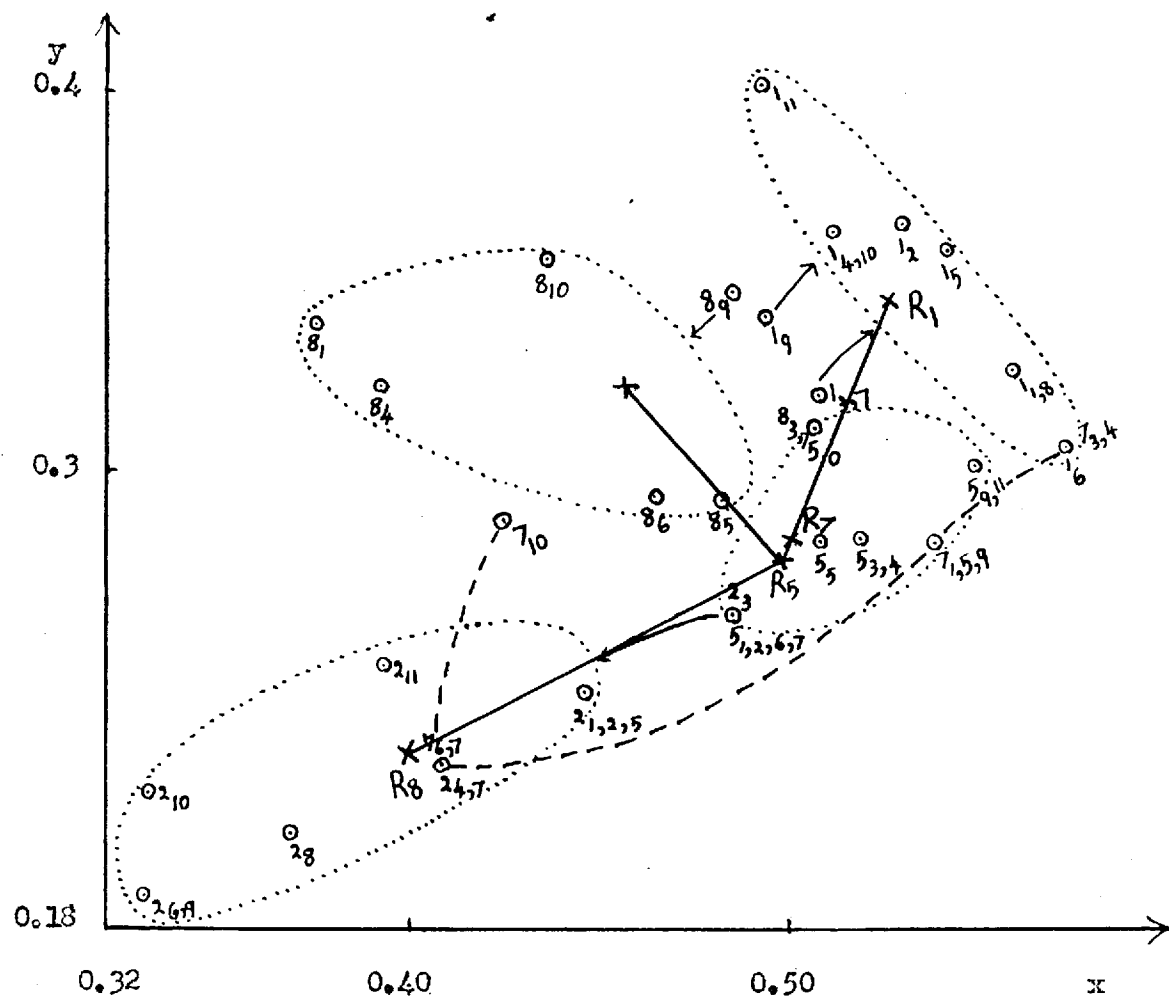


Figure (67) The results of all observers and their average, for the Green Test Colour.







Figure(69) The results of all observers and their average, for the Red Test Colour.

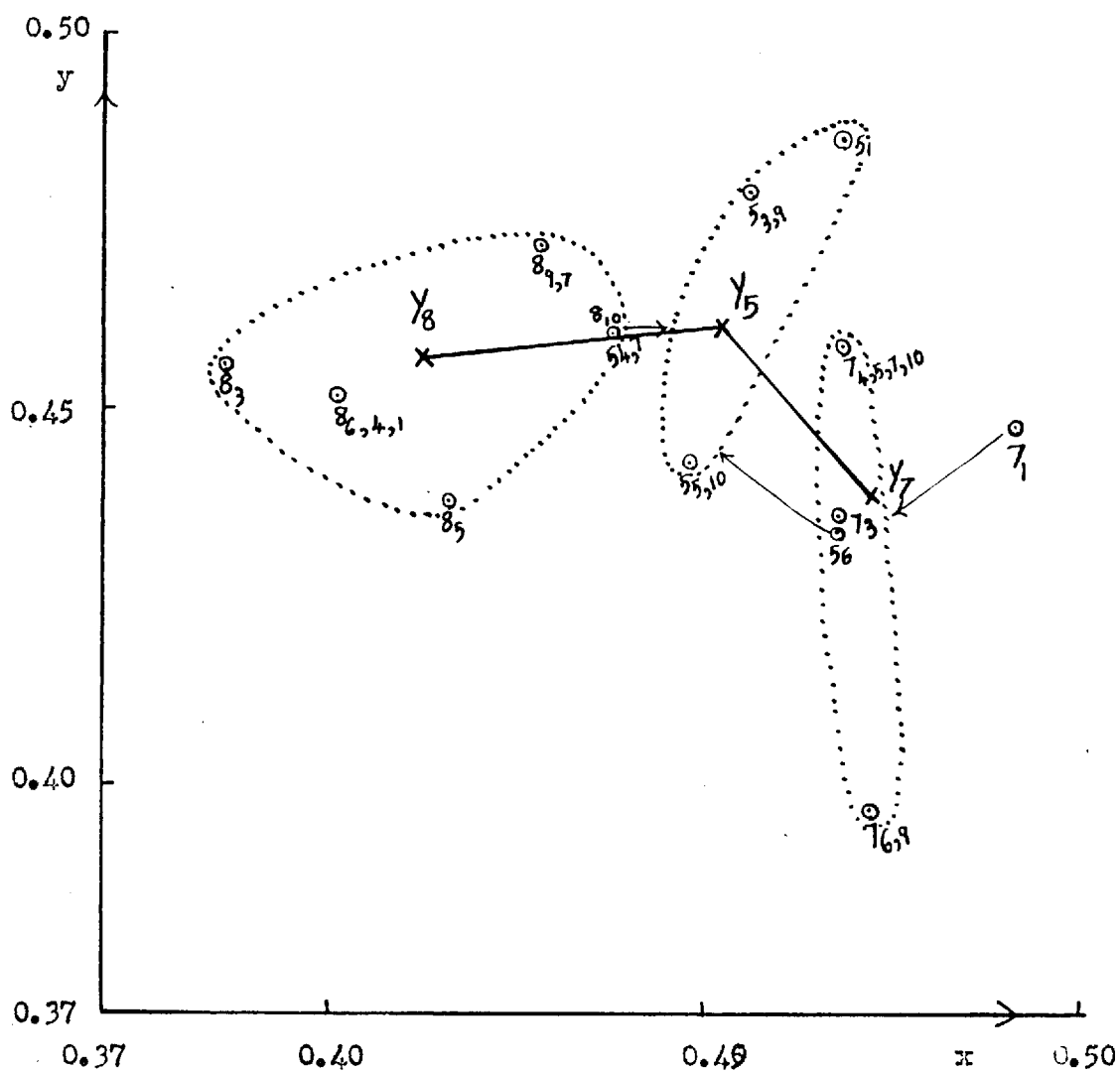


Figure (70) The results of all observers and their average, for the Yellow Test Colour.

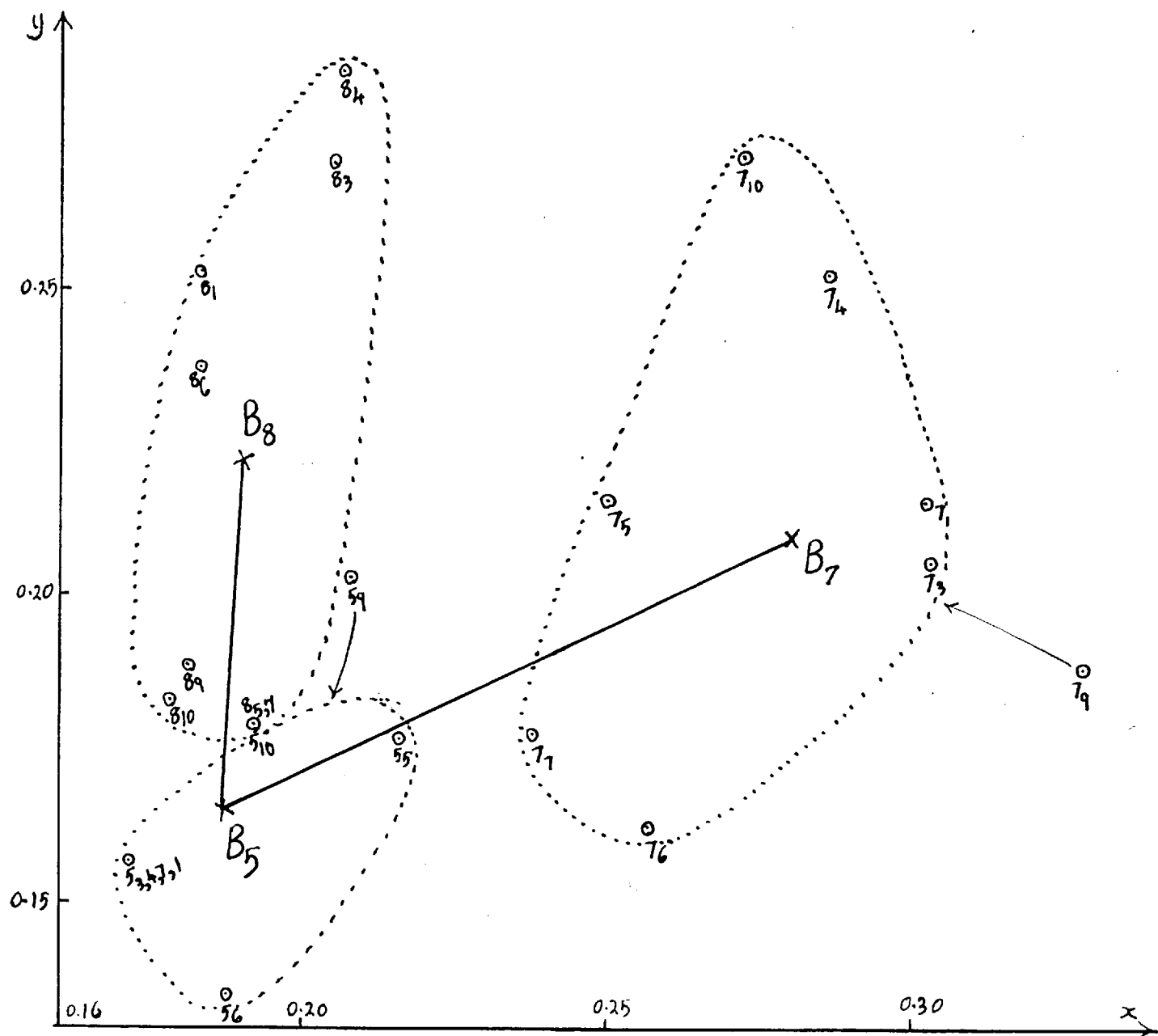


Figure (71) The results of all observers and their average., for the Blue Test Colour.

(1) The shifts due to different surrounds as obtained by individual observers of normal colour vision are in the same sense.

(2) The magnitudes and the actual directions of these shifts vary considerably from one observer to the other.

These differences in magnitude and direction of the shifts may be due to experimental and personal factors.

(A) THE EXPERIMENTAL FACTORS:

(1) The variability of quality and brightness of natural daylight, at the different times in which the different observers did the experiment. Although the matching was carried out only when the sky was bright, which reduces these variations, but does not eliminate them.

(2) The rather big steps of hue, value and chroma between the neighbouring coloured chips of the Munsell Book of Color. Interpolating or extrapolating between the hues, values and chromas of the coloured chips may therefore be required to define the sample which matches the colour appearance under test, and this may be very difficult for the untrained observers.

(B) THE PERSONAL FACTORS:

Assuming that the variation in quality and intensity of natural daylight at the matching time of the different observers is small enough to be neglected, and that each observer has tried his best to get matches as accurately as possible, then these differences may indicate that different persons perceive colour contrast differently. This may be due to the following reasons:

(1) Different sensitivities of colour receptors of different observers.

(2) Different densities of macular pigmentation (affecting mostly

TABLE (14). RESULTS OF DIFFERENT OBSERVERS FOR THE ORANGE TEST COLOUR SHOWN IN THE MUNSSELL & C.I.E. SYSTEMS

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND (5) |      |     |      |      |      |      | (1)  |   |    |      |      |      | (2)   |     |      |      |      |      |
|--------------|------|-----|------|------|------|------|------|---|----|------|------|------|-------|-----|------|------|------|------|
| NAME         | H    | V   | C    | x    | y    | Y    | H    | V | C  | x    | y    | Y    | H     | V   | C    | x    | y    | Y    |
| 1- D.E.P     | 7.5  | 5.5 | 10   | .479 | .341 | 24.6 | 12.5 | 7 | 14 | .548 | .395 | 43.1 | 95.0  | 4.5 | 10   | .393 | .256 | 15.6 |
| 2- K.H.R.    | 10.0 | 5.0 | 10   | .512 | .363 | 19.8 | 12.5 | 6 | 14 | .548 | .394 | 30.1 | 7.5   | 5.0 | 12   | .528 | .389 | 19.8 |
| 3-P.B.       | 10.0 | 5.0 | 10   | .512 | .363 | 19.8 | 10.0 | 6 | 10 | .547 | .370 | 36.1 | 100.  | 4.0 | 10   | .453 | .281 | 12.0 |
| 4-R.A.H.     | 10.0 | 5.5 | 10   | .485 | .363 | 24.6 | 12.5 | 6 | 14 | .548 | .394 | 30.1 | 100.  | 5.0 | 10   | .434 | .292 | 19.8 |
| 5-S.B.       | 7.5  | 5.0 | 10   | .493 | .341 | 19.8 | 15.0 | 6 | 12 | .520 | .412 | 30.1 | 2.5   | 5.0 | 10   | .454 | .306 | 19.8 |
| 6-S.S.G.     | 5.0  | 5.0 | 12   | .507 | .320 | 19.8 | 10.0 | 6 | 10 | .546 | .370 | 30.1 | 95.0  | 5.0 | 10   | .388 | .263 | 19.8 |
| 7-W.H.K.     | 7.5  | 5.0 | 10   | .493 | .335 | 19.8 | 10.0 | 6 | 10 | .547 | .370 | 30.1 | 5.0   | 5.0 | 10   | .476 | .322 | 19.8 |
| 8-J.B.       | 10.0 | 6.0 | 10   | .482 | .362 | 30.1 | 12.5 | 6 | 14 | .548 | .395 | 30.1 | 5.0   | 4.0 | 14   | .503 | .318 | 12.0 |
| 9-I.N.       | 10.0 | 5.0 | 10   | .512 | .363 | 19.8 | 12.5 | 6 | 12 | .521 | .369 | 30.1 | 5.0   | 4.0 | 12   | .538 | .313 | 12.0 |
| 10-P.C.      | 10.0 | 6.0 | 10   | .482 | .362 | 30.1 | 15   | 6 | 12 | .520 | .412 | 30.1 | 100.0 | 5.0 | 10   | .457 | .284 | 19.8 |
| 11-I.G.I     | 10.0 | 5   | 12   | .548 | .366 | 19.8 | 15   | 6 | 12 | .520 | .412 | 30.1 | 100.0 | 4.0 | 8    | .428 | .289 | 12.0 |
| AVERAGE      | 8.9  | 5.3 | 10.4 | .500 | .353 | 22.5 | 12.5 | 6 | 12 | .538 | .392 | 31.3 | 101.4 | 4.6 | 10.1 | .459 | .301 | 16.6 |

TABLE (15) RESULTS OF DIFFERENT OBSERVERS FOR THE GREEN TEST COLOUR SHOWN IN THE MUNSELL & C.I.E. SYSTEMS

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND  | (5)  |     |     |      |      |      | (1)  |     |    |      |      |      | (2)  |     |   |      |      |       |
|-----------|------|-----|-----|------|------|------|------|-----|----|------|------|------|------|-----|---|------|------|-------|
| NAME      | H    | V   | C   | x    | y    | Y    | H    | V   | C  | x    | y    | Y    | H    | V   | C | x    | y    | Y     |
| 1-D.H.P.  | 42.5 | 7   | 8   | .286 | .413 | 43.1 | 35.0 | 7   | 9  | .378 | .486 | 43.1 | 49.0 | 5.5 | 6 | .252 | .360 | 24.6  |
| 2-K.H.R.  | 40.0 | 6   | 8   | .312 | .457 | 30.1 | 37.5 | 8   | 8  | .342 | .477 | 59.1 | 42.5 | 5.0 | 8 | .284 | .405 | 19.8  |
| 3-P.B.    | 40.0 | 6   | 6   | .313 | .418 | 30.1 | 35.0 | 7   | 8  | .372 | .467 | 43.1 | 50.0 | 5.0 | 6 | .252 | .359 | 19.8  |
| 4-R.A.H.  | 40.0 | 6   | 7   | .313 | .435 | 30.1 | 37.5 | 8   | 8  | .341 | .445 | 59.1 | 55.0 | 6   | 4 | .264 | .326 | 30.1  |
| 5-S.B.    | 45.0 | 6   | 6   | .274 | .379 | 30.1 | 37.5 | 7   | 8  | .341 | .456 | 43.1 | 50.0 | 6   | 6 | .258 | .357 | 30.1  |
| 6-SSG     | 42.5 | 6   | 6   | .289 | .397 | 30.1 | 37.5 | 7   | 10 | .346 | .455 | 43.1 | 60.0 | 6   | 6 | .233 | .302 | 30.1  |
| 7-W.H.K.  | 42.5 | 7   | 8   | .286 | .413 | 43.1 | 40.0 | 6   | 6  | .336 | .433 | 30.1 | 50.  | 5   | 6 | .252 | .359 | 19.8  |
| 8-J.B.    | 45.0 | 7   | 6   | .280 | .373 | 43.1 | 35.0 | 7   | 8  | .372 | .468 | 43.1 | 52.5 | 6   | 6 | .252 | .345 | 30.1  |
| 9-I.F.    | 40.0 | 7   | 8   | .314 | .439 | 43.1 | 37.5 | 7   | 6  | .334 | .419 | 43.1 | 45.0 | 5   | 6 | .269 | .387 | 19.8  |
| 10-P.C.   | 40.0 | 6   | 8   | .311 | .457 | 30.1 | 40.0 | 7   | 8  | .314 | .438 | 43.1 | 55.0 | 6   | 6 | .244 | .329 | 30.1  |
| 11-I.G.I. | 40.0 | 7   | 8   | .314 | .439 | 43.1 | 35.0 | 8   | 8  | .370 | .455 | 59.1 | 50.0 | 5   | 6 | .252 | .359 | 19.8  |
| AVERAGE   | 41.6 | 6.5 | 7.2 | .299 | .420 | 35.5 | 37.0 | 7.1 | 8  | .350 | .454 | 46.3 | 51.0 | 5.5 | 6 | .256 | .353 | 24.9. |

TABLE (16) RESULTS OF DIFFERENT OBSERVERS FOR THE GREY TEST COLOUR SHOWN IN THE MUNSELL &amp; C.I.E. SYSTEMS.

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND | (5) |     |   |      |      |      | (1)  |     |   |      |      |      | (2)  |     |     |      |      |      |
|----------|-----|-----|---|------|------|------|------|-----|---|------|------|------|------|-----|-----|------|------|------|
| NAME     | H   | V   | C | x    | y    | Y    | H    | V   | C | x    | y    | Y    | H    | V   | C   | x    | y    | Y    |
| 1-D.H.P  | N   | 4.5 |   | .333 | .333 | 15.6 | 25.  | 5.5 | 6 | .437 | .451 | 24.6 | 77.5 | 3   | 6   | .202 | .210 | 6.6  |
| 2-W.H.R. | N   | 3.5 |   | .333 | .333 | 9.0  | 22.5 | 5.0 | 6 | .397 | .396 | 19.3 | 65.  | 2   | 2   | .286 | .255 | 3.1  |
| 3-P.B.   | 25  | 4.0 | 2 | .359 | .370 | 12.0 | 25.  | 5.0 | 6 | .430 | .443 | 19.8 | 75   | 3   | 2   | .272 | .272 | 6.6  |
| 4-R.A.H. | 25  | 3.0 | 2 | .365 | .375 | 6.6  | 25   | 6.0 | 6 | .413 | .431 | 30.1 | 67.5 | 4   | 2   | .285 | .253 | 12.0 |
| 5-S.B.   | 25  | 3.0 | 2 | .365 | .375 | 6.6  | 25   | 5.0 | 6 | .430 | .443 | 19.8 | 77.5 | 2   | 6   | .266 | .193 | 3.1  |
| 6-S.S.G. | N   | 3.0 |   | .333 | .333 | 6.6  | 20   | 4.0 | 4 | .419 | .398 | 12.0 | 80   | 2   | 6   | .244 | .174 | 3.1  |
| 7-W.H.K. | N   | 3.0 |   | .333 | .333 | 6.6  | 25   | 6.0 | 6 | .413 | .431 | 24.6 | 75   | 2   | 6   | .194 | .181 | 3.1  |
| 8-J.B.   | 75  | 4.0 | 2 | .256 | .256 | 12.0 | 27.5 | 5.0 | 4 | .347 | .366 | 19.8 | 70   | 3   | 4   | .224 | .247 | 6.7  |
| 9-I.N.   | 20  | 3.0 | 2 | .375 | .364 | 6.7  | 22.5 | 5.0 | 6 | .438 | .429 | 19.8 | 77.5 | 2   | 6   | .213 | .179 | 3.1  |
| 10-P.C.  | 25  | 4.0 | 2 | .360 | .371 | 12.0 | 22.5 | 5.0 | 6 | .438 | .429 | 19.8 | 72.5 | 3   | 4   | .231 | .240 | 6.6  |
| 11-I.G.I | 25  | 3.0 | 2 | .365 | .375 | 6.7  | 20   | 7   | 8 | .440 | .416 | 43.1 | 77.5 | 2   | 4   | .242 | .214 | 3.1  |
| AVERAGE  | 24  | 3.4 | 2 | .352 | .356 | 8.8  | 23.2 | 5.3 | 6 | .426 | .427 | 23.3 | 74.5 | 2.5 | 4.4 | .244 | .217 | 5.0  |

TABLE (17) RESULTS OF DIFFERENT OBSERVERS FOR THE RED TEST COLOUR SHOWN IN THE MUNSELL & C.I.E. SYSTEMS

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND  | (5)   |   |     |      |      |     | (1)  |     |      |      |      |      | (2)   |   |     |      |      |      |
|-----------|-------|---|-----|------|------|-----|------|-----|------|------|------|------|-------|---|-----|------|------|------|
| NAME      | H     | V | C   | x    | y    | Y   | H    | V   | C    | x    | y    | Y    | H     | V | C   | x    | y    | Y    |
| 1-D.H.P   | 100   | 3 | 10  | .485 | .262 | 6.6 | 7.5  | 5   | 14   | .559 | .327 | 19.8 | 97.5  | 3 | 10  | .446 | .242 | 6.6  |
| 2-K.H.R.  | 100   | 3 | 10  | .485 | .262 | 6.6 | 10.0 | 4   | 11   | .530 | .365 | 19.8 | 97.5  | 3 | 10  | .446 | .242 | 6.6  |
| 3-P.B.    | 102.5 | 3 | 10  | .513 | .282 | 6.6 | 5.0  | 5   | 12   | .507 | .320 | 19.8 | 100.0 | 3 | 10  | .485 | .262 | 6.6  |
| 4-R.A.H.  | 2.5   | 3 | 10  | .519 | .281 | 6.6 | 10.0 | 5   | 10   | .512 | .363 | 19.8 | 95.0  | 3 | 10  | .408 | .223 | 6.6  |
| 5-S.B.    | 2.5   | 3 | 10  | .508 | .281 | 6.6 | 10.0 | 4   | 10   | .542 | .358 | 12.0 | 97.5  | 3 | 10  | .446 | .242 | 6.6  |
| 6-S.S.G.  | 100   | 3 | 10  | .485 | .262 | 6.6 | 5    | 4   | 14   | .573 | .306 | 12.0 | 90.0  | 3 | 10  | .329 | .189 | 6.6  |
| 7-W.H.K.  | 100   | 3 | 10  | .485 | .262 | 6.6 | 5    | 5   | 12   | .507 | .320 | 19.8 | 95.0  | 3 | 10  | .408 | .223 | 6.6  |
| 8-J.B.    | 97.5  | 3 | 10  | .445 | .242 | 6.6 | 7.5  | 4   | 12   | .560 | .332 | 12.0 | 92.5  | 3 | 10  | .368 | .205 | 6.6  |
| 9-I.N.    | 5.0   | 3 | 10  | .550 | .302 | 6.6 | 7.5  | 5   | 10   | .493 | .341 | 19.8 | 90.0  | 3 | 10  | .329 | .189 | 6.6  |
| 10-P.C.   | 5     | 3 | 8   | .506 | .311 | 6.6 | 10.0 | 5   | 10   | .512 | .363 | 19.8 | 90.0  | 4 | 10  | .331 | .216 | 12.0 |
| 11-I.G.I. | 5.0   | 3 | 10  | .549 | .302 | 6.6 | 15.0 | 6   | 10   | .493 | .402 | 30.1 | 97.5  | 2 | 6   | .392 | .249 | 3.1  |
| AVERAGE   | 1.6   | 3 | 9.8 | .498 | .276 | 6.6 | 8.4  | 4.8 | 11.4 | .526 | .345 | 18.6 | 94.8  | 3 | 9.6 | .399 | .226 | 6.9  |



TABLE (13) RESULTS OF DIFFERENT OBSERVERS FOR THE GREY TEST COLOUR SHOWN IN THE MUNSSELL & C.I.E. SYSTEMS

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND | (5)  |     |   |      |      |      | (8)  |   |   |      |      |      | (7)  |     |     |      |      |      |
|----------|------|-----|---|------|------|------|------|---|---|------|------|------|------|-----|-----|------|------|------|
| NAME     | H    | V   | C | x    | y    | Y    | H    | V | C | x    | y    | Y    | H    | V   | C   | x    | y    | Y    |
| 1-D.H.P. | 25.  | 3   | 2 | .365 | .375 | 6.56 | 42.5 | 4 | 4 | .269 | .362 | 12.0 | 2.5  | 3   | 2   | .358 | .313 | 6.6  |
| 3-P.R.B. | 25   | 4   | 2 | .359 | .370 | 12.0 | 40   | 5 | 6 | .311 | .431 | 19.3 | 10   | 3   | 6   | .484 | .346 | 6.6  |
| 4-R.A.H. | 25   | 3   | 2 | .365 | .375 | 6.6  | 40   | 5 | 4 | .311 | .389 | 19.3 | 17.5 | 5   | 6   | .444 | .396 | 19.8 |
| 5-S.P.B. | 25   | 3   | 2 | .365 | .375 | 6.6  | 35   | 3 | 4 | .356 | .443 | 6.6  | 2.5  | 3   | 8   | .482 | .292 | 6.6  |
| 6-S.S.G. | N    | 3   |   | .333 | .333 | 6.6  | 50   | 4 | 4 | .263 | .349 | 12.0 | 100  | 2   | 4   | .385 | .276 | 3.1  |
| 7-M.H.K. | N    | 3   |   | .333 | .333 | 6.6  | 37.5 | 3 | 2 | .312 | .365 | 6.6  | 100  | 2   | 2   | .353 | .246 | 3.1  |
| 9-I.H.   | 20   | 3   | 2 | .375 | .364 | 6.6  | 50   | 4 | 4 | .263 | .349 | 12.0 | 100  | 3   | 10  | .484 | .262 | 6.6  |
| 10-P.C.  | 25   | 4   | 2 | .359 | .371 | 12.0 | 37.5 | 4 | 4 | .328 | .416 | 12.0 | 10   | 3   | 2   | .373 | .332 | 6.6  |
| AVERAGE  | 25.4 | 3.3 | 2 | .355 | .364 | 8.2  | 40.6 | 4 | 4 | .305 | .391 | 12.6 | 5.3  | 3.3 | 5.3 | .425 | .314 | 7.78 |

TABLE (19) RESULTS OF DIFFERENT OBSERVERS FOR THE YELLOW TEST COLOUR SHOWN IN THE MUNSELL & C.I.E. SYSTEM

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND | (5)  |     |      |      |      |      | (8)  |   |     |      |      |      | (7)  |     |      |      |      |      |
|----------|------|-----|------|------|------|------|------|---|-----|------|------|------|------|-----|------|------|------|------|
| NAME     | H    | V   | C    | x    | y    | Y    | H    | V | C   | x    | y    | Y    | H    | V   | C    | x    | y    | Y    |
| 1-D.H.P. | 25   | 7   | 12   | .468 | .486 | 43.1 | 30   | 8 | 8   | .401 | .452 | 59.1 | 20   | 7   | 12   | .491 | .448 | 43.1 |
| 3-P.H.B. | 25   | 8   | 12   | .456 | .479 | 59.1 | 32.5 | 8 | 8   | .386 | .456 | 59.1 | 20   | 7   | 10   | .468 | .434 | 43.1 |
| 4-R.A.H. | 25   | 8   | 10   | .438 | .460 | 59.1 | 30   | 8 | 8   | .401 | .452 | 59.1 | 22.5 | 8   | 12   | .468 | .459 | 59.1 |
| 5-C.P.B. | 22.5 | 8   | 10   | .448 | .443 | 59.1 | 25   | 8 | 8   | .416 | .438 | 59.1 | 20   | 7   | 10   | .468 | .434 | 43.1 |
| 6-S.S.G. | 20   | 7   | 10   | .468 | .434 | 43.1 | 30   | 8 | 10  | .401 | .452 | 59.1 | 15   | 7   | 10   | .472 | .397 | 43.1 |
| 7-W.H.K. | 25   | 8   | 10   | .437 | .460 | 59.1 | 27.5 | 8 | 10  | .428 | .472 | 59.1 | 22.5 | 8   | 12   | .468 | .459 | 59.1 |
| 9-I.F.   | 25   | 8   | 12   | .456 | .479 | 59.1 | 27.5 | 8 | 10  | .428 | .472 | 59.1 | 15   | 7   | 10   | .472 | .397 | 43.1 |
| 10-P.C.  | 22.5 | 8   | 10   | .448 | .443 | 59.1 | 25   | 8 | 10  | .438 | .460 | 59.1 | 22.5 | 8   | 12   | .468 | .459 | 59.1 |
| AVERAGE  | 23.8 | 7.8 | 10.8 | .452 | .461 | 55.1 | 28.4 | 8 | 9.0 | .412 | .457 | 59.1 | 20.0 | 7.5 | 11.3 | .472 | .439 | 51.1 |

TABLE (20) RESULTS OF DIFFERENT OBSERVERS FOR THE BLUE TEST COLOUR SHOWN IN THE MUNSELL AND C.I.E. SYSTEM

(ELEMENT ANGLE OF SUBTENSE = 6°)

| SURROUND | (5)  |     |     |      |      |      | (8)  |     |     |      |      |      | (7)  |      |    |      |      |      |
|----------|------|-----|-----|------|------|------|------|-----|-----|------|------|------|------|------|----|------|------|------|
| NAME     | H    | V   | C   | x    | y    | Y    | H    | V   | C   | x    | y    | Y    | H    | V    | C  | x    | y    | Y    |
| 1-D.H.P. | 75   | 3   | 10  | .172 | .157 | 6.6  | 62.5 | 3   | 6   | .133 | .253 | 6.6  | 87.5 | 2    | 6  | .302 | .206 | 3.1  |
| 3-P.R.B. | 75   | 3   | 10  | .172 | .157 | 6.6  | 62.5 | 4   | 6   | .205 | .271 | 12.0 | 87.5 | 2    | 6  | .303 | .206 | 3.1  |
| 4-P.A.H. | 75   | 3   | 10  | .172 | .157 | 6.6  | 60.0 | 4   | 6   | .206 | .286 | 12.0 | 82.5 | 4    | 4  | .286 | .253 | 12.0 |
| 5-S.P.B. | 77.5 | 3   | 8   | .216 | .177 | 6.6  | 75.0 | 3   | 8   | .192 | .179 | 6.6  | 80.0 | 2    | 4  | .250 | .216 | 3.1  |
| 6-S.S.G. | 77.5 | 3   | 12  | .188 | .136 | 6.6  | 65.0 | 3   | 6   | .183 | .237 | 6.6  | 82.5 | 2    | 8  | .257 | .163 | 3.1  |
| 7-W.H.K. | 75   | 3   | 10  | .172 | .156 | 6.6  | 75.0 | 3   | 8   | .192 | .179 | 6.6  | 80.0 | 3    | 8  | .238 | .178 | 6.6  |
| 9-I.E.   | 75   | 5   | 10  | .208 | .203 | 19.3 | 72.5 | 4   | 10  | .131 | .189 | 12.0 | 90.0 | 3    | 10 | .328 | .189 | 6.6  |
| 10-P.O.  | 75   | 3   | 8   | .192 | .179 | 6.6  | 72.5 | 3   | 8   | .173 | .183 | 6.6  | 75.0 | 3    | 2  | .272 | .272 | 6.6  |
| AVERAGE  | 75.6 | 3.3 | 9.8 | .187 | .165 | 8.2  | 68.7 | 3.4 | 7.3 | .190 | .222 | 8.6  | 82.1 | 2.63 | 6  | .280 | .210 | 5.5  |

TABLE (21) RESULTS OF DIFFERENT OBSERVERS FOR THE RED TEST COLOUR SHOWN IN THE MUNSELL AND C.I.E. SYSTEMS

(ELEMENT ANGLE OF SUBTENSE = 6')

| SURROUND | (5) |   |     |      |      |     | (8)  |   |     |      |      |      | (7) |     |      |      |      |      |
|----------|-----|---|-----|------|------|-----|------|---|-----|------|------|------|-----|-----|------|------|------|------|
| NAME     | H   | V | C   | x    | y    | Y   | H    | V | C   | x    | y    | Y    | H   | V   | C    | x    | y    | Y    |
| 1-D.H.P. | 100 | 3 | 10  | .485 | .262 | 6.6 | 12.5 | 3 | 2   | .375 | .339 | 6.6  | 2.5 | 4   | 10   | .538 | .281 | 12.0 |
| 3-P.E.B. | 2.5 | 3 | 10  | .519 | .282 | 6.6 | 5.0  | 3 | 8   | .506 | .311 | 6.6  | 5.0 | 4   | 14   | .573 | .303 | 12.0 |
| 4-R.A.H. | 2.5 | 3 | 10  | .519 | .282 | 6.6 | 5.0  | 4 | 4   | .392 | .323 | 12.0 | 5.0 | 4   | 14   | .574 | .303 | 12.0 |
| 5-S.P.B. | 2.5 | 3 | 10  | .508 | .281 | 6.6 | 2.5  | 3 | 8   | .482 | .292 | 6.6  | 5   | 4   | 12   | .538 | .313 | 12.0 |
| 6-S.S.G. | 100 | 3 | 10  | .485 | .262 | 6.6 | 5.0  | 2 | 6   | .464 | .293 | 3.1  | 95  | 3   | 10   | .408 | .223 | 6.6  |
| 7-W.H.K. | 100 | 3 | 10  | .485 | .262 | 6.6 | 5    | 3 | 8   | .506 | .311 | 6.6  | 95  | 3   | 10   | .408 | .223 | 6.6  |
| 9-I.N.   | 5   | 3 | 10  | .549 | .302 | 6.6 | 10   | 3 | 6   | .485 | .347 | 6.6  | 5   | 4   | 12   | .538 | .313 | 12.0 |
| 10-P.C.  | 5   | 3 | 8   | .506 | .311 | 6.6 | 12.5 | 3 | 4   | .436 | .356 | 6.6  | 100 | 3   | 6    | .421 | .286 | 6.6  |
| AV PAGE  | 3.5 | 3 | 9.8 | .506 | .279 | 6.6 | 7.2  | 3 | 5.8 | .456 | .322 | 7.2  | 1.5 | 3.6 | 11.0 | .500 | .281 | 10.0 |

the cases of blue test and surround colours).

(3) Different interactions between adjacent retinal zones and their associated neurones.

(4) Different psychological interpretation of the colour appearance.

Although there is no direct means of measuring the actual sensation due to any colour stimulus, yet they are indirectly studied from the relative luminosity curve, the spectral coefficient curves and the wavelength discrimination curve. These curves and others, show that different persons perceive colour differently <sup>(22)</sup>. This led the C.I.E. to adopt the mean values of 17 observers to define the colour matching characteristics as the 1931 standard observer, <sup>(13)</sup> in order to derive the colour specifications of any object independent of the colour vision of any individual.

#### THE EFFECT OF DIFFERENT SURROUNDS ON THE APPARENT BRIGHTNESS AS PERCEIVED BY THE DIFFERENT OBSERVERS:

The apparent brightness (in this method) is measured in terms of the Munsell notation (Value). Since this scale was originally developed on subjective measurements, then it is suitable for estimating the apparent brightness of the test colours in this investigation.

Although the final results obtained by different observers as shown in the hue chart or the C.I.E. chromaticity chart, varied considerably among the observers, yet there is only a small difference (if any) in the Value recorded by them, as shown in Tables (14-21) inclusive. This indicates the following two points:-

(1) The perception of value (or brightness) is fairly constant among different observers.

(2) The observers find it rather easy to pick out the Munsell chip of the same value as the test colour. (This is probably easier than in the case of using the colorimeter since in this case, the test colour and the comparison patch are both coloured paper).

Comparing the individual and average results shown in Tables (14-21) inclusive, the following conclusions can be drawn:-

(1) The apparent brightness of the test colours on surround (1) is higher than on surround (2).

(2) The apparent brightness of the test colours on surround (8) is higher than that on surround (7) (except for the case of the red, which is the other way round).

(3) The apparent brightness of the test colours on white surround (5) is less than that on surround (1) and surround (8), (except in the case of the red, where they are nearly equal) and is higher than that on surround (2) and surround (7) (except in the case of the red, which is the other way round).

Actually, the exception of the case of the red test colour in these general conclusions, may be due to the fact that it is too dark to be matched accurately in all the cases. Perhaps that is why the individual differences among observers, for this test colour, are rather large, compared with all other test colours.

The first two conclusions (1 & 2) agree with conclusions (4 & 6) respectively in the analysis of the brightness results of the first method (page/44 ).

The third present conclusion agrees partially with conclusion (1) in that analysis for the surrounds (5), (1) & (8), but does not agree for the surrounds (5), (2) and (7).

This may be due to the fact that the square test colour on white surround was intentionally made double the size of the squares in the other patterns. The reason why this was done is that, if the former was made of the same size as the latter, it would not have been seen clearly amidst the scattered light coming from the diffuse white surround, and hence comparing it with the Munsell chips, would be of the utmost difficulty. (This was tried by the author). As for the case of the other patterns, the whole pattern was imaged on the retina of the observer's eye and hence can be seen more clearly, and, at the same time, the brightness of the coloured surrounds are less than that of the white. So the equality of the conditions (the same size of the squares of the test colours) was sacrificed to facilitate the judgement on the matches made by the different observers.

As will be seen in Chapter VII, the change of the angle of subtense is followed by a change in the apparent brightness (the bigger the angle of subtense is, the more bright the test colour appears). So the partial discrepancy between the third conclusion in the present analysis and the first conclusion in the last analysis, can easily be explained. Had the size of the square of the test colour on the white surround, been the same as that of the squares in the patterns, its apparent brightness should be less (and probably smaller than the corresponding values for surrounds(2) and (7)) and hence the discrepancy would have been out of place.

#### BLACK-WHITE SURROUNDS:

The patterns of the charts similar to the plates (1b & 2b) with black-white surrounds were studied by the author using this method.

TABLE (22) THE COMPARATIVE RESULTS OBTAINED BY THE AUTHOR FOR WHITE AND WHITE-BLACK SURROUNDS,  
FOR ELEMENT ANGLE OF SUBTENSE 6', (1) HORIZONTAL STRIPES, (2) VERTICAL STRIPES.

| SURROUND    |    | (5)  |   |    |      |      |      | (1)  |     |    |      |      |      | (12) |     |    |      |      |      |
|-------------|----|------|---|----|------|------|------|------|-----|----|------|------|------|------|-----|----|------|------|------|
| TEST COLOUR |    | H    | V | C  | x    | y    | Y    | H    | V   | C  | x    | y    | Y    | H    | V   | C  | x    | y    | Y    |
| Orange      | 1. | 5    | 5 | 12 | .507 | .320 | 19.8 | 100  | 6   | 10 | .415 | .289 | 30.1 | 5    | 4   | 14 | .573 | .306 | 12.0 |
|             | 2. | 5    | 5 | 12 | .507 | .320 | 19.8 | 5    | 5   | 12 | .507 | .320 | 19.8 | 7.5  | 4   | 10 | .493 | .330 | 12.0 |
| Green       | 1. | 42.5 | 6 | 6  | .289 | .397 | 30.1 | 45   | 7   | 6  | .280 | .372 | 42.5 | 42.5 | 8   | 8  | .272 | .439 | 19.8 |
|             | 2. | 42.5 | 6 | 6  | .289 | .397 | 30.1 | 42.5 | 7   | 8  | .286 | .413 | 43.1 | 45.0 | 6   | 10 | .247 | .419 | 30.1 |
| Grey        | 1. | H    | 3 |    | .333 | .333 | 6.6  | 25   | 5   | 2  | .351 | .362 | 19.8 | H    | 1.5 |    | .333 | .333 |      |
|             | 2. | H    | 3 |    | .333 | .333 | 6.6  | H    | 4   |    | .333 | .333 | 12.0 | H    | 2.5 |    | .333 | .333 | 4.9  |
| Yellow      | 1. | 20   | 7 | 10 | .468 | .434 | 43.1 | 20   | 6   | 6  | .400 | .390 | 59.1 | 20   | 6   | 10 | .485 | .432 | 30.1 |
|             | 2. | 20   | 7 | 10 | .468 | .434 | 43.1 | 22.5 | 8   | 10 | .448 | .443 | 59.1 | 20   | 7   | 10 | .468 | .435 | 43.1 |
| Blue        | 1. | 77.5 | 3 | 12 | .188 | .135 | 6.6  | 77.5 | 4.5 | 10 | .200 | .195 | 15.4 | 77.5 | 2   | 6  | .219 | .179 | 3.1  |
|             | 2. | 77.5 | 3 | 12 | .188 | .135 | 6.6  | 75   | 4   | 10 | .193 | .186 | 12.0 | 75   | 3   | 8  | .191 | .170 | 6.6  |

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W

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The results are shown in Table (22) and figure (60). It can be easily seen that:

(1) The apparent brightness of the test colour in white surround(5), is lower than that in surround (11) and higher than that in surround (12) which satisfies rules (6 & 5) as shown in Chapter V.

(2) The change of colour appearance due to these two surrounds affects both the saturation and the hue of the test colour. However, it seems that the saturation is more affected than the hue.

## CHAPTER VII

### THE STUDY OF THE EFFECTS OF DIFFERENT VISUAL CONDITIONS ON

#### THE COLOUR CONTRAST PHENOMENA.

It was found that the difference in the colour appearance of the test colours on the different surrounds as measured by the comparison patch, varies with the variation of the visual conditions used. The following visual conditions, which were studied in this investigation will now be discussed:

- (a) The luminance of the surround of the comparison patch.
- (b) The luminance of the surround of the test colour.
- (c) The luminance of the whole test patch (the test colour and its surround).
- (d) The angle of subtense of the test patch.
- (e) The inclination of the test patch.
- (f) The orientation of the stripes.
- (g) The Dynamic Colour Contrast Effects.

These conditions being of delicate nature, which can not be conveniently studied by using the Munsell Book of Color, the first method using the colorimeter was applied for the study of the effects of the first 6 conditions. Only the two conditions (d) & (f) were studied also by the second method. The last condition was studied qualitatively.

#### (A) THE LUMINANCE OF THE SURROUND OF THE COMPARISON PATCH.

The surround of the comparison patch was white. Its spectrophotometric reflection curve is shown in figure (31) and its unit trichromatic co-ordinates are shown in Table (7). It was illuminated by standard source  $S_A$  and was kept at the same luminance (and hence the same brightness) for a whole set of readings using all the test colours against

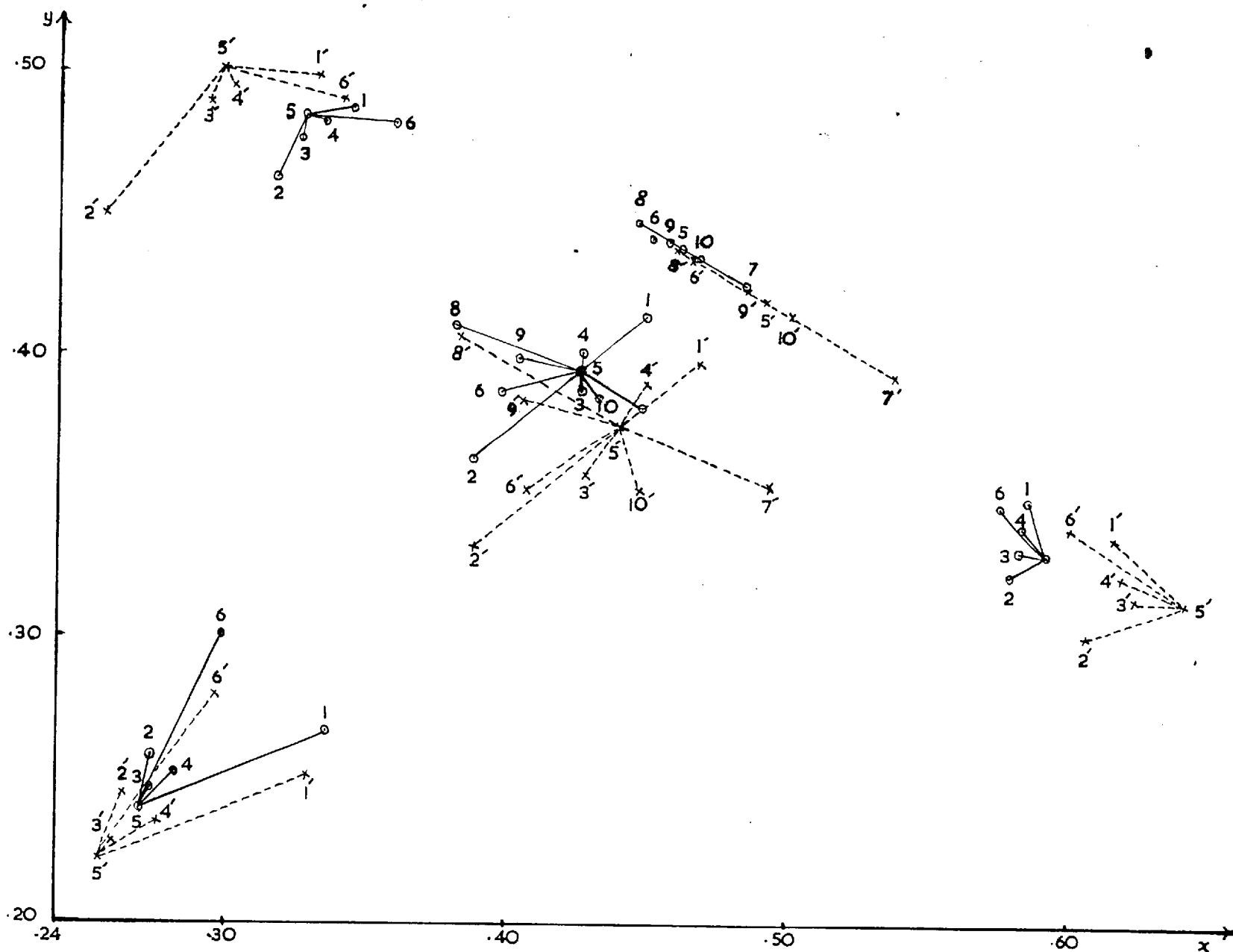


Figure (72) The effect of the luminance of the surround of the comparison patch, (—) for higher luminance, (---) for lower luminance.

their different backgrounds. This luminance was then changed for another set of readings to study the effects due to the corresponding change in the brightness.

Figure (72) shows the chromatic effects of the brightness of the surround of the comparison patch on the appearance of all the test colours used against their different backgrounds, in the case of complex pattern of 15' element angle of subtense in vertical plane. From this figure and tables (8-12) inclusive, the following general empirical rules can be deduced for all the test colours:

As the luminance of the surround of the comparison patch is reduced.

Rule (7) The separation between the chromaticities corresponding to different colour surrounds gets larger. This means that although the differences in colour appearance of the test-colour due to different surrounds, are the same, independent of the brightness of the surround of the comparison patch, yet they look bigger for the eye adapted to lower level of luminance.

Rule (8) The points in the chromaticity chart are shifted in the same order. Their shifts show two obvious trends:

(a) Change in hue (or dominant wavelength). Towards  $0.59 \mu$  for the yellow test colour and away from the yellow for other colours).

(b) Change in saturation: (towards more saturation )

This means that as the level of luminance of the surround of the comparison patch was lowered:

(a) The colour of the comparison patch looks as if it is shifted towards the yellow, such that in matching the test patch (which remains the same), the observer tends to compensate for this, and hence the shifts away from the yellow occur.

(b) The comparison patch looks desaturated, and so the observer needs to increase its saturation to match the unchanged test patch.

Rule (9) The luminance of the comparison patch has to be decreased for matching. This means that the darker the surround of the comparison patch, the lighter the comparison patch appears, such that its intensity needs to be decreased to match the test patch of the same lightness.

Figures (73-81) inclusive, show the effects of the brightness of the surround of the comparison patch in more detail in the cases of the orange, green, yellow, blue and grey test colours respectively.

#### THE LEVELS OF LUMINANCE OF THE SURROUND OF THE COMPARISON PATCH USED.

(1) FOR THE ORANGE AND YELLOW TEST COLOURS: the levels of luminance used were 2.9 and 0 ft. lambert. For higher levels of luminance, the intensities of the primaries required for matching were off the scale and it was not preferred to reduce the luminosity of the test patch to a level suitable for matching, since this introduces another effect, as will be shown later. For an intermediate level of luminance the effect was small, such that the relative experimental errors will be considerable with respect to the effect.

(2) FOR THE GREEN TEST COLOUR: the levels of luminance used were 17.4, 2.9 and 0 ft. lambert. This enables the study of the gradation of the effect.

(3) FOR THE GREY AND BLUE TEST COLOURS: They were so dark that no satisfactory match was obtained in the case of the dark surround (0 ft. Lambert), so the levels of luminances used in these two cases were 17.4 and 2.9 ft. lambert.

It can be seen that the case of 2.9 ft. lambert luminance is common for all the test colours used, and so it was taken as reference to other

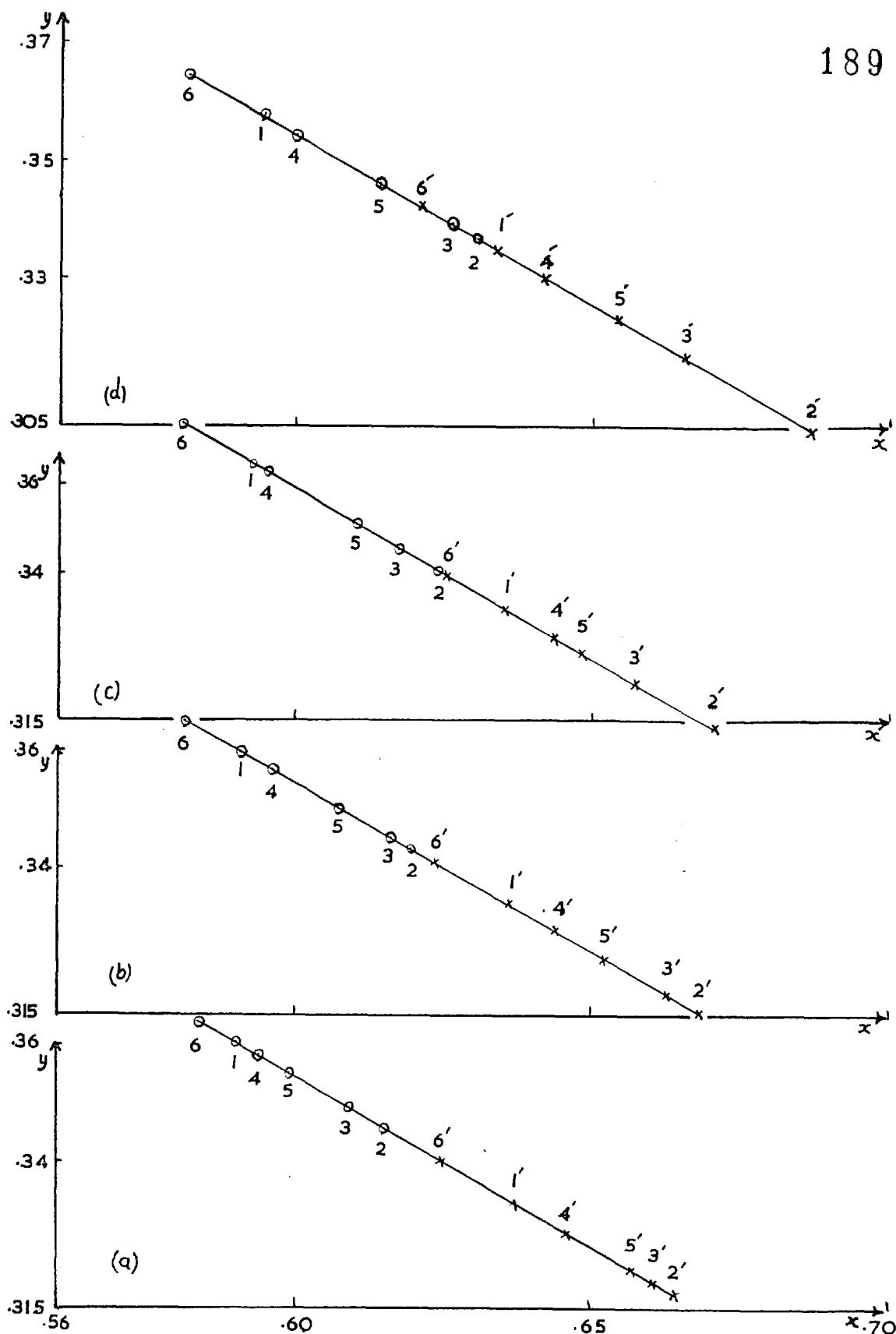


Figure (73) The effect of the luminance of the surround of the comparison patch, with varying angle of subtense ( $\odot$ ) for higher and ( $\times$ ) for lower luminance, (a)  $2^\circ$ , (b)  $1^\circ 30'$ , (c)  $1^\circ$ , (d)  $30'$ . (For the Orange test colour)

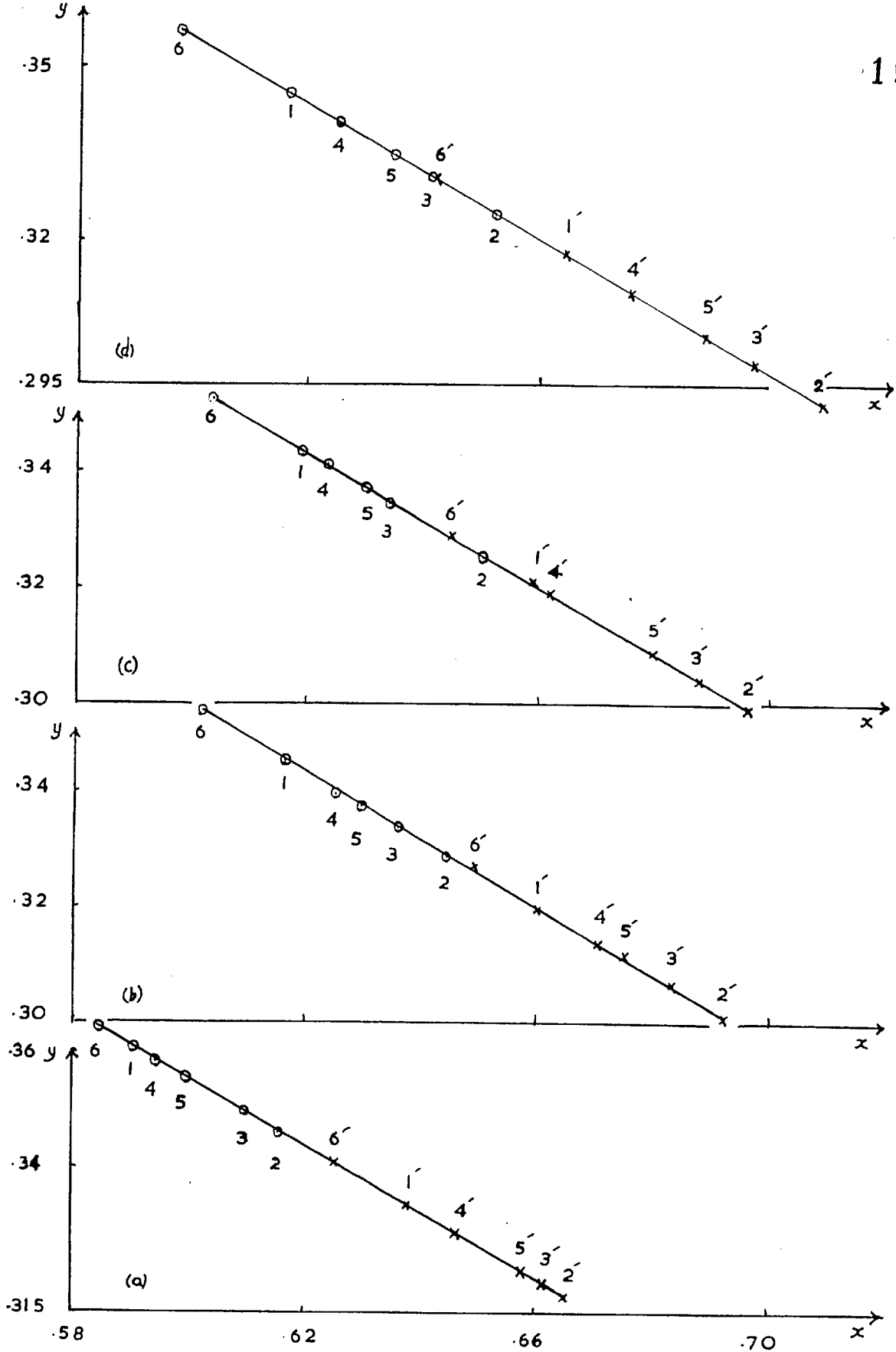


Figure (74) The effect of the luminance of the surround of the comparison patch for the Orange Test Colour at varying inclinations (a) vertical, (b) 40°, (c) 20°, (d) 5°.

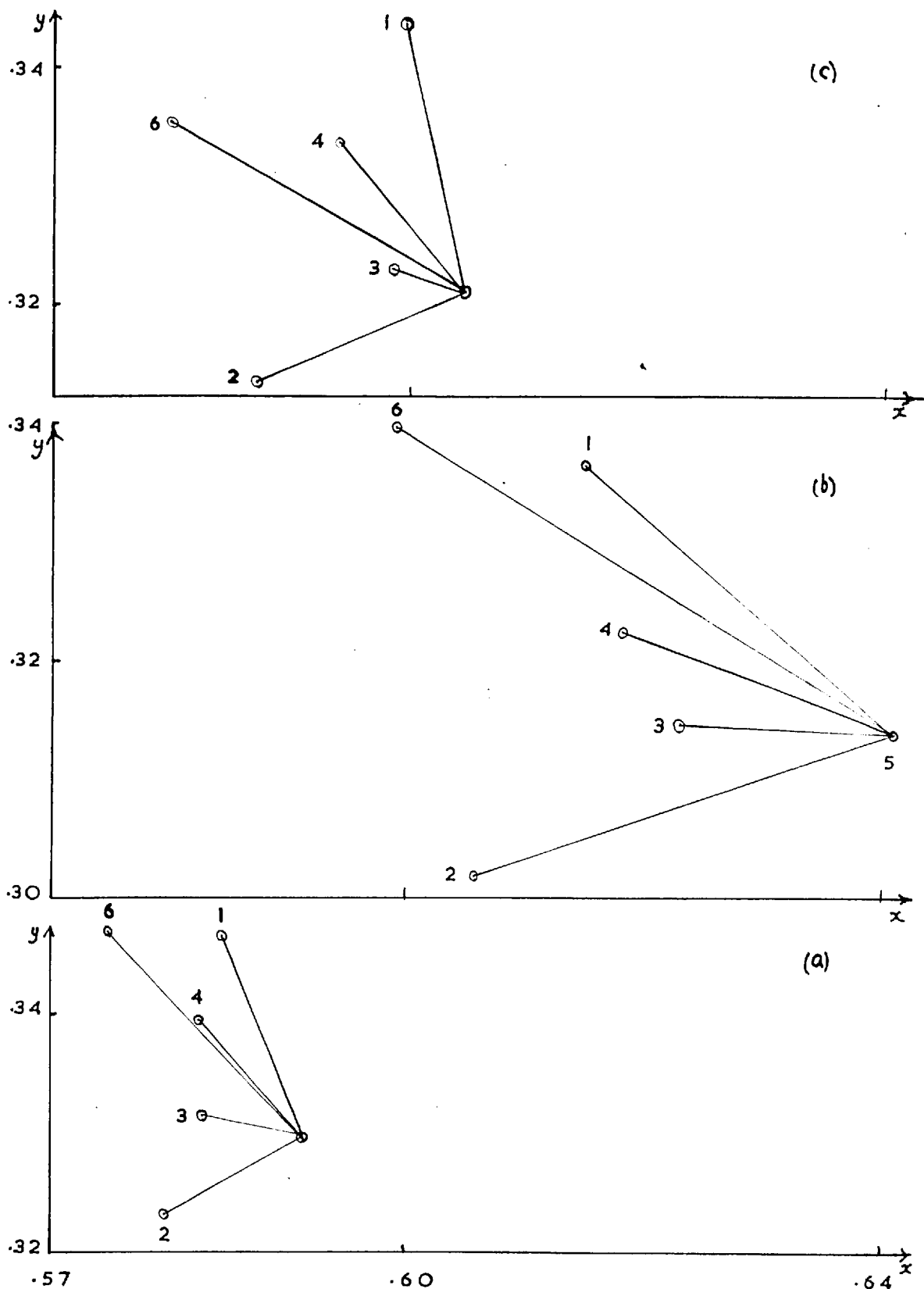


Figure (75) The effect of Luminance. Orange Test Colour. (a) Higher, (b) Lower luminances of the surround of the comparison patch, (c) the same as case (a) with lower luminance of the test patch. (Compound Pattern).



levels of luminance used.

## I THE ORANGE TEST COLOUR.

(1) For the Simple Patterns: Figure (73) shows the effect of the lightness of the surround of the comparison patch with varying angles of subtense  $2^\circ$ ,  $1^\circ$  and  $30'$  and figure (74) shows the same effect with varying inclinations ( $90^\circ$ ,  $40^\circ$ ,  $26^\circ$  and  $5^\circ$ ). In all these cases the (R) and (G) primary stimuli only (no blue) were needed to match the appearance of the orange test colour on the different surrounds, so all the corresponding points lie on the straight line joining the points corresponding to (R) and (G) primary filters.

Rules (7) & (9) (concerning the size of the shifts, and the luminosity of the comparison patch), apply directly as shown in the different cases of the two figures and rows (I - XIII) inclusive in Table (8).

Part (a) of rule (8) (concerning the shift of the whole set of points away from yellow, i.e. away from the red end of the chromaticity chart) applies also. As for part (b) of this rule (concerning the change in saturation), it does not show in this case, due to the fact that all the points are on the same straight line (R) (G) .

(2) For the compound Pattern: Figures (75 a & b) and rows (XIV and XV) in Table (8) show the cases of bright and dark surrounds of the comparison patch respectively. It is clear that the three general empirical rules (7-9) apply satisfactorily in this case.

## II THE GREEN TEST COLOUR.

The case of the green test colour is very similar to the case of the orange test colour. It has a further advantage that it was possible to apply three different levels of luminance of the surround of the

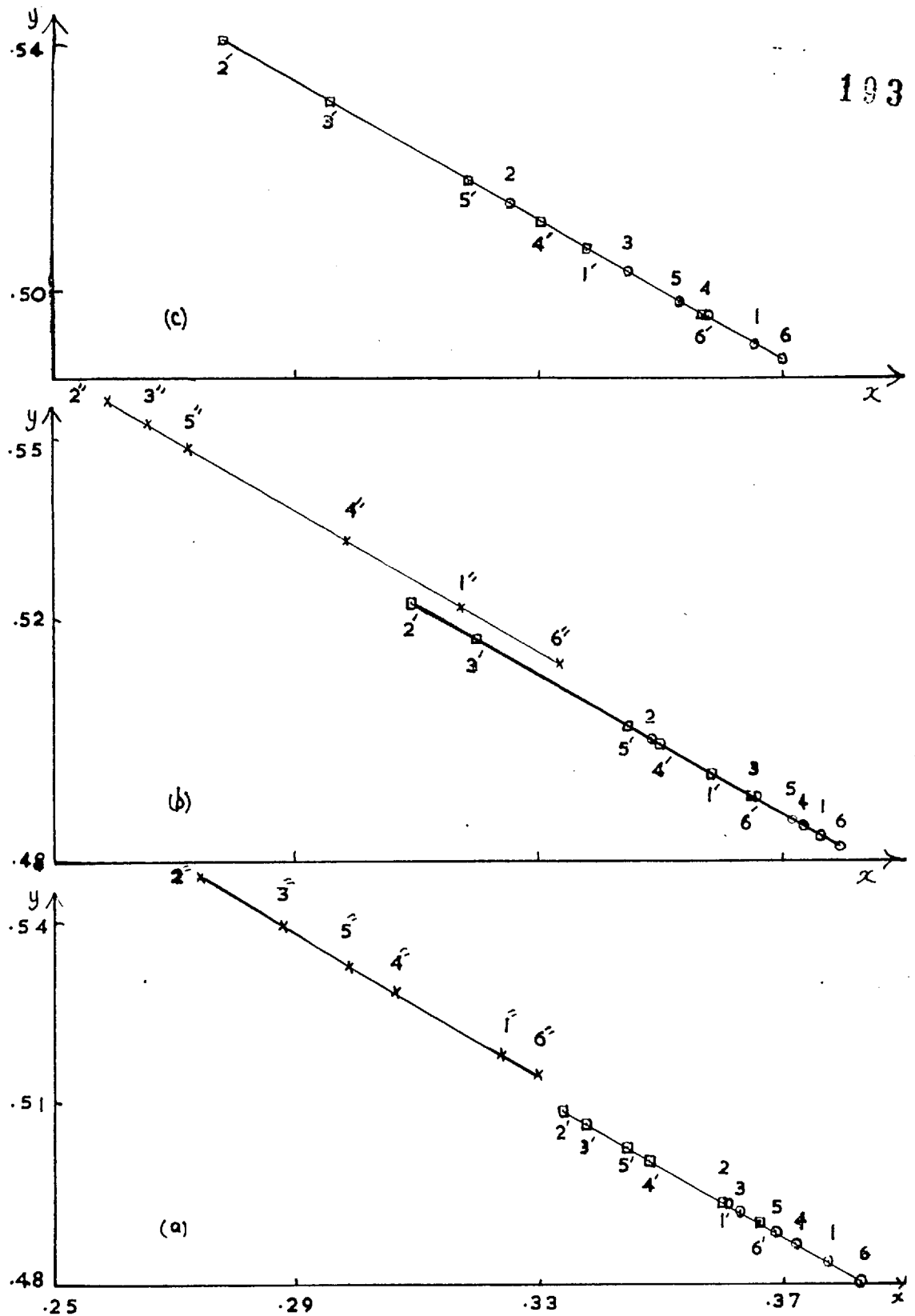


Figure (76) The effect of the luminance of the surround of comparison patch for the green simple pattern, with varying the angle of subtense, (a,°) for higher, and (x) for lower luminance, (a) 2°, (b) 1°, (c) 30°.

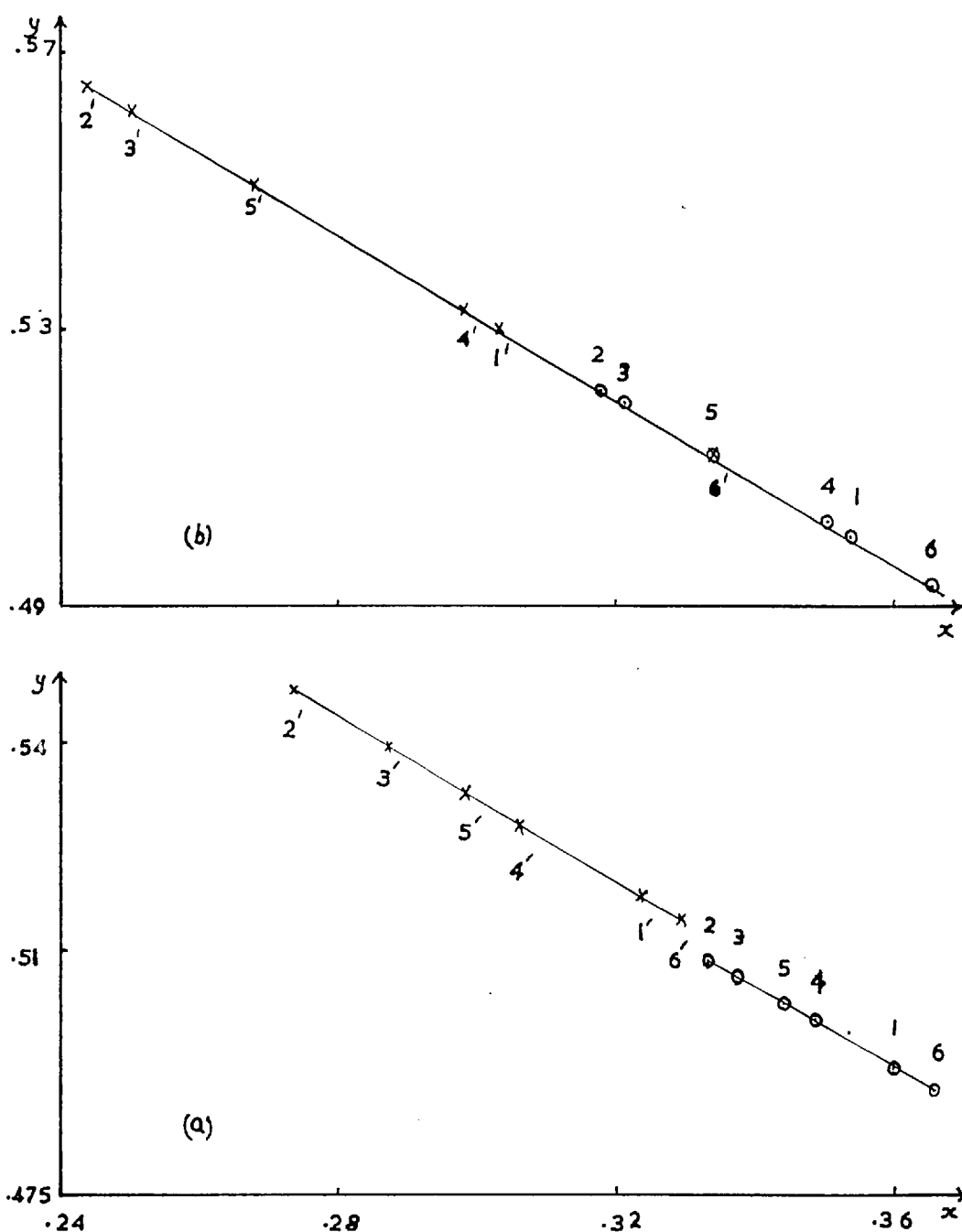


Figure ( 77) The effect of the luminance of the surround of the comparison patch for the Green simple pattern with varying inclination, (o) for higher, and (x) for lower luminance, (a) vertical, (b) 5°.

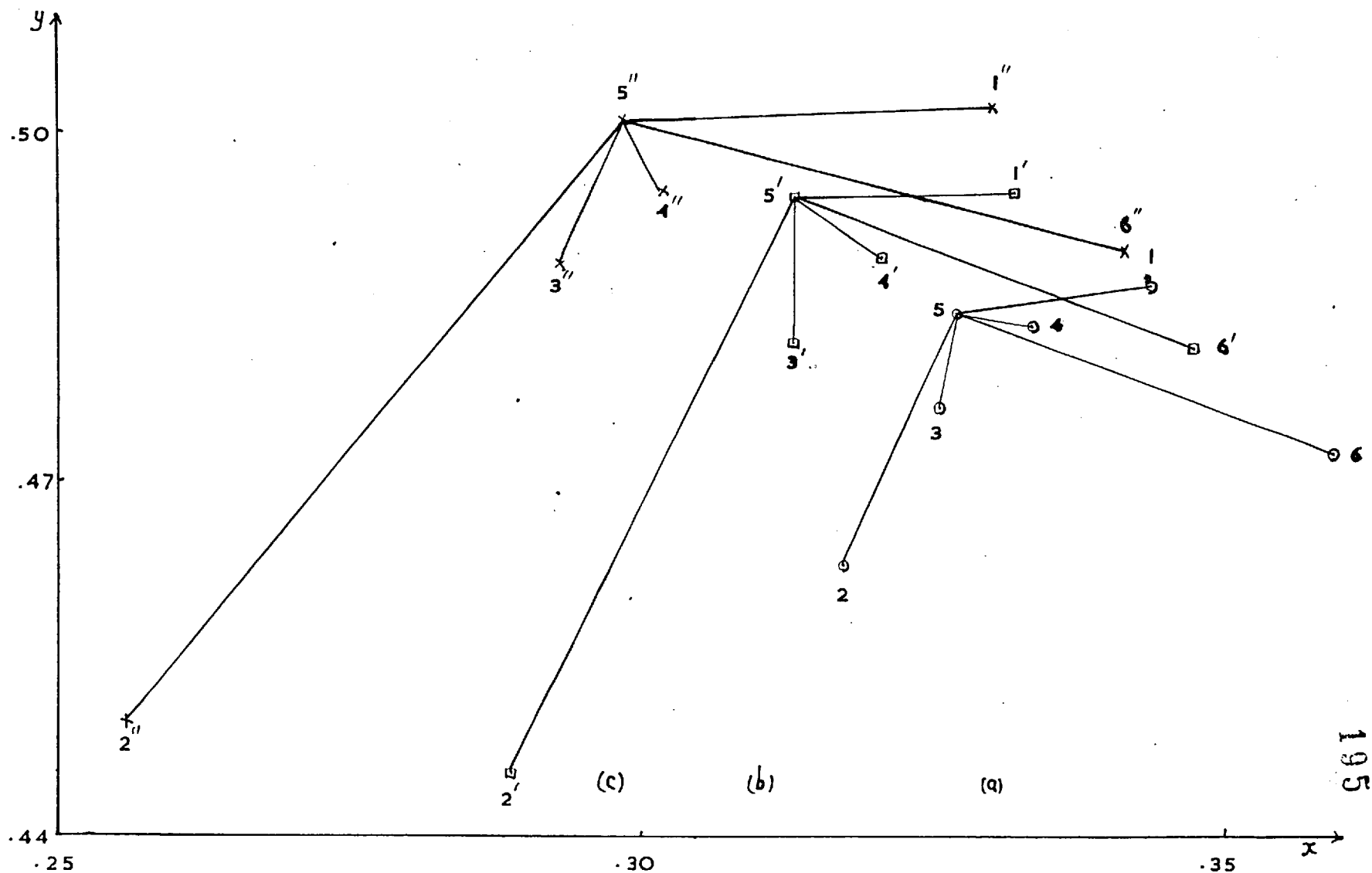


Figure (73) The effect of the luminance, The Green Test Colour, (a) Higher, (b) Lower luminance of the surround of the comparison patch, and (c) the same as (a) with lower luminance of the test patch.

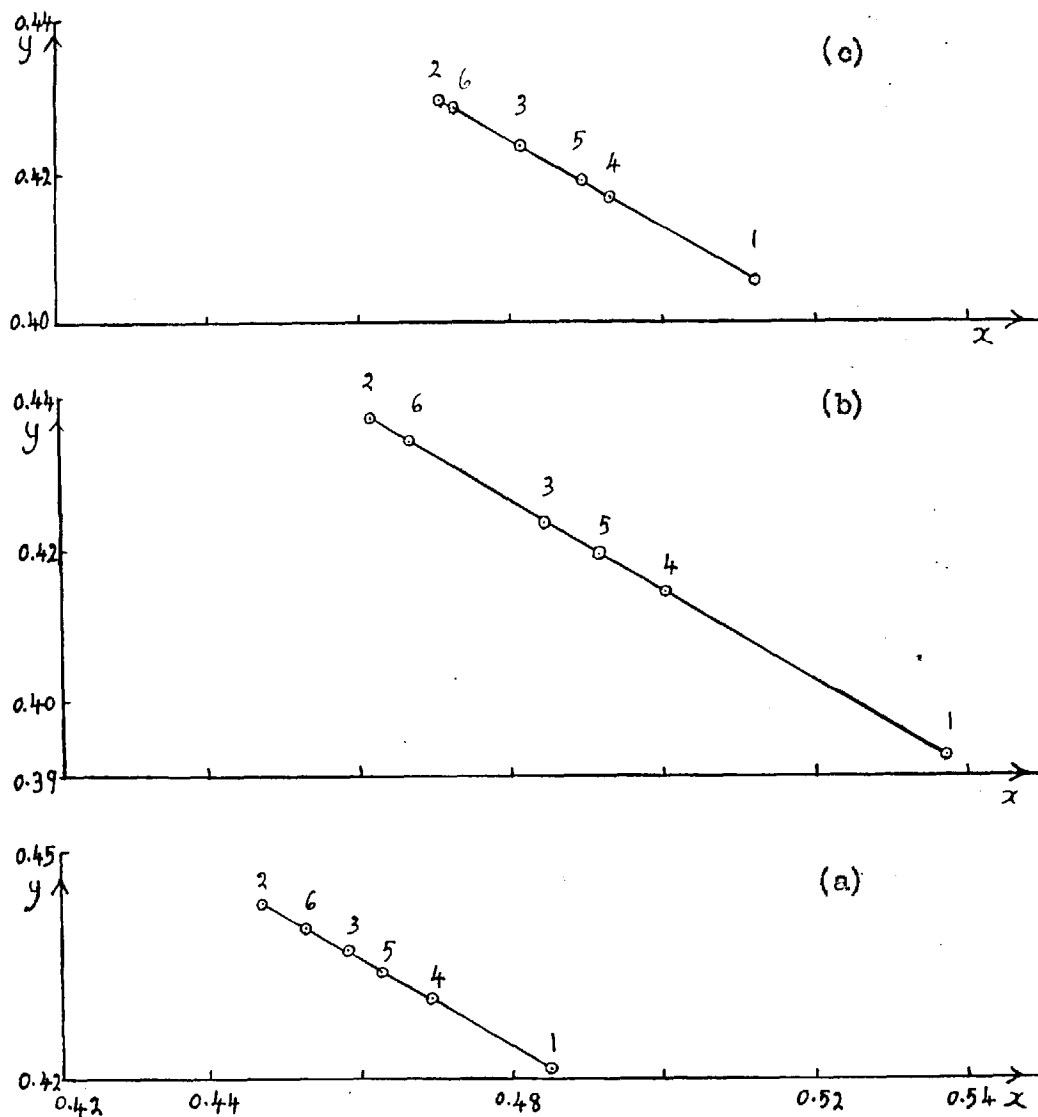


Figure (79) The effect of the Luminance , The Yellow Compound Pattern, (a) Higher, (b) lower luminance of the surround of the comparison patch, and (c) the same as (a) with lower luminance of the test patch.

comparison patch in the case of the simple pattern. For the dark surround, neutral density filter  $F_4$  was introduced in the path of R,G,B, mixture from the colorimeter to use higher intensity of the mixture and hence to avoid small readings of the scales where the percentage error becomes considerable. That is why the corresponding points lie on another straight line joining the points (R') & (G') (corresponding to the combined C.I.E. specification of the R.G. B. primary filters and the neutral density filter).

(1) For the Simple Pattern: Figures (76,77) show that rules (7 & 8a) apply directly with clear gradation. Rule (8b) does not show for the same reason mentioned in the case of the orange test colour. Rows (I-VI inclusive, VII-III' inclusive and X, XIII) in Table (9) show that rule (9) also applies in this case.

(2) For the Compound Pattern: Figures (78 a & c) Rows (XIV and XV) of Table (9), show that the three general empirical rules (7-9) apply satisfactorily.

For the yellow, blue and grey test colours the effects of the ~~surround of the~~ brightness of the comparison patch were studied in the case of the compound pattern only, which, as seen from the cases of the orange and green test colours, obeys all the rules (7-9) satisfactorily.

### III THE YELLOW TEST COLOUR:

In this case also the appearance of the yellow test colours on all its surrounds was matched by a mixture of (R) & (G) primaries only (no blue was needed). So rules (7 & 9) only can be shown satisfactorily in Figures (79 a & b), and rows (XIV and XV) in Table (10), the shift of the whole set of points (rule 8a) is away from the green, and rule (8b) does

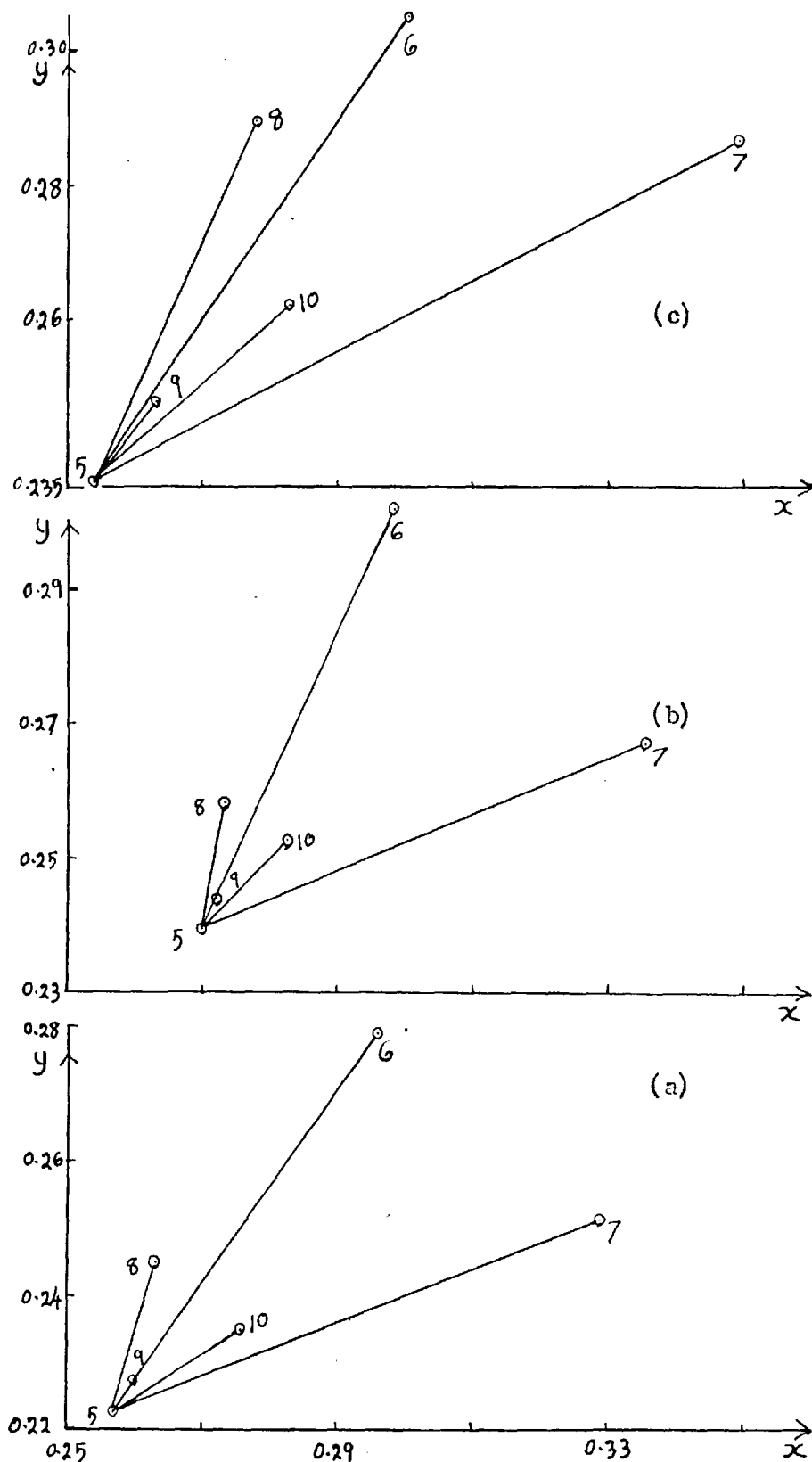


Figure (30) The effect of the Luminance, The Blue Compound Pattern, (a) Higher, (2) Lower luminance of the surround of the comparison patch, and (c) the same as (a) with lower luminance of the test patch.

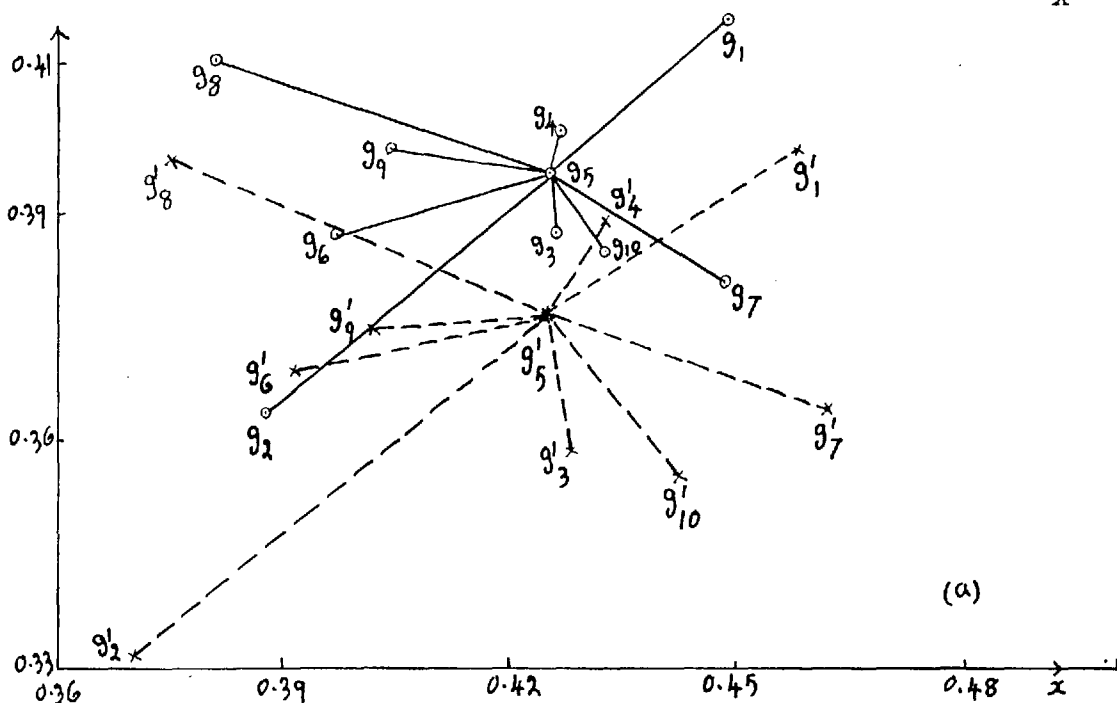
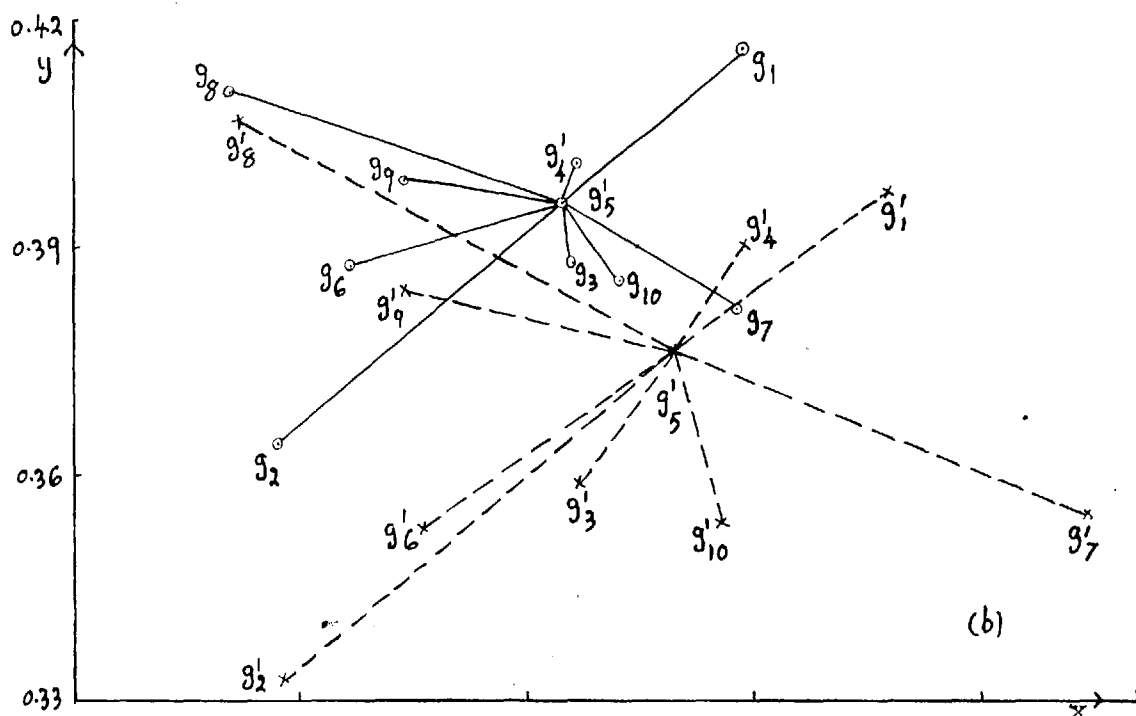


Figure (C1) The effect of the luminance, The Grey Compound Pattern, (b) (—) higher, (---) lower luminance of the surround of the comparison patch, (a) (—) higher, (---) lower luminance of the test patch.



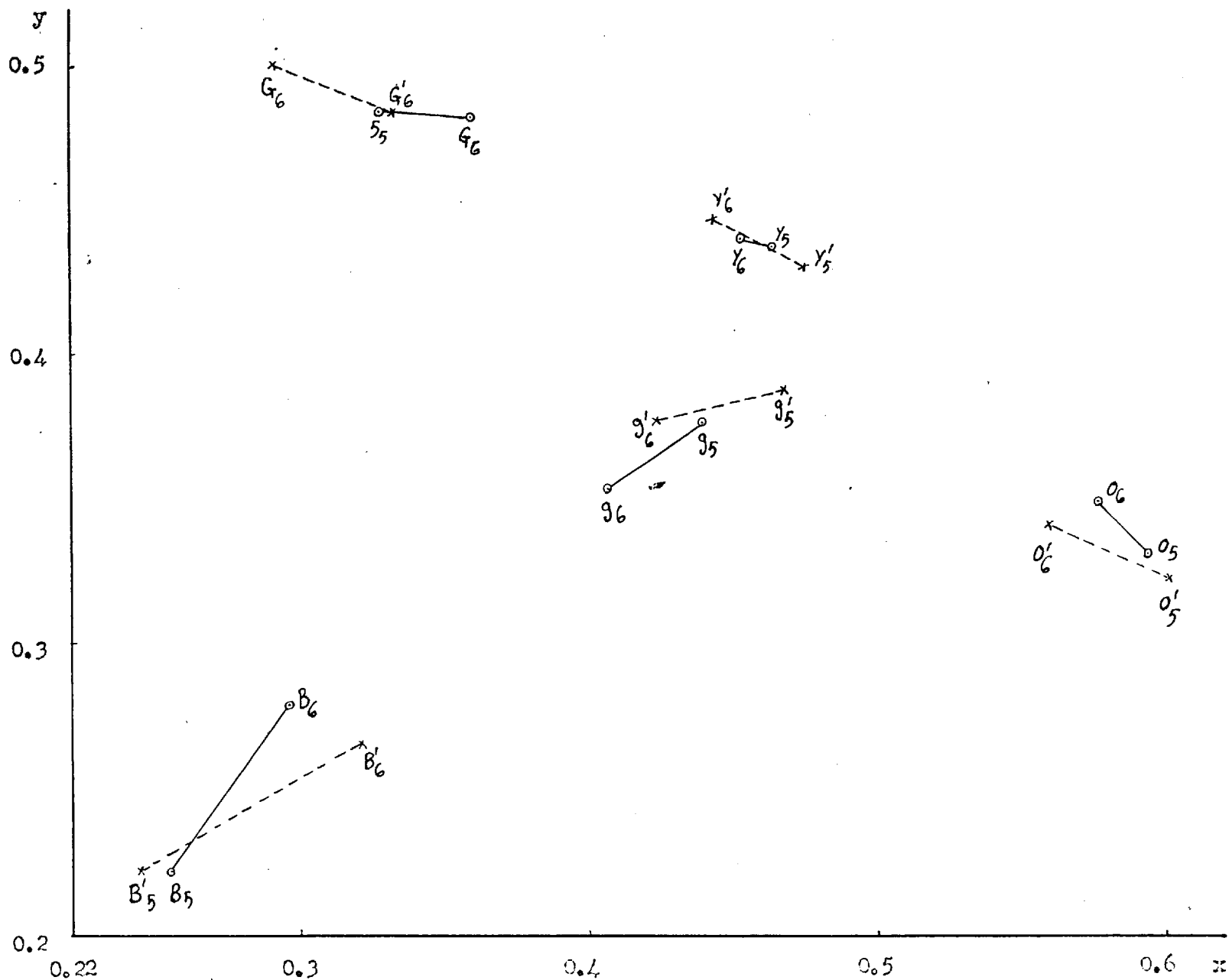


Figure (G2) The effect of the luminance of the surround of the test colour, (—) for vertical, and (---) for 20° inclination. (Compound Pattern of the Test Patch).

not show, for the same reason mentioned before.

#### IV THE BLUE TEST COLOUR:

Figures (80 a & b) and rows (XIV and XV) in table (11) show the cases of bright and brighter surround of comparison patch. It is clear that all rules (7-9) apply satisfactorily in this case.

#### V THE GREY TEST COLOUR.

Figures (81 b) and rows XIV and XV) in tables (12 & 13) show the cases of bright (x---x) and brighter (o---o) surround of the comparison patch. It is clear also that the three general rules (7 & 9) only apply satisfactorily in this case. The shift of the whole set of points is towards the green and can not convey any definite trend w.r.t. saturation.

#### B THE LUMINANCE OF THE SURROUND OF THE TEST COLOUR.

White and black surrounds were used to give bright and dark neutral surrounds to the test colour. Their percentage luminances are 77.62 and 4.45 respectively (Table 7). The luminance of the white surface in the vertical test patch is 57.9 ft. lambert and hence that of the black surface is 3.3 ft. lambert. The corresponding luminances for the inclined test patch are 148.3 and 8.5 ft. lambert.

Figure (82) shows the general shifts due to the brightness of the surround of the test colour for all the test colours used in the compound pattern for vertical (O-----O) and 20° viewing angle (X-----X). It is obvious from that figure and from columns 5 and 6 in tables (8-12) inclusive to deduce the following general empirical rules:

As the luminance of the surround of the test patch is reduced.

Rule (10) The corresponding shifts in the chromaticity chart show

changes of (a) hue and (b) saturation, as follows:

(a) Towards the yellow i.e. away from the red, green and blue ends of the chromaticity chart for orange, green and blue test colours respectively and away from  $0.59 \mu$  in the spectrum for both yellow and grey test colours.

(b) Towards desaturation for orange, green and blue test colours.

Rule(11.) The test colours appeared lighter and hence higher intensity of R,G,B mixture was used for matching.

These two rules are equivalent to rules (8 & 9) mentioned before in the study of the effect of the brightness of the comparison patch on the appearance of the comparison patch itself, although at first sight they appear contradictory. In fact, this case of the test patch is a straightforward result since the test colour is matched directly by the comparison patch. In the case of the comparison patch, changing the luminance of its surround changes its appearance and the observer tries to retain its original appearance (i.e. to match the test colour which remains the same all the time). As a matter of fact he is compensating the change in its appearance that took place due to change in brightness of its surround. So the actual change is the reverse process to what he is doing (and hence the opposite directions of shifts and the reverse action in intensity).

Hunt, (87) using a binocular matching technique and standard illuminant  $S_D$ , found that colours (Red, Green and blue) tend to become desaturated as the illumination level of their surround falls. This result is the same as rules (8b and 10b)

#### C THE LUMINANCE OF THE WHOLE TEST PATCH.

The luminance of the test patch (for the white paper), used in all

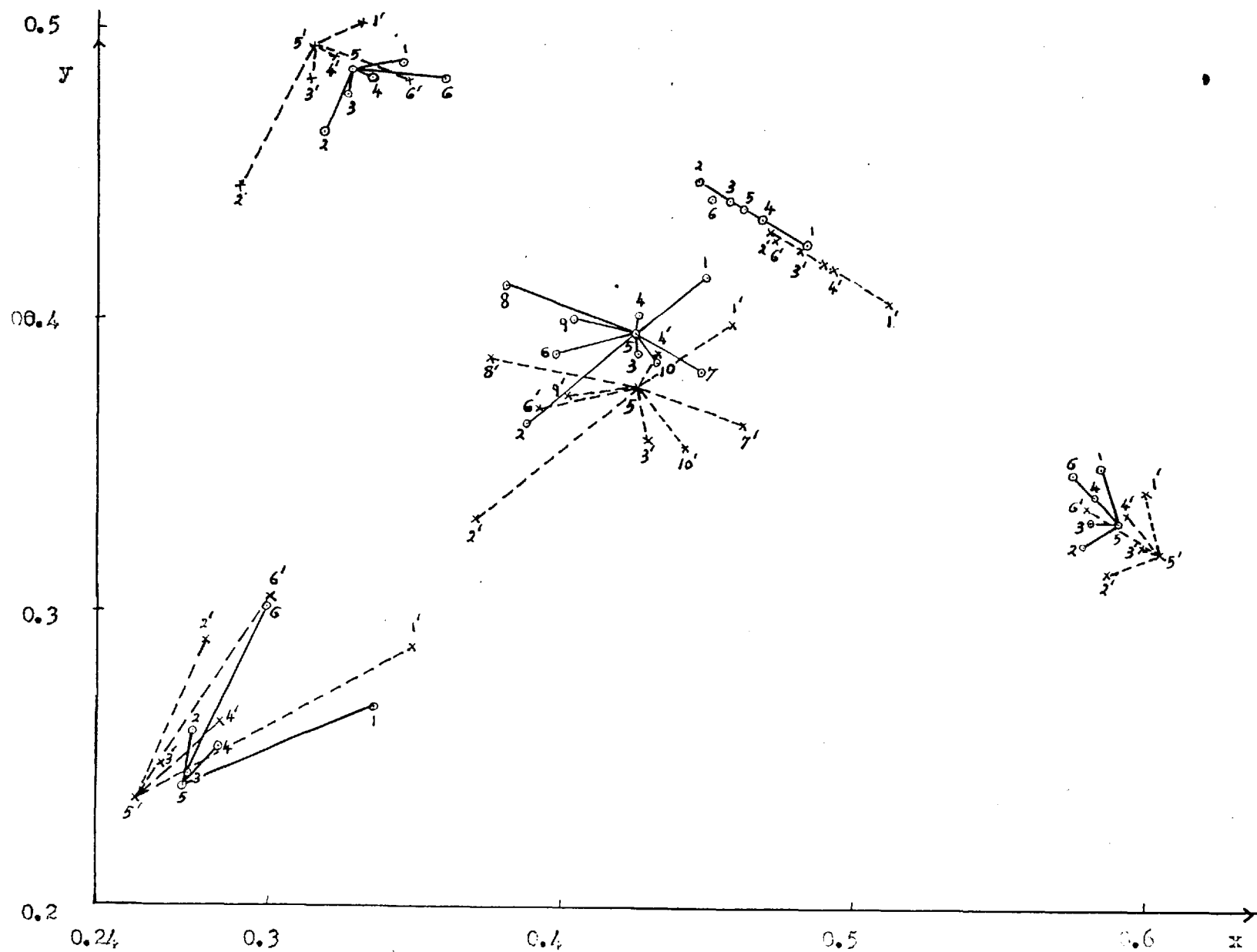


Figure (33) The effect of the luminance of the whole test patch, (—) Higher and (---) lower luminance.

the cases of this investigation is 47.9 ft. lambert. Then the neutral density filter  $F_3$  (of transmission factor = 0.450) was introduced to the patch of the beam illuminating the test patch. The trichromatic coordinates of the appearance of the test colour in its different surrounds in this case did not significantly change from the corresponding coordinates before introducing the filter. The differences were so small (no more than 0.002), that they hardly exceed the experimental error.

This result is very important when applied to the second method in this work, namely by using the Munsell Book of Color. Even if the levels of luminance due to natural daylight (for clear sky around mid-day) may vary from one day to the other, yet this variation is not likely to be as much as the ratio 0.45, which does not give any practically significant difference in the appearance of the test colour.

When the neutral density filter  $F_3$  was replaced by filter  $F_5$  (of transmission factor 0.162) large changes in colour appearance occurred. Figure (83) shows the general chromatic effects of the illumination of the test patch on the appearance of the test colours used against their different backgrounds in the case of the complex pattern of 15' element angle of subtense in the vertical plane. (o—o corresponds to high luminance and x—x corresponds to low luminance of the test patch). From this figure and tables (8-12) inclusive, conditions XIV and XVI, the following general empirical rules can be deduced for all test colours:

As the luminance of the test patch is reduced.

Rule(12) The separation between the points corresponding to different colour surrounds increases. This means that the smaller the luminance of the test patch, the bigger the differences in colour appear-

ance of the test colour due to different surrounds.

Rule (13). The points in the chromaticity chart are shifted in the same order showing two obvious trends:

(A) Change in hue (or dominant wavelength) away from the yellow but towards  $0.59 \mu$  in the case of yellow test colour.

(b) Change in saturation. (increase of saturation in the cases of orange, green and blue test colours).

Rule (14) The lightness of the test colour is decreased which is a direct result of reducing the luminance of the whole test patch.

Figures (75 a & c), (78 a & b) (79 a & c), (80 a & c) and (81 a) show in larger scale the chromatic effect of the luminance of the test patch in the cases of orange, green, yellow, blue and grey test colours respectively.

#### (D) THE ANGLE OF SUBTENSE OF THE TEST PATCH.

It was noticed, in the charts shown in plates (I & II), that the differences in the appearance of the test colours due to different surrounds, seem to increase as the viewing distance is increased or the size of the pattern <sup>is</sup> decreased. This means that the colour contrast effects get bigger as the angle of subtense is reduced. That is why the effects of the angle of subtense on these phenomena were studied.

The element angles of subtense (corresponding to the square of the test colour) used were  $2^{\circ}$ ,  $1^{\circ}$ ,  $30'$  and  $15'$  for the simple pattern, and  $15'$ ,  $12'$  and  $6'$  for the compound pattern. The case of the charts at element angles of subtense  $12'$  and  $6'$  were measured by using both the colorimeter and the Munsell Book of Color, the cases of the other angles of subtense were measured by using the colorimeter method only.

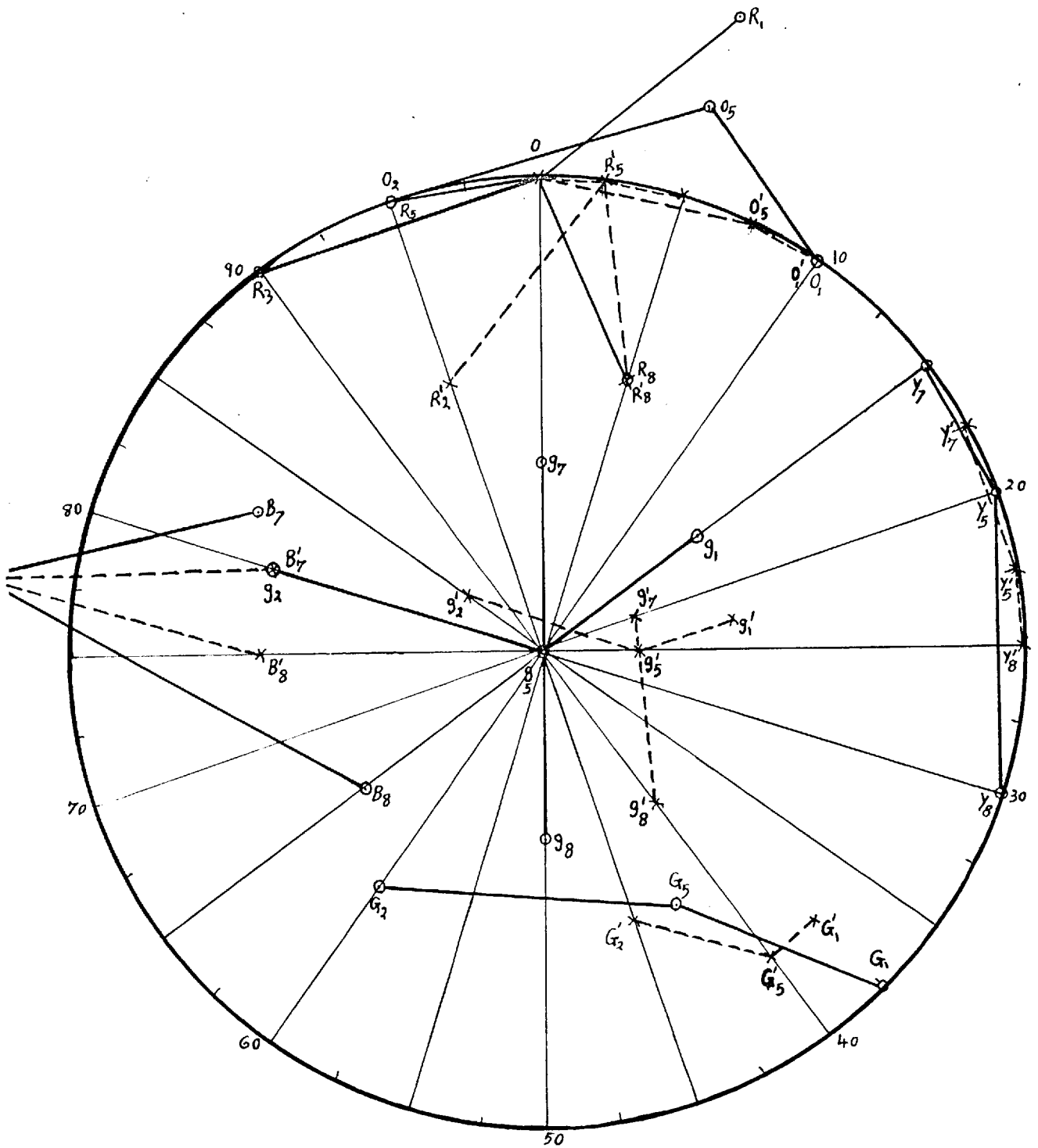
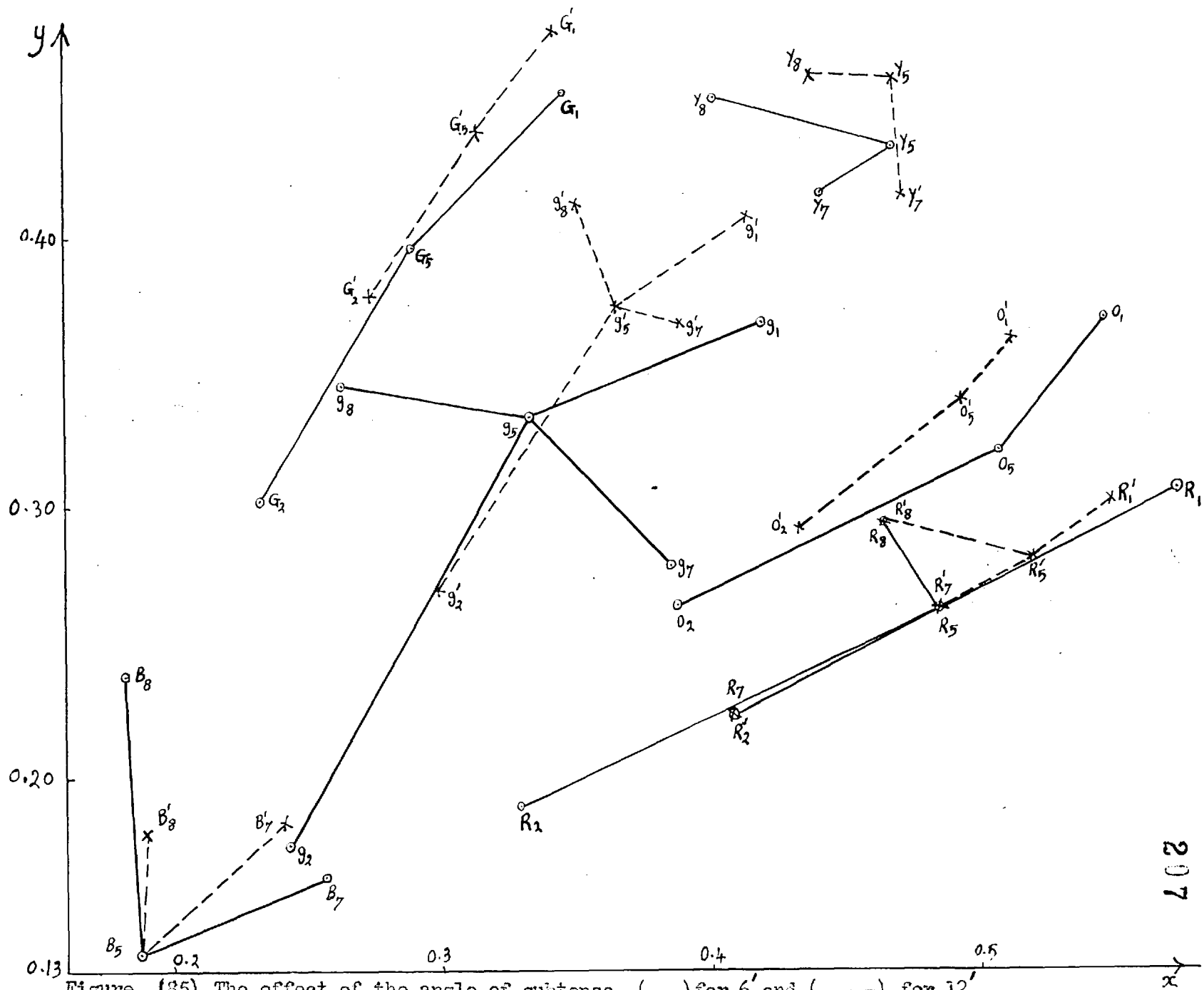


Figure (84), The effect of the angle of subtense of the test pattern.  
 (—) for 6' and (---) for 12'; shown in the hue chart.





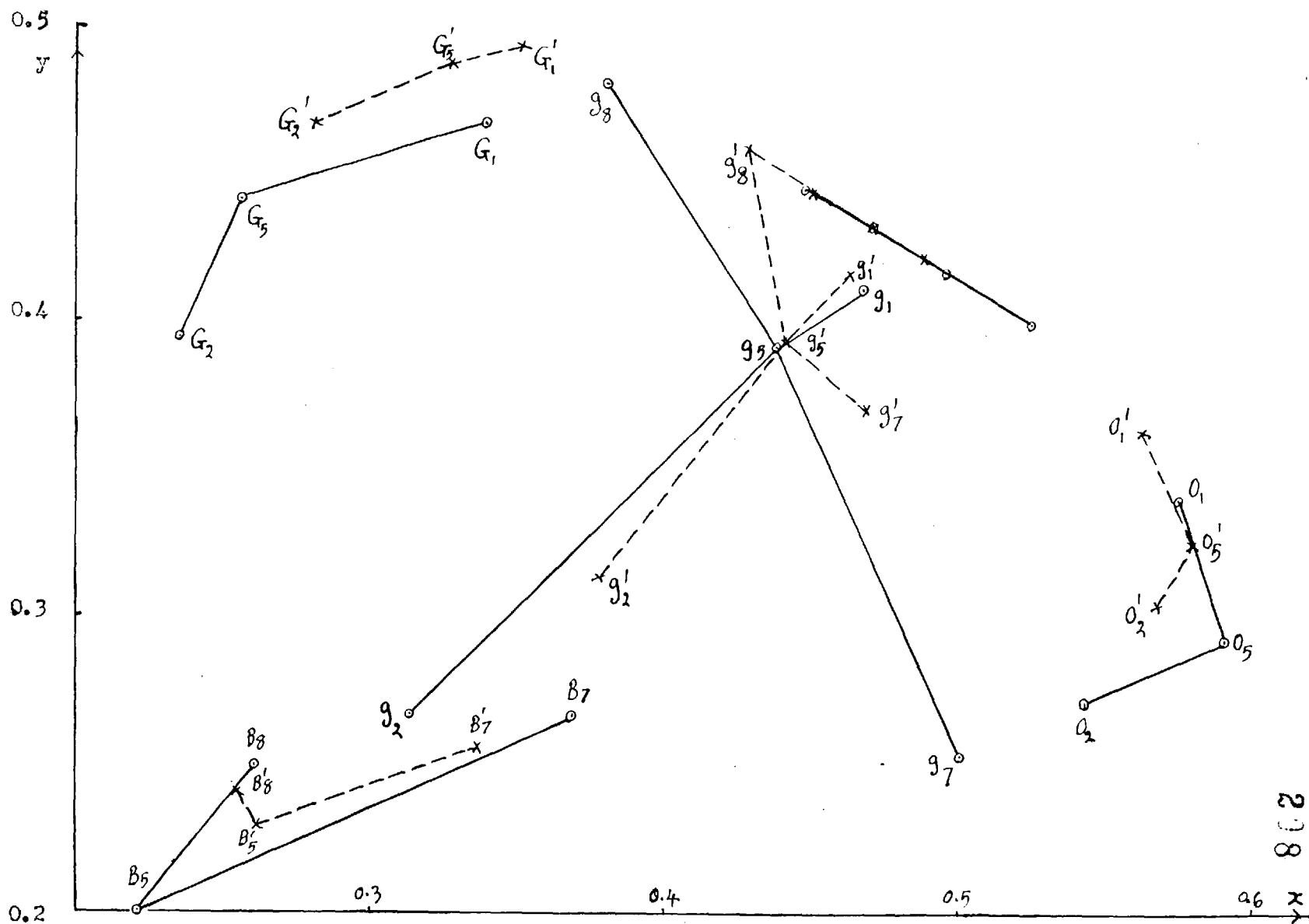


Figure (86) The effect of the angle of subtense as obtained for the charts by using the colorimeter ,  
 (—) for 6' and (---) for 12' .

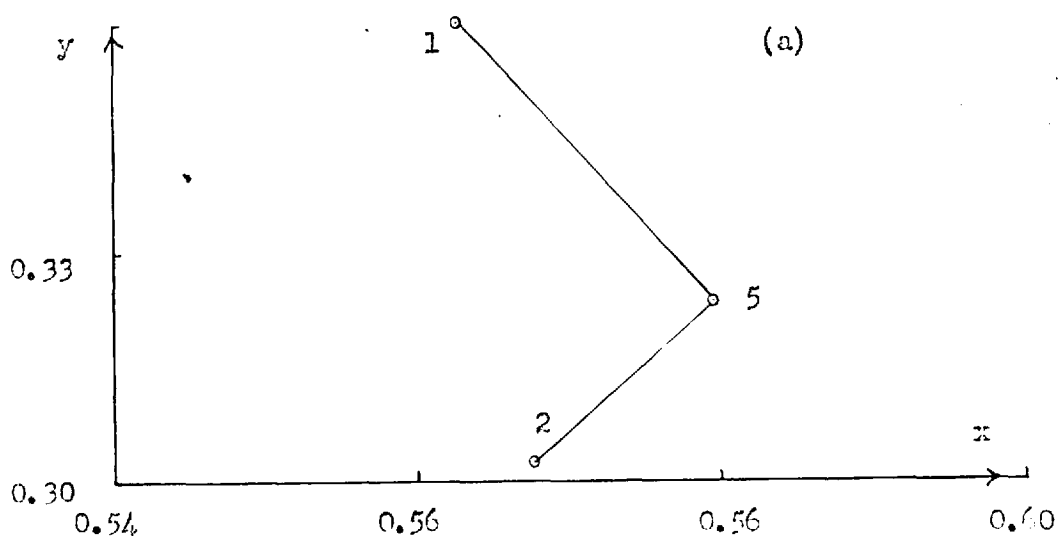
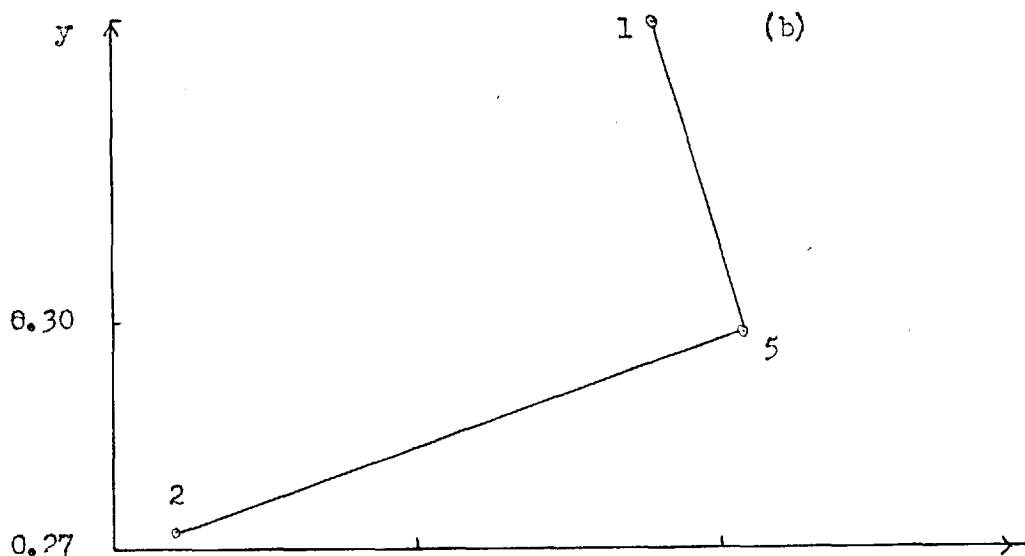
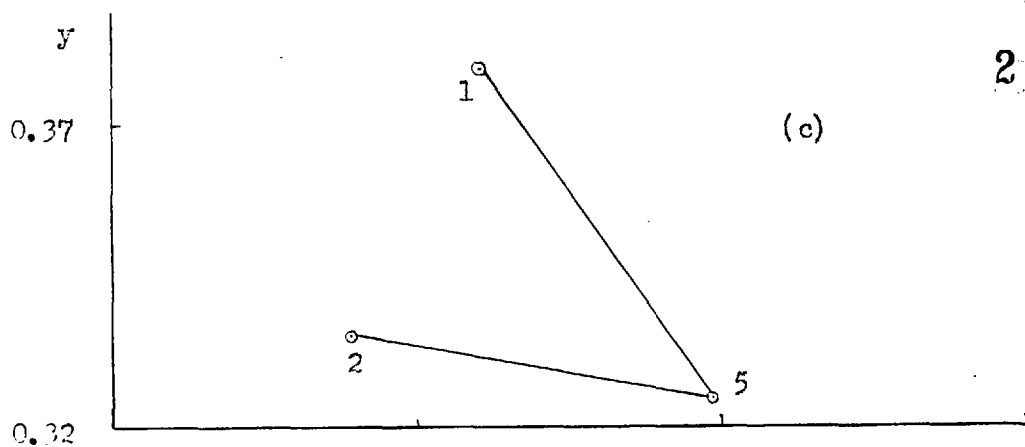


Figure (37) The effects of the angle of subtense and the orientation of the stripes of the chart for the Orange Test Colour, (a) 12', (b) 6' angles of subtense for horizontal stripes, and (c) 6 angle of subtense for vertical stripes.

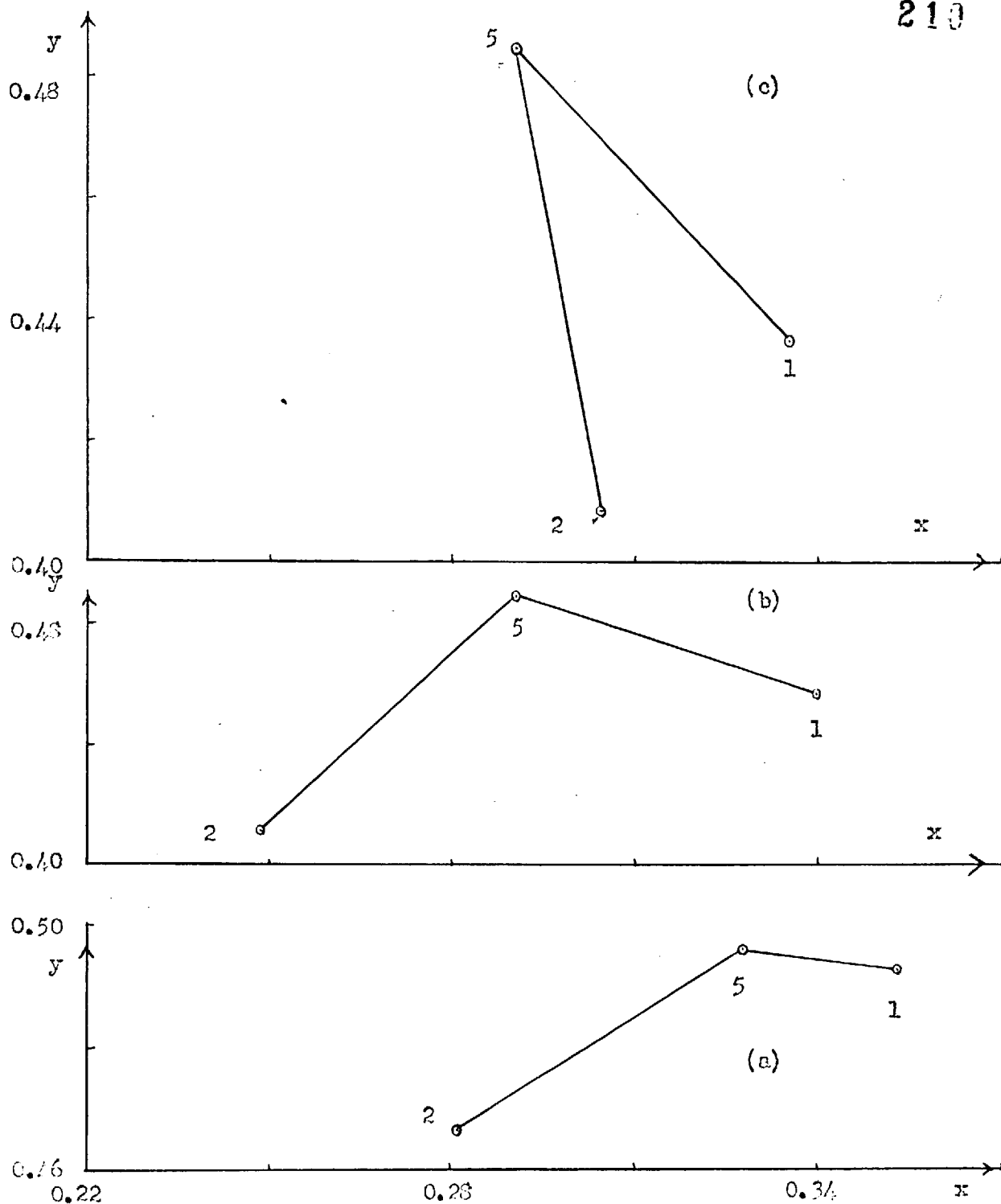


Figure (88) The effects of the angle of subtense and the orientation of the stripes of the chart for the Green Test Colour, (a)  $12'$ , (b)  $6'$  angles of subtense for horizontal stripes, and (c)  $6'$  angle of subtense for vertical stripes.

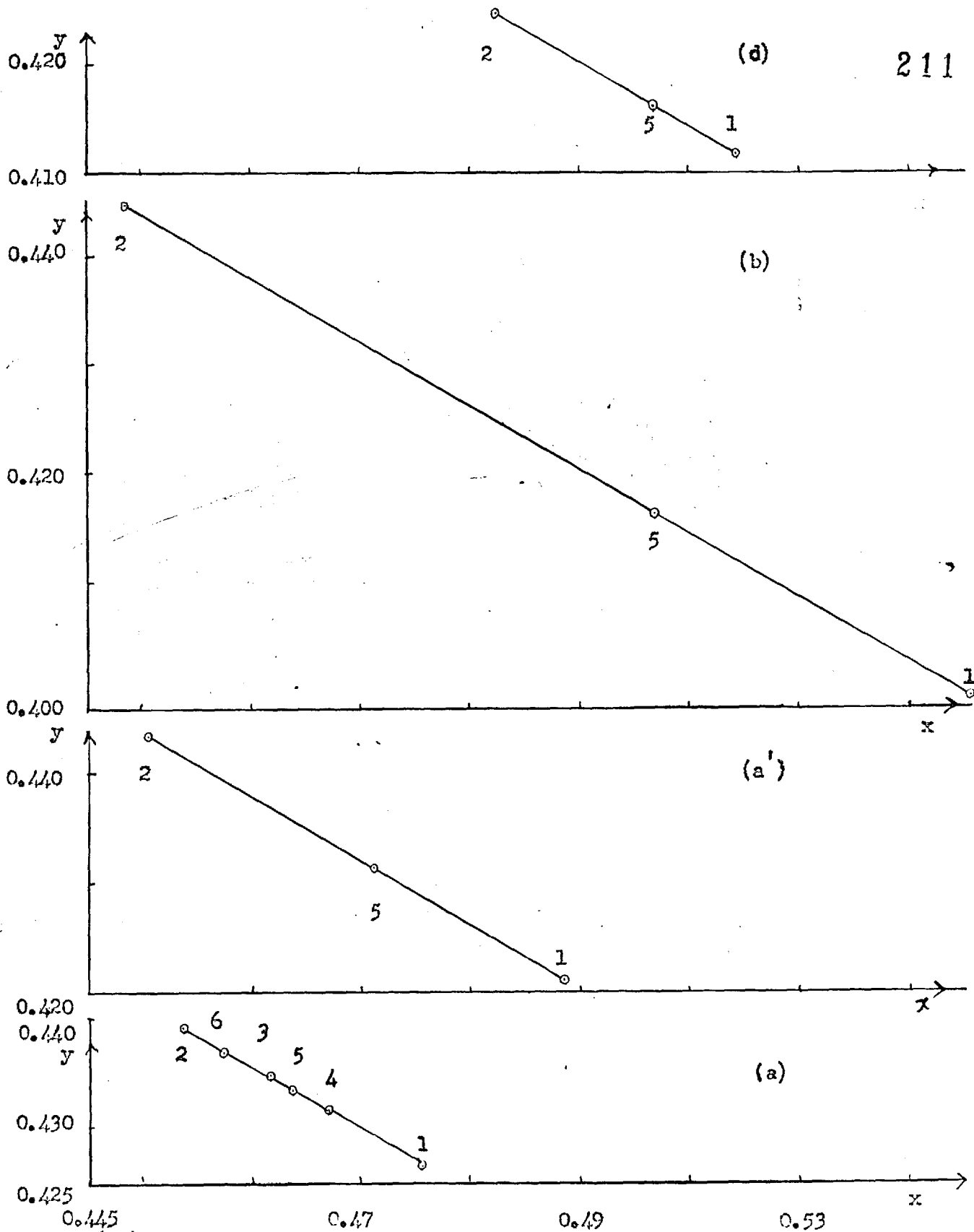


Figure (89) The effects of the angle of subtense and the orientation of the stripes of the chart, for the Yellow Test Colour, (a) 15', (a') 12', (b) 6' angles of subtense for horizontal stripes, and (c) 6' angle of subtense for vertical stripes.

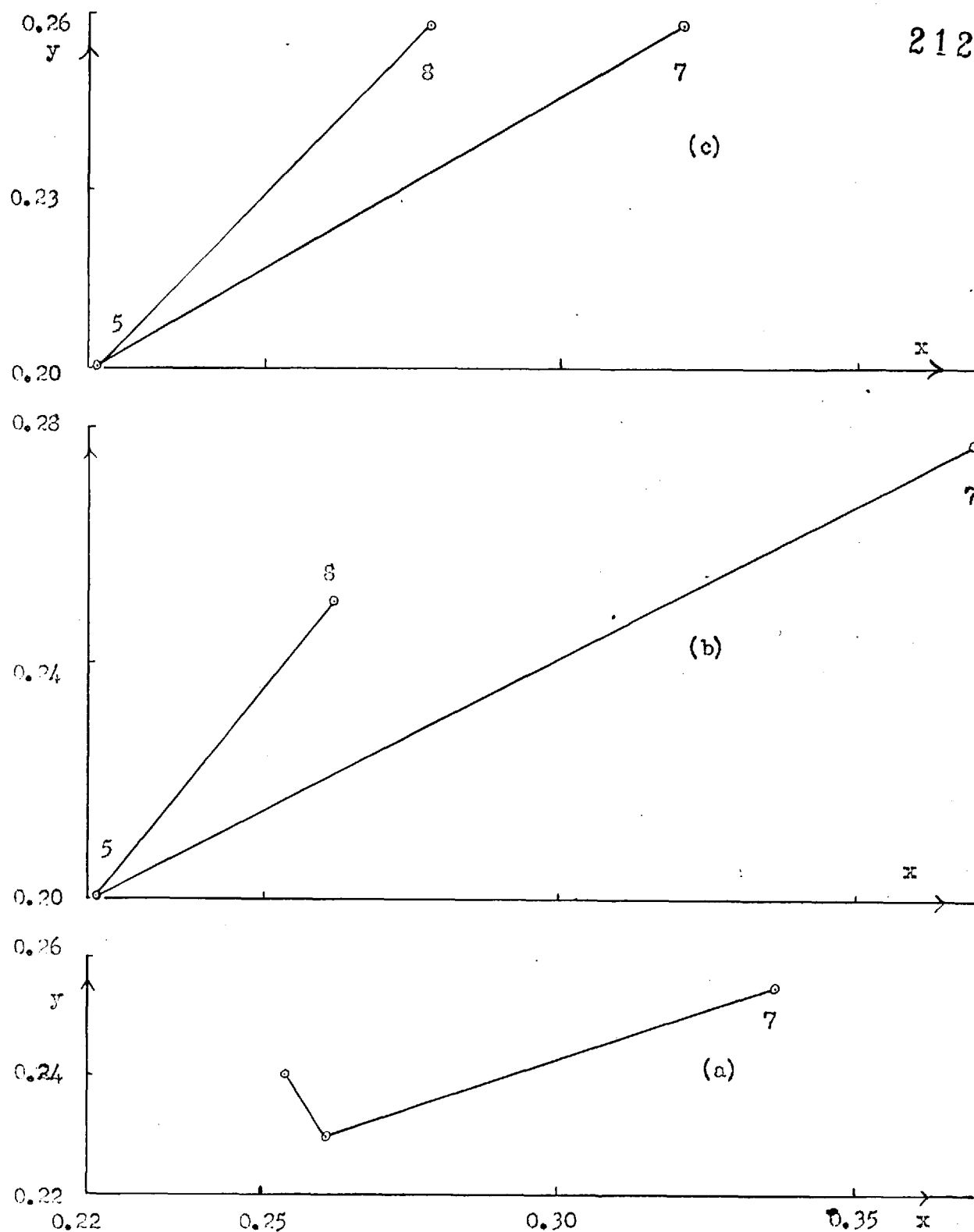


Figure (90) The effects of the angle of subtense and the orientation of the stripes of the chart for the Blue Test Colour, (a)  $12'$ , (b)  $6'$  angles of subtense for horizontal stripes, and (c)  $6'$  angle of subtense for vertical stripes.

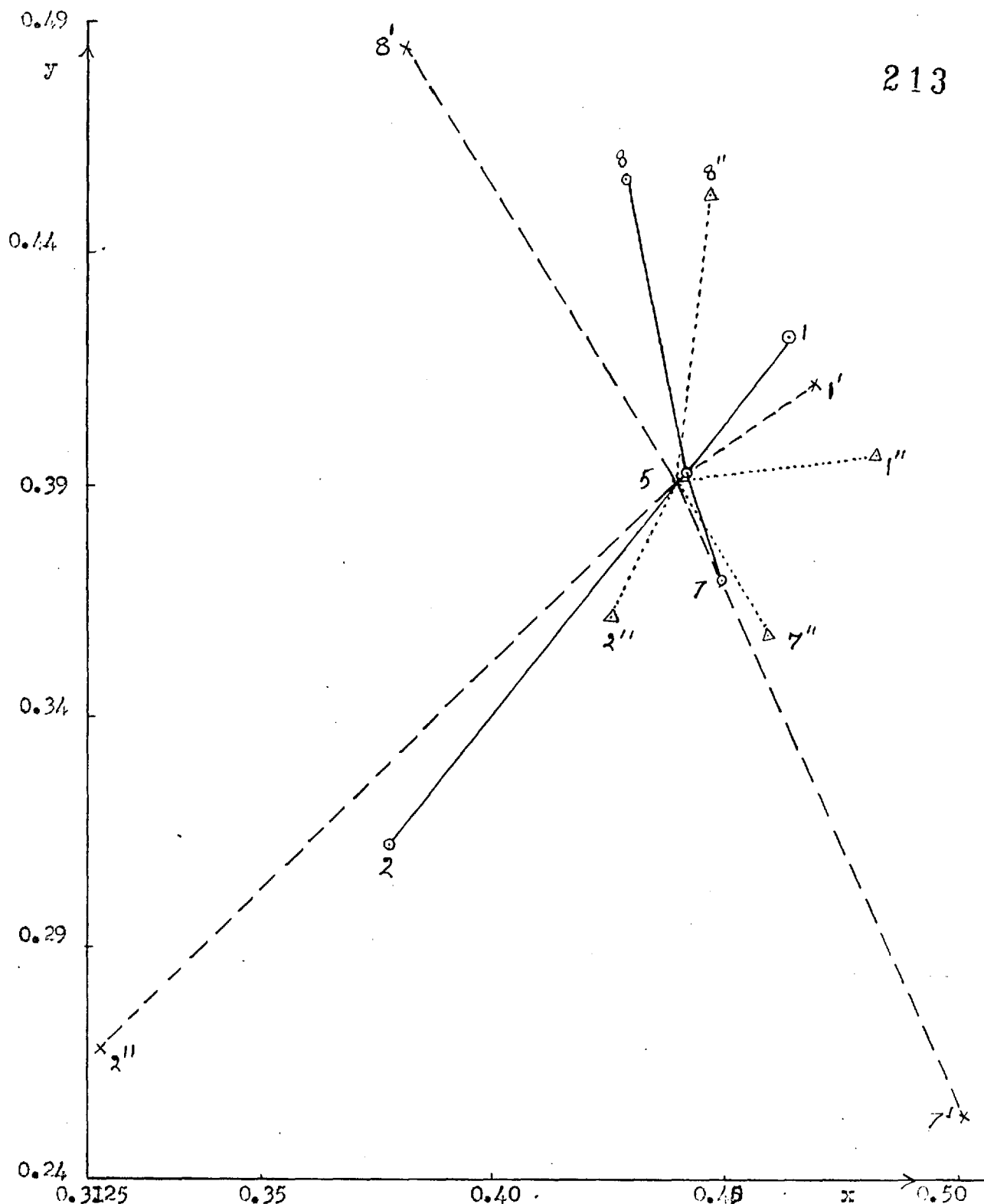


Figure (91) The effects of the angle of subtense and the orientation of the stripes of the chart for the Grey Test Colour, (—○—) 12', (x - -x) 6' angles of subtense for horizontal stripes, and (Δ....Δ) 6' angle of subtense for vertical stripes.

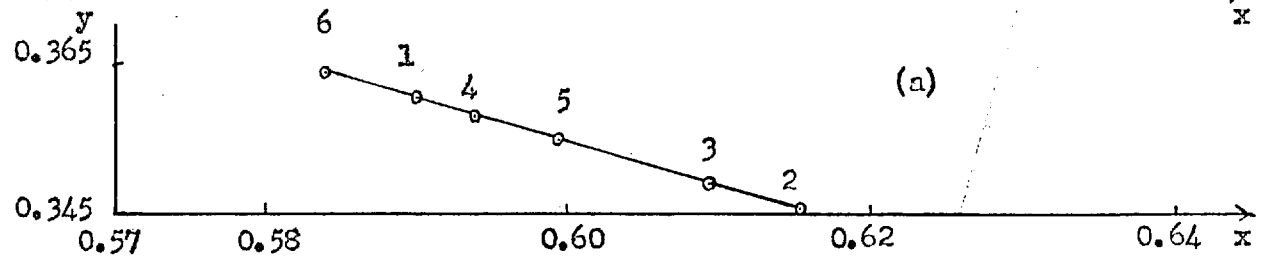
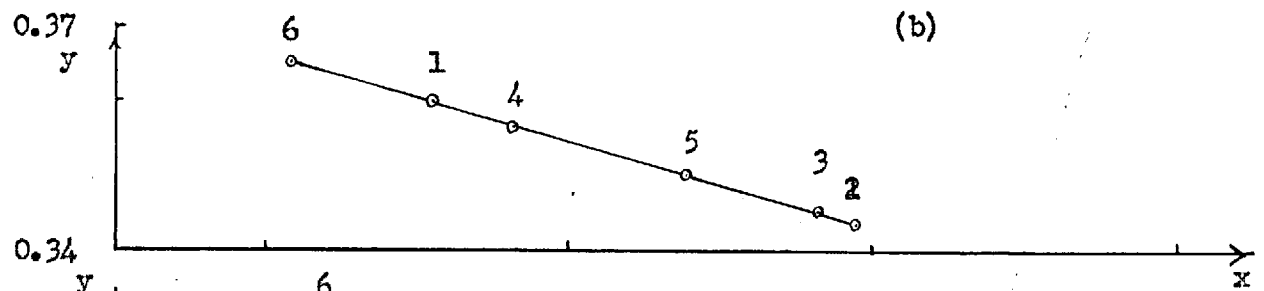
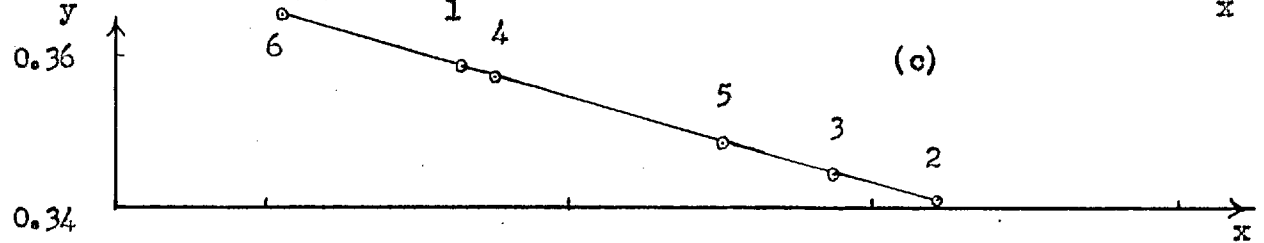
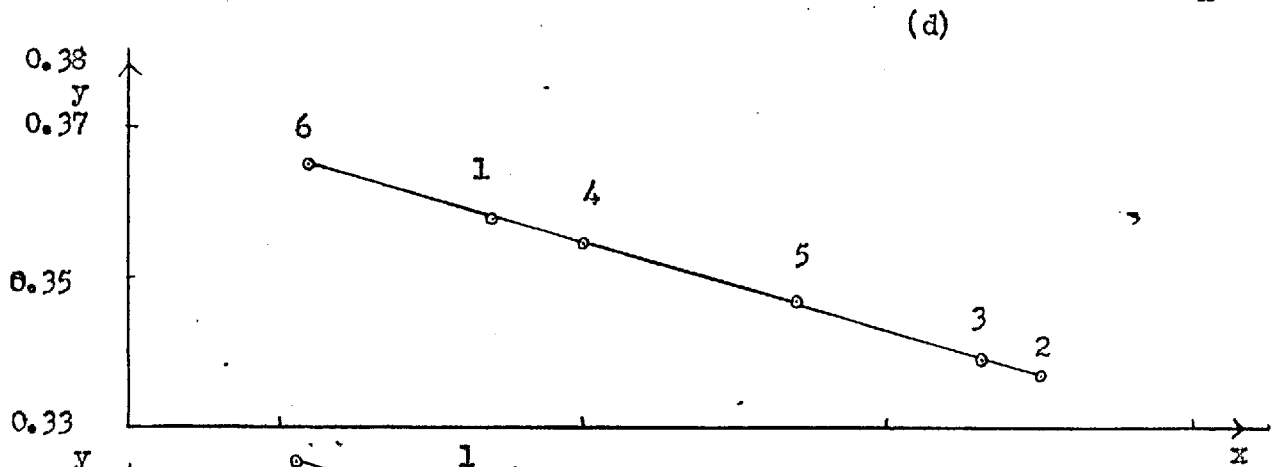
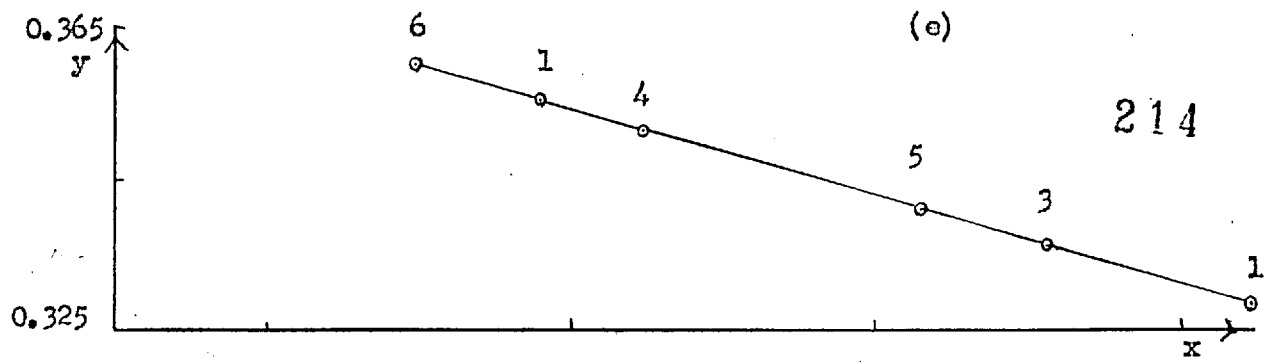
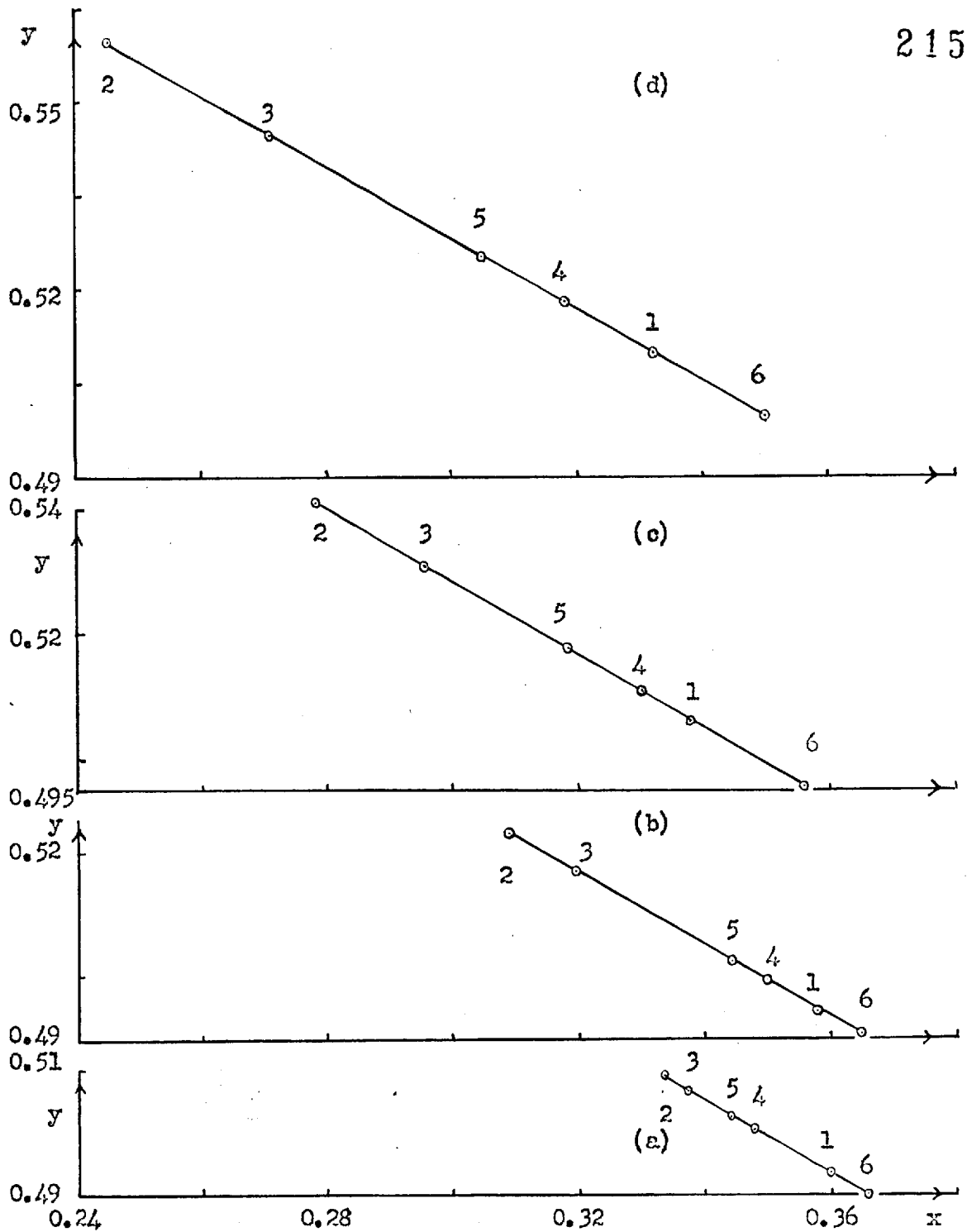


Figure (92) The effect of angle of subtense, Orange Test Colour.  
 (a)  $2^\circ$ , (b)  $1^\circ 30'$ , (c)  $1^\circ$ , (d)  $30'$ , (d)  $15'$  angles of subtense.



Figure(93) The effect of the angle of subtense, Green Test Colour.  
 (a)  $2^\circ$ , (b)  $1^\circ$ , (c)  $30'$ , (d)  $15'$  angles of subtense.



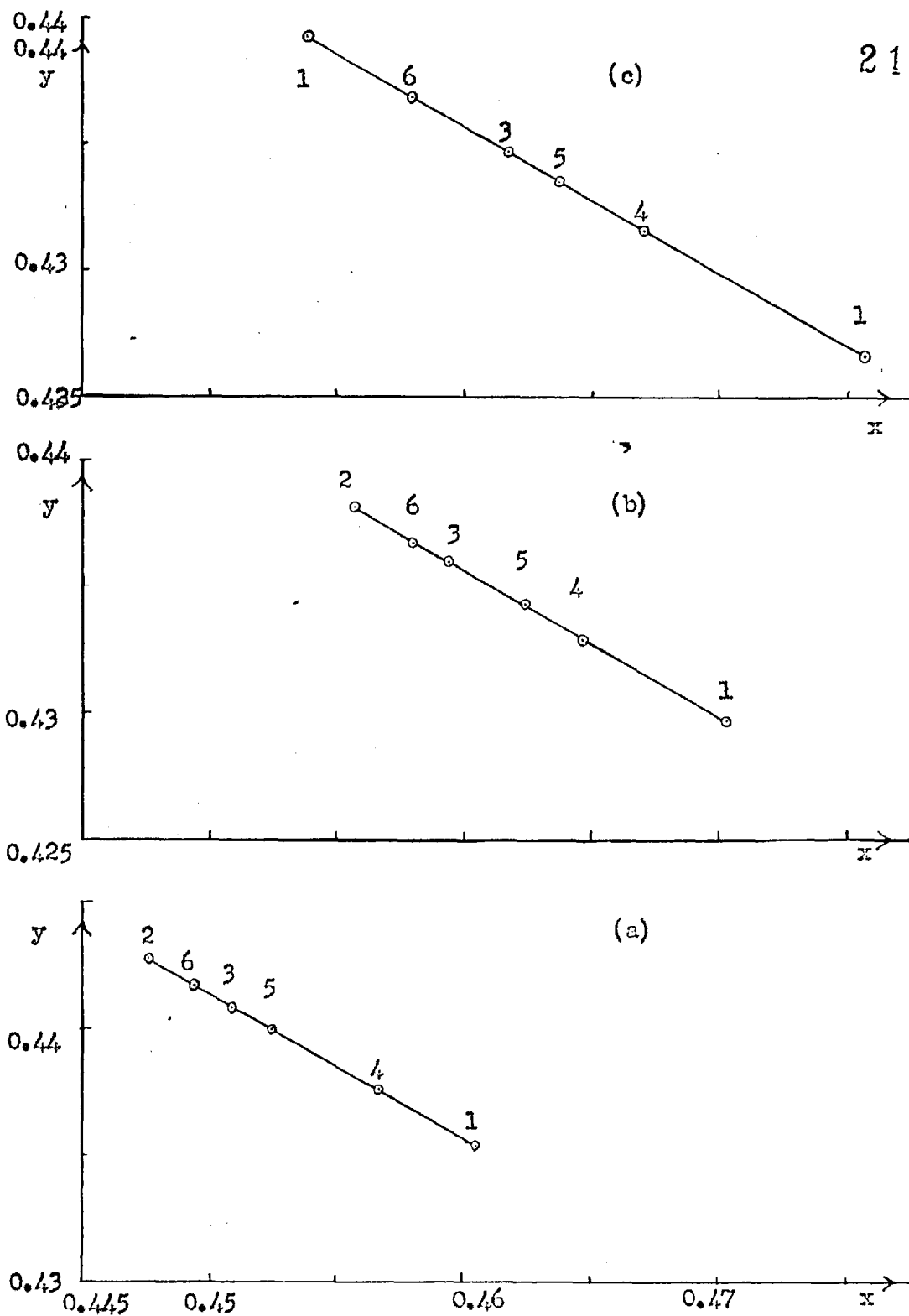


Figure (94) The effect of the angle of subtense, Yellow Test Colour, (a) 2°, (b) 30', (c) 15' angles of subtense.

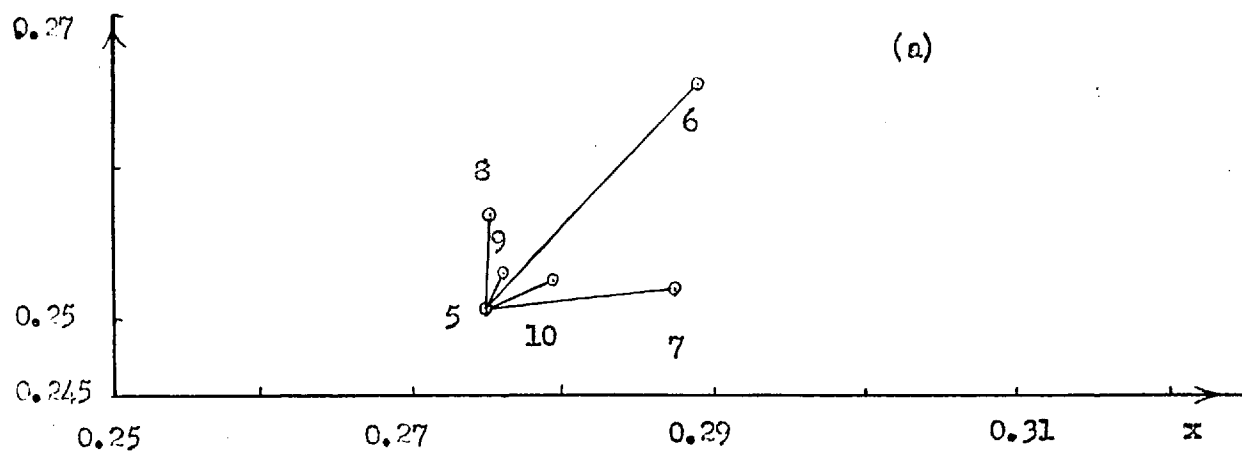
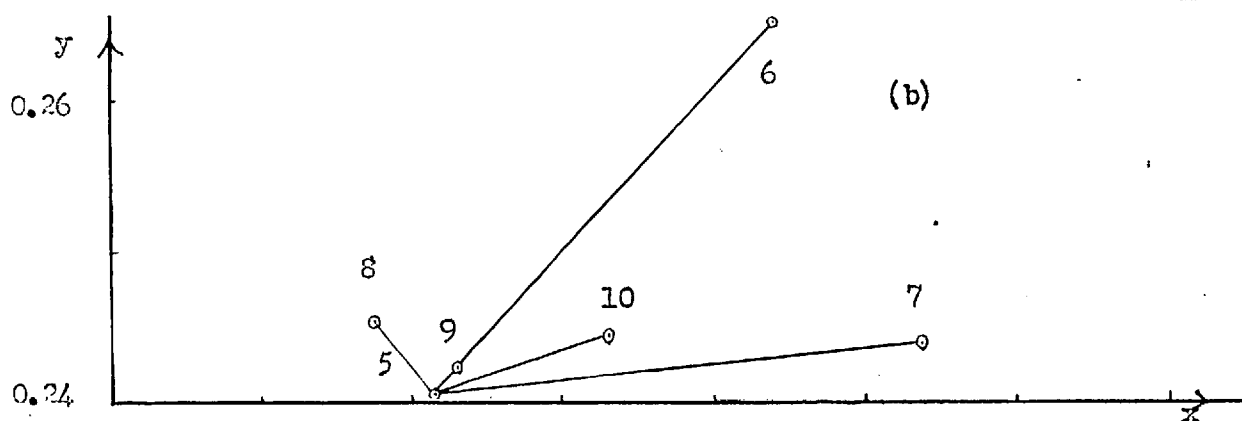
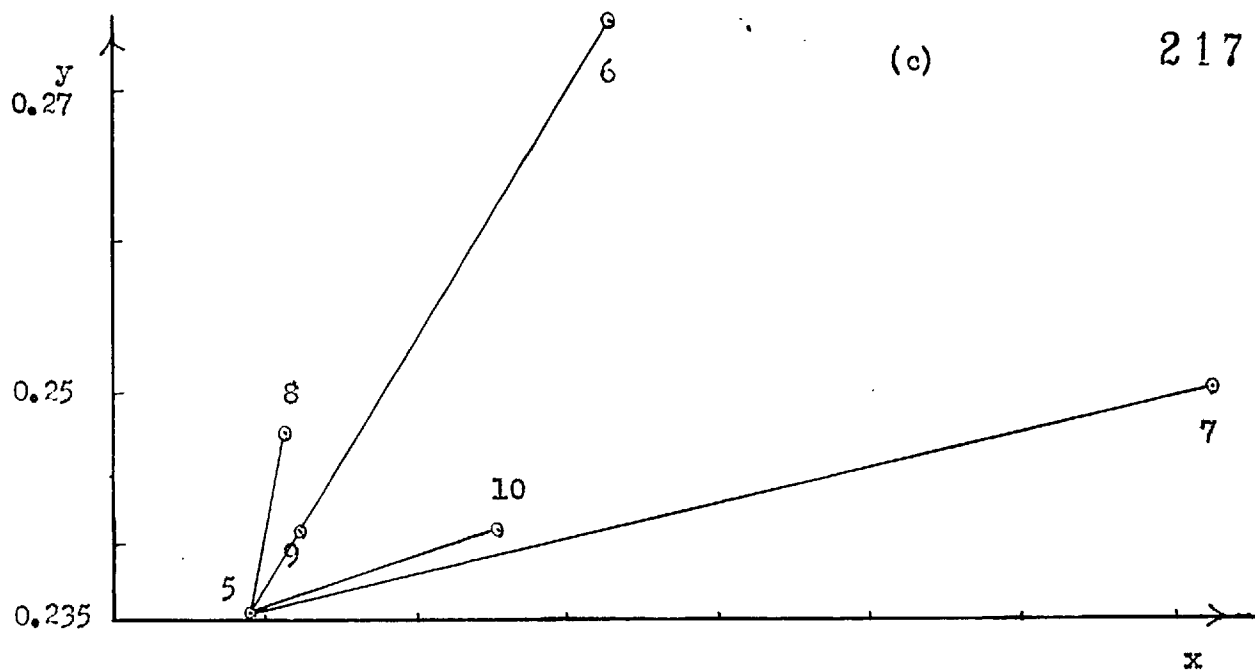


Figure (95) The effect of angle of subtense, The Blue Test Colour.  
 (a) 2°, (b) 30', (c) 15' angles of subtense.

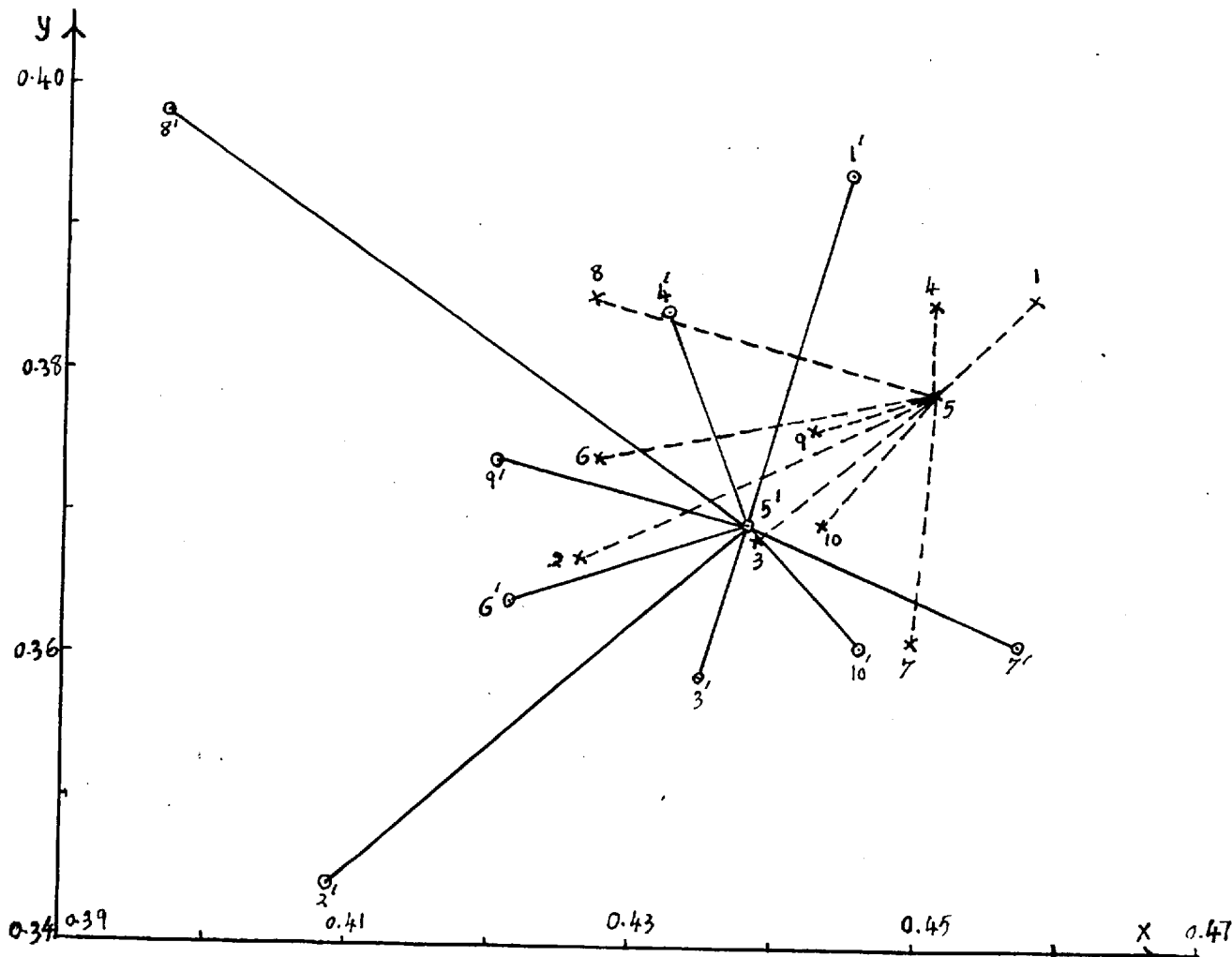


Figure (96) The effect of angle of subtense, The Grey Test Colour, (x....x) for 2° and (o—o) for 15'.

A.

**TABLE (22) THE COMPARATIVE RESULTS OBTAINED BY THE AUTHOR FOR (1) ELEMENT ANGLE OF SUBTENSE 6', (2) ELEMENT ANGLE OF SUBTENSE 12', (3) ELEMENT ANGLE OF SUBTENSE 6' WITH VERTICAL STRIPES.**

| SURROUND    |    | (5)  |   |    |      |      |      | (1)  |   |    |      |      |      | (2)  |   |    |      |      |      |
|-------------|----|------|---|----|------|------|------|------|---|----|------|------|------|------|---|----|------|------|------|
| TEST COLOUR |    | H    | V | C  | x    | y    | Y    | H    | V | C  | x    | y    | Y    | H    | V | C  | x    | y    | Y    |
| Orange      | 1. | 5    | 5 | 12 | .507 | .320 | 19.8 | 10   | 6 | 10 | .546 | .370 | 30.1 | 95   | 5 | 10 | .383 | .263 | 19.8 |
|             | 2. | 7.5  | 5 | 10 | .493 | .340 | 19.8 | 10   | 5 | 10 | .512 | .363 | 19.8 | 8    | 5 | 10 | .433 | .292 | 19.8 |
|             | 3. | 5.0  | 5 | 12 | .507 | .320 | 19.8 | 5    | 5 | 10 | .476 | .323 | 19.8 | 2.5  | 5 | 10 | .454 | .306 | 19.3 |
| Green       | 1. | 42.5 | 6 | 6  | .239 | .397 | 30.1 | 37.5 | 7 | 10 | .346 | .455 | 43.1 | 60   | 6 | 6  | .233 | .382 | 30.1 |
|             | 2. | 40.0 | 7 | 8  | .314 | .439 | 44.5 | 37.5 | 6 | 8  | .342 | .477 | 30.1 | 45   | 6 | 6  | .274 | .379 | 30.1 |
|             | 3. | 42.5 | 6 | 6  | .239 | .397 | 30.9 | 40   | 6 | 8  | .312 | .456 | 30.1 | 47.5 | 6 | 6  | .276 | .368 | 30.1 |
| Red         | 1. | 100  | 3 | 10 | .435 | .262 | 6.6  | 5    | 4 | 14 | .573 | .306 | 12.0 | 90   | 3 | 10 | .329 | .189 | 6.6  |
|             | 2. | 2.5  | 3 | 10 | .519 | .281 | 6.6  | 5    | 3 | 10 | .549 | .302 | 6.6  | 95   | 3 | 10 | .408 | .223 | 6.6  |
|             | 3. | 100  | 3 | 10 | .485 | .262 | 6.6  | 2.5  | 3 | 10 | .518 | .281 | 6.6  | 97.5 | 3 | 10 | .435 | .242 | 6.6  |
| Grey        | 1. | N    | 3 |    | .333 | .333 | 6.6  | 20   | 4 | 4  | .419 | .398 | 12.0 | 80   | 2 | 6  | .244 | .174 | 3.1  |
|             | 2. | 25   | 3 | 2  | .365 | .375 | 6.6  | 22.5 | 4 | 4  | .414 | .407 | 12.0 | 85   | 3 | 2  | .299 | .270 | 6.6  |
|             | 3. | N    | 3 |    | .333 | .333 | 6.6  | 20   | 3 | 2  | .375 | .364 | 6.6  | 75   | 3 | 2  | .271 | .272 | 6.6  |

B. TABLE (22)

| SURROUND    |    | (5)  |   |    |      |      |      | (3)  |   |    |      |      |      | (7)  |   |    |      |      |      |
|-------------|----|------|---|----|------|------|------|------|---|----|------|------|------|------|---|----|------|------|------|
| TEST COLOUR |    | H    | V | C  | x    | y    | Y    | H    | V | C  | x    | y    | Y    | H    | V | C  | x    | y    | Y    |
| Yellow      | 1. | 20   | 7 | 10 | .468 | .434 | 43.1 | 30   | 8 | 10 | .401 | .452 | 59.1 | 15   | 7 | 10 | .472 | .397 | 43.1 |
|             | 2. | 22.5 | 8 | 12 | .468 | .453 | 59.1 | 25   | 8 | 10 | .438 | .460 | 59.1 | 17.5 | 7 | 10 | .471 | .415 | 43.1 |
|             | 3. | 20   | 7 | 10 | .468 | .434 | 43.1 | 22.5 | 7 | 10 | .451 | .451 | 43.1 | 17.5 | 7 | 10 | .471 | .415 | 43.1 |
| Blue        | 1. | 77.5 | 3 | 12 | .188 | .136 | 6.6  | 65   | 3 | 6  | .183 | .237 | 6.6  | 82.5 | 2 | 8  | .25  | .163 | 3.1  |
|             | 2. | 77.5 | 3 | 12 | .188 | .136 | 6.6  | 75.0 | 2 | 6  | .180 | .181 | 3.1  | 80.0 | 2 | 6  | .244 | .134 | 3.1  |
|             | 3. | 77.5 | 3 | 12 | .188 | .136 | 6.6  | 77.5 | 2 | 10 | .172 | .156 | 3.1  | 77.5 | 2 | 6  | .218 | .179 | 3.1  |
| Red         | 1. | 100  | 3 | 10 | .485 | .262 | 6.6  | 5.0  | 2 | 6  | .464 | .293 | 3.1  | 95   | 3 | 10 | .408 | .223 | 6.6  |
|             | 2. | 2.5  | 3 | 10 | .519 | .231 | 6.6  | 5.0  | 2 | 6  | .464 | .293 | 3.1  | 100  | 3 | 10 | .485 | .262 | 6.6  |
|             | 3. | 100  | 3 | 10 | .485 | .262 | 6.6  | 2.5  | 2 | 6  | .439 | .276 | 3.1  | 97.5 | 3 | 10 | .445 | .242 | 6.6  |
| Grey        | 1. | N    | 3 |    | .333 | .333 | 6.6  | 50   | 4 | 4  | .263 | .349 | 12.0 | 100  | 2 | 4  | .385 | .278 | 3.1  |
|             | 2. | Y    | 3 | 2  | .365 | .375 | 6.6  | 40   | 2 | 4  | .358 | .413 | 6.6  | 20   | 2 | 2  | .308 | .368 | 3.1  |
|             | 3. | N    | 3 |    | .333 | .333 | 6.6  | 34.5 | 4 | 4  | .262 | .433 | 12.0 | 20.0 | 2 | 2  | .308 | .368 | 3.1  |

First. THE RESULTS OBTAINED (BY THE AUTHOR) BY USING THE MUNSELL  
BOOK OF COLOR.

Table (22) shows the comparative results obtained for the two angles of subtense 12' and 6'.

Figure (84) shows in a hue chart the effects of the angle of subtense on the appearance of the test colours used: Orange (O), red (R), yellow (Y), green (G), blue (B) and grey (g).

Figure (85) shows, in the chromaticity chart, the same results after being transformed to the C.I.E. system.

Second: THE RESULTS OBTAINED BY USING THE COLORIMETER...

Rows I-VII inclusive, XIV, XVIII and XIX of Tables (8-12) inclusive, show the comparative results for the different angles of subtense used for different test colours.

Figure (86) shows the general effects of the angle of subtense on the appearance of the test colours used (for the charts at angles of subtense 12' and 6').

Figures (87-91) inclusive, show these effects for the orange, green, yellow, blue and grey test colours respectively in a larger scale for the compound pattern.

Figures (92-96) inclusive, shows these effects for the same test colours in the simple pattern.

The following general empirical rules can be deduced from the tables and figures just mentioned before for all the test colours measured by the two methods:

AS THE ANGLE OF SUBTENSE IS REDUCED:

Rule (15) The separation between the points corresponding to

different colour surrounds increases. This means that the smaller the angle of subtense of the test patch the bigger the difference in the colour appearance of the test colours due to different surrounds.

Rule (16) The points in the chromaticity chart are shifted in the same order showing the following two obvious trends.

(a) Change in hue (or dominant wavelength) away from the yellow (towards  $0.59 \mu$  in the case of the yellow test colour).

(b) Change in saturation:

(1) There is no change in saturation shown in the case of the simple pattern for both the orange and green test colours and both the simple and compound patterns for the yellow test colour. This is because all their points lie on the straight line (R) (G) since there was no need to use any blue component in these matches.

(2) There is no definite general trend in the other cases used for the study of the effect of the angle of subtense as in the previously studied conditions of viewing. Nevertheless there is an obvious change in saturation (figures 78 & 79) which varies from one test colour to the other e.g. the colours of the grey on different surrounds get more saturated, the green and blue get less saturated (except blue on white surround), the orange gets more saturated (except  $O_2$ ); as the angle of subtense is decreased.

Rule (17) The brightness of the test colour is decreased. This rule is obvious in the first method by using the colorimeter, with few exceptions which can be considered mainly as due to experimental error for the difficulty of matching brightness, and not to the invalidity of this rule. The second method by using the Munsell Book of

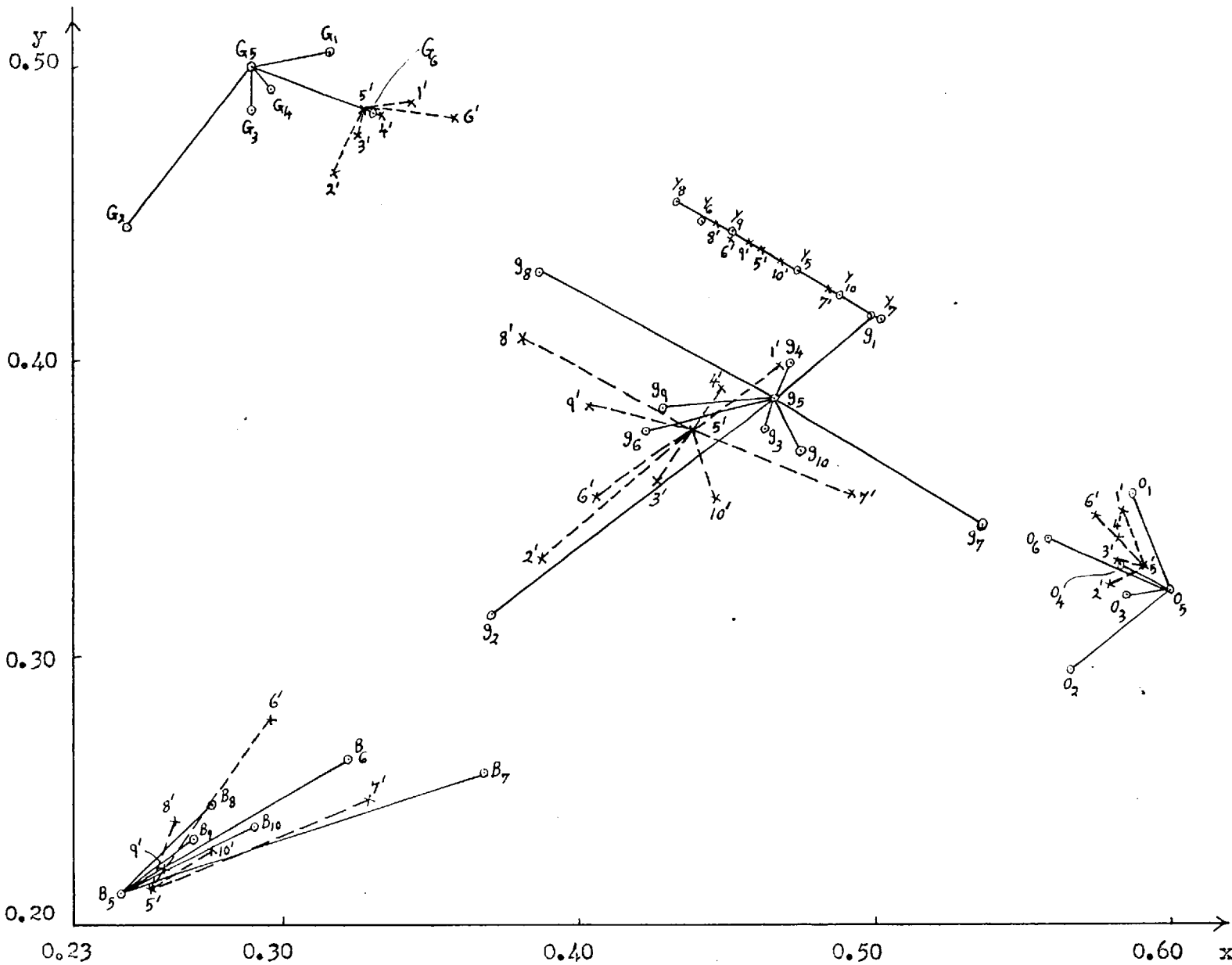


Figure (97) The effect of the inclination of the test patch, (x - x) vertical, (o—o) 20° inclination.



Color, fails in showing this rule. This is mainly due to the large steps of value as seen in Table (24). There is no means in this method (as in the case of the colorimeter) to make a gradual change in value. The only possible thing is to interpolate between the given values which is rather difficult.

| MUNSELL VALUE        | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|----------------------|-------|-------|-------|-------|-------|-------|-------|
| C.I.E. Y EQUIVALENT. | 0.031 | 0.066 | 0.120 | 0.198 | 0.301 | 0.431 | 0.591 |

(TABLE 24) RELATION BETWEEN THE MUNSELL VALUES AND THE C.I.E.  
Y EQUIVALENT.

#### E. THE INCLINATION OF THE TEST PATCH:

Looking at the charts in Plates (I & 2.) at a very short distance a small difference (if any) in the appearance of the test colours in the two patterns can be seen. But if they are tilted about an axis parallel to the direction of the stripes, the differences increase. This may be partially due to the fact that tilting the chart reduces the visual angle of subtense in a direction normal to the axis of rotation. That is why the effects of the viewing angle on the colour contrast phenomena were studied.

The viewing angles used were  $90^{\circ}$ ,  $20^{\circ}$  and  $5^{\circ}$ .

Rows I, IV, (VII-XIV) inclusive and XVII in Tables (8-12) inclusive show the comparative results for different viewing angles used for different test colours.

Figure (97) shows the general effects of the viewing angle on the appearance of the test colour used for the case of compound pattern of element angle of subtense  $15'$  for vertical and  $20^{\circ}$  inclination.

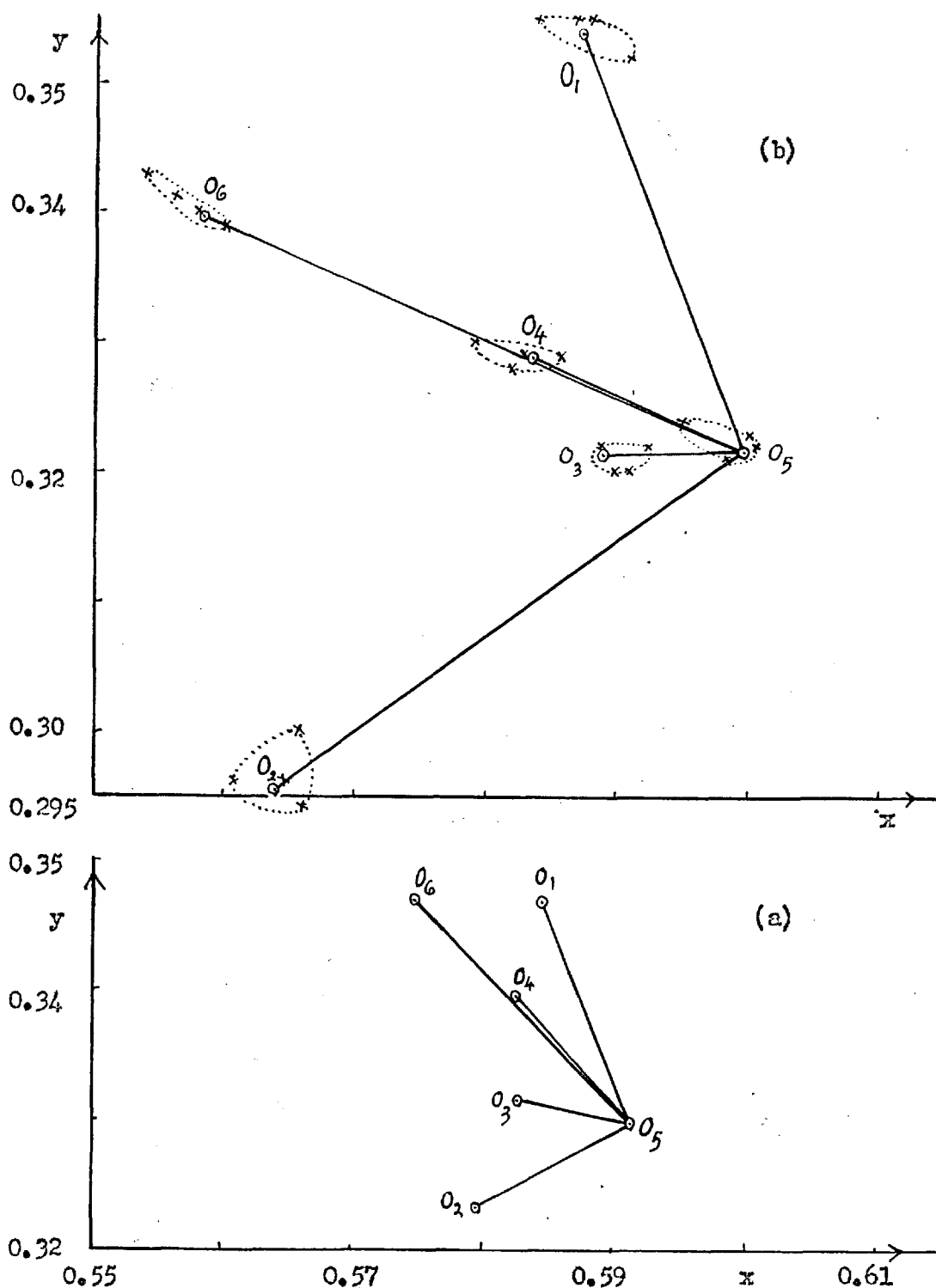


Figure (98) The effect of the inclination of the test patch, for the Orange test colour. (a) for vertical and (b) for  $20^\circ$  inclination. (b) also shows the spread of the results due to the 4 settings for each point.

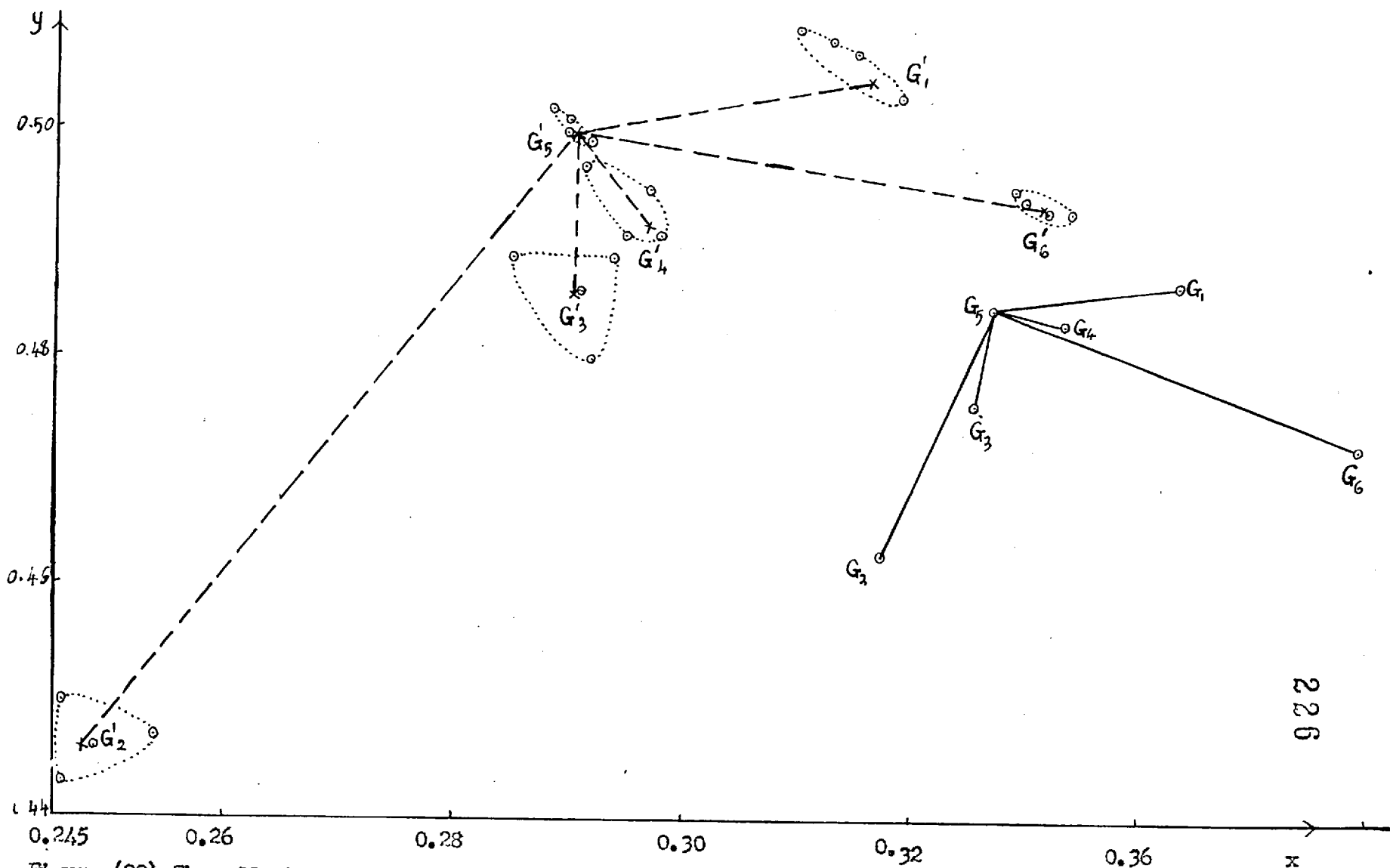


Figure (99) The effect of the inclination of the test patch, for the Green Test Colour, (o—o) for vertical and (x—x) for 20° inclination and shows also the spread of the results due to the 4 settings for each point.

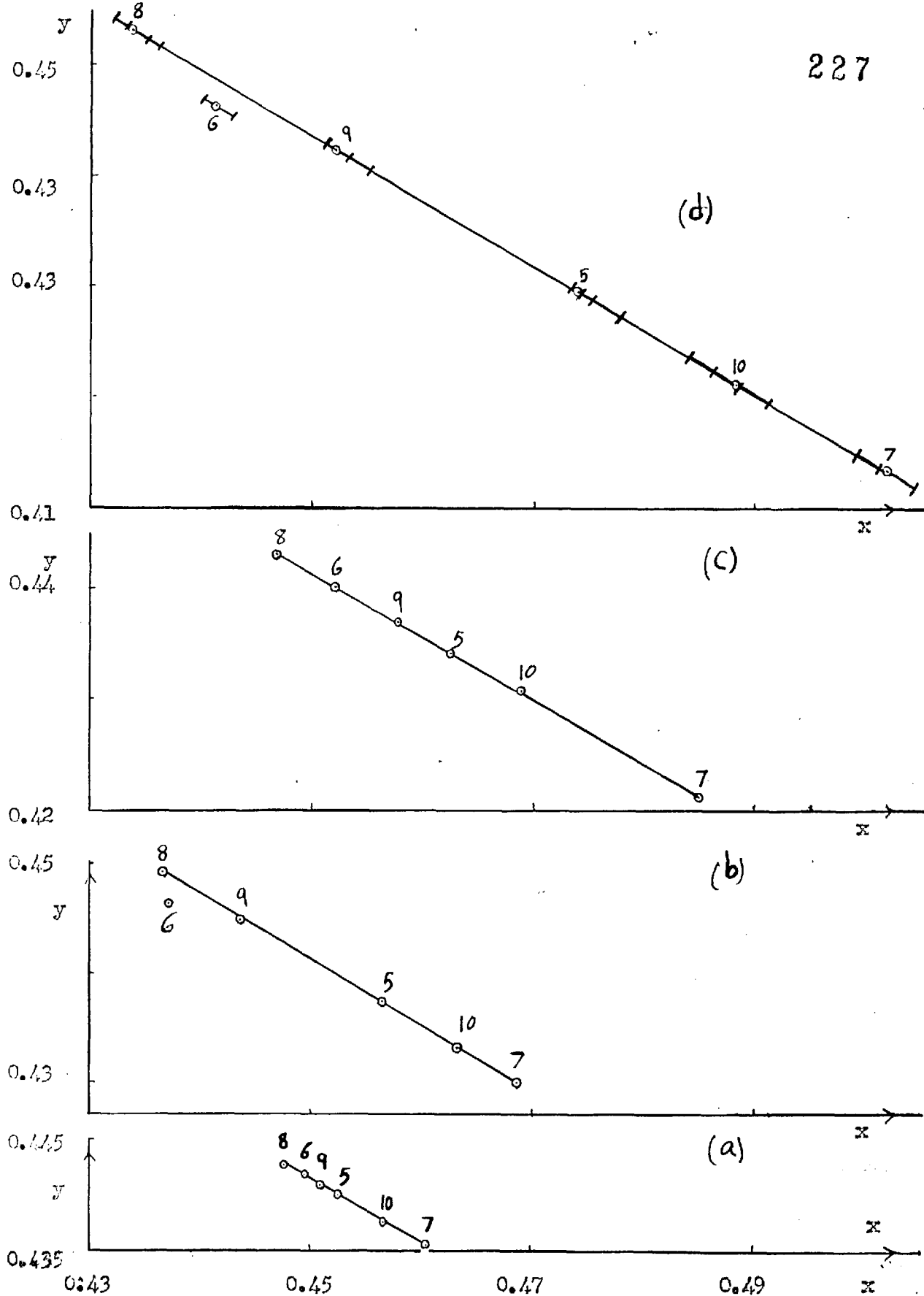


Figure (100) The effect of the inclination, for the Yellow Test Colour. (a) for vertical, (b) for 5° inclination (simple pattern), (c) vertical, (d) 20° inclination (compound pattern). (d) shows also the spread of the results.

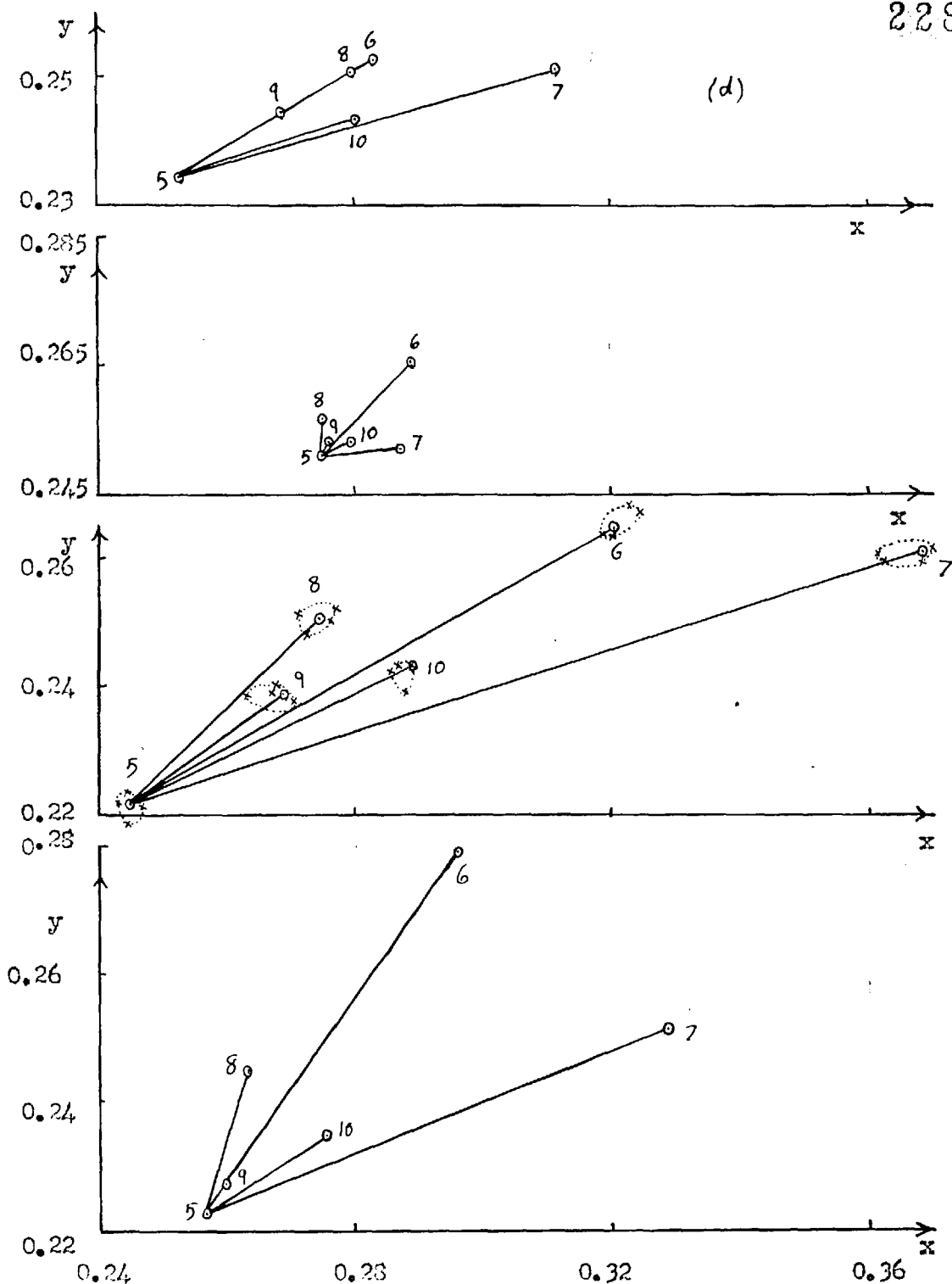


Figure  
(101)

The effect of the inclination of the test patch, (a) for vertical, (b) for  $20^\circ$  inclination, for the compound pattern, (c) for vertical and (d) for  $5^\circ$  inclination for the simple pattern, for the Blue Test Colour.

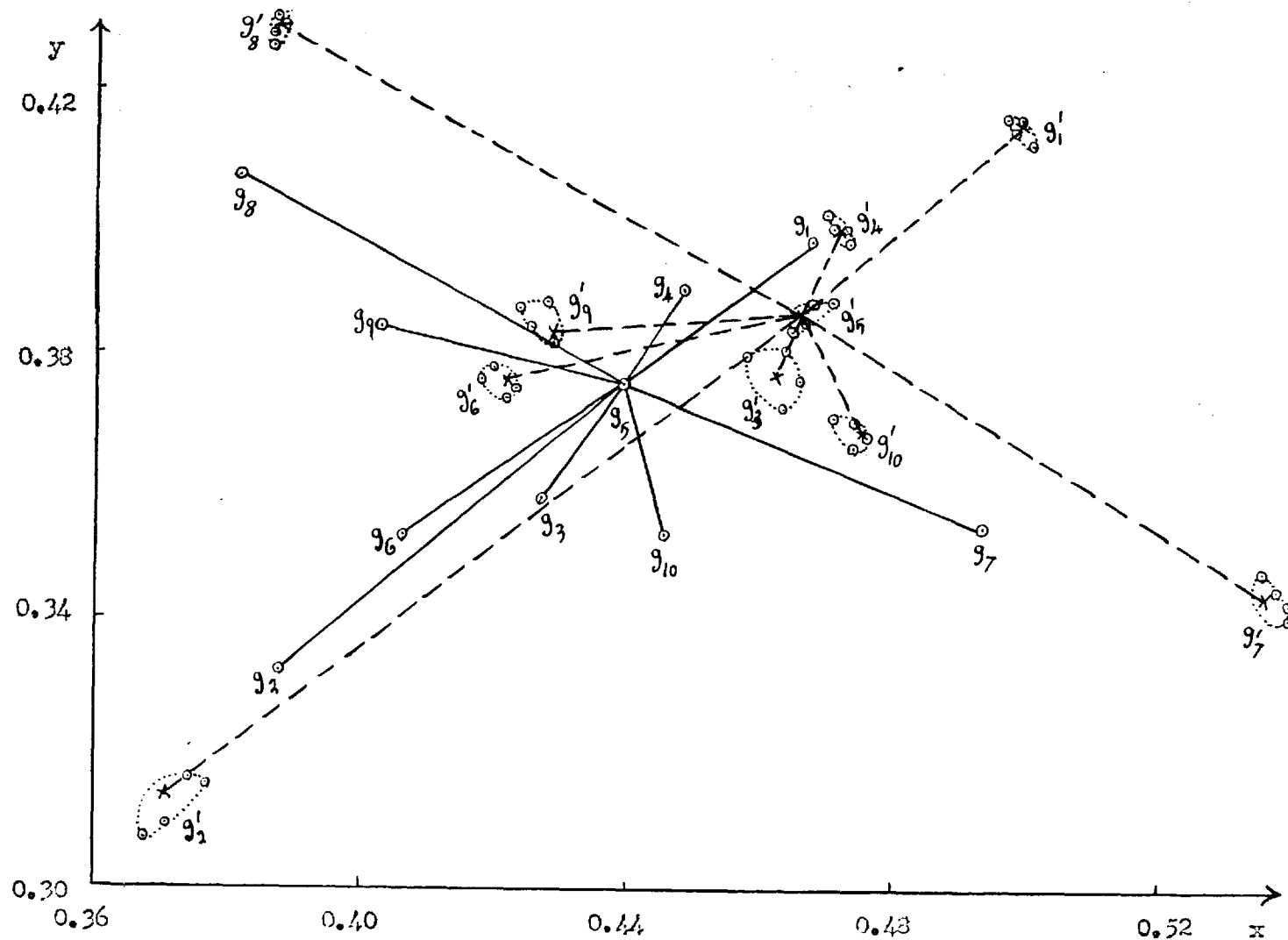


Figure (102) The effect of the inclination of the test patch, (—) for vertical and (---) for 20° inclination ( and it shows also the spread of the results for the 4 settings for each point), for the Grey Compound Pattern of the test patch.

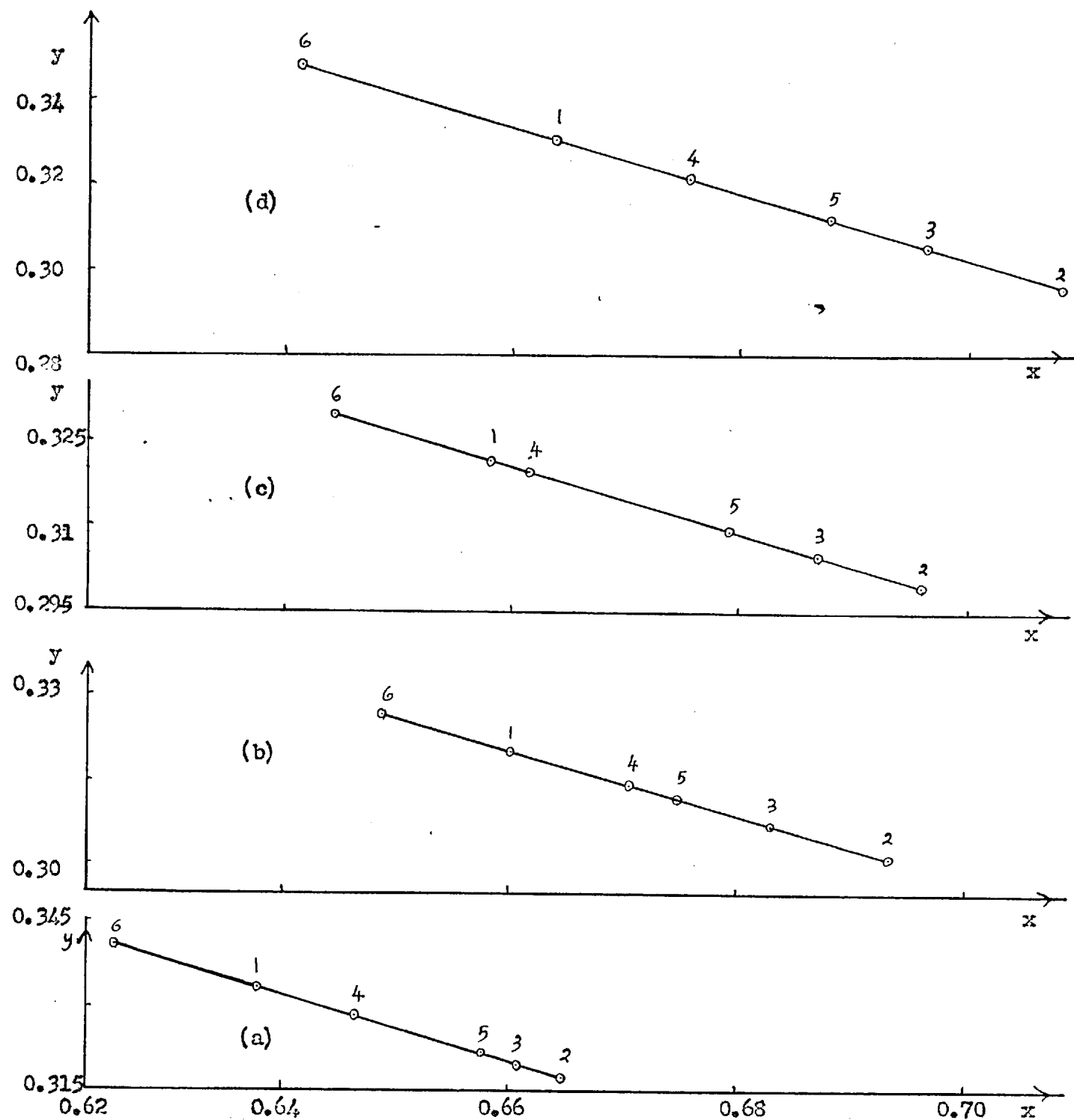


Figure (103) The effect of the inclination of the test patch, (a) for vertical, (b) 40°, (c) 20°, (d) 5° inclination, for the orange test colour.

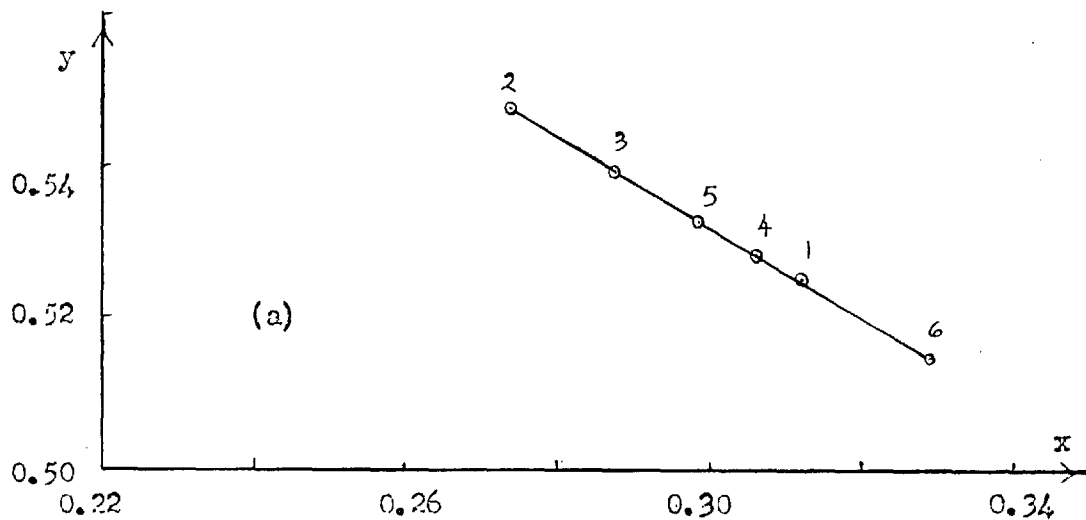
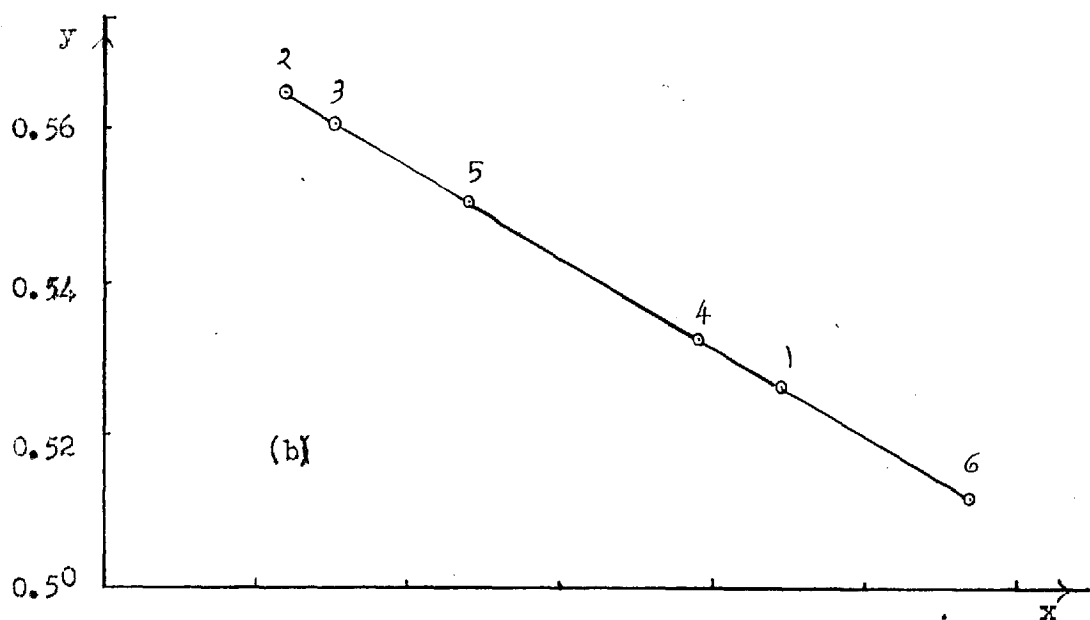


Figure (104) The effect of the inclination of the test patch, (a) for vertical and (b) for 5° inclination, for the Green Test Colour.



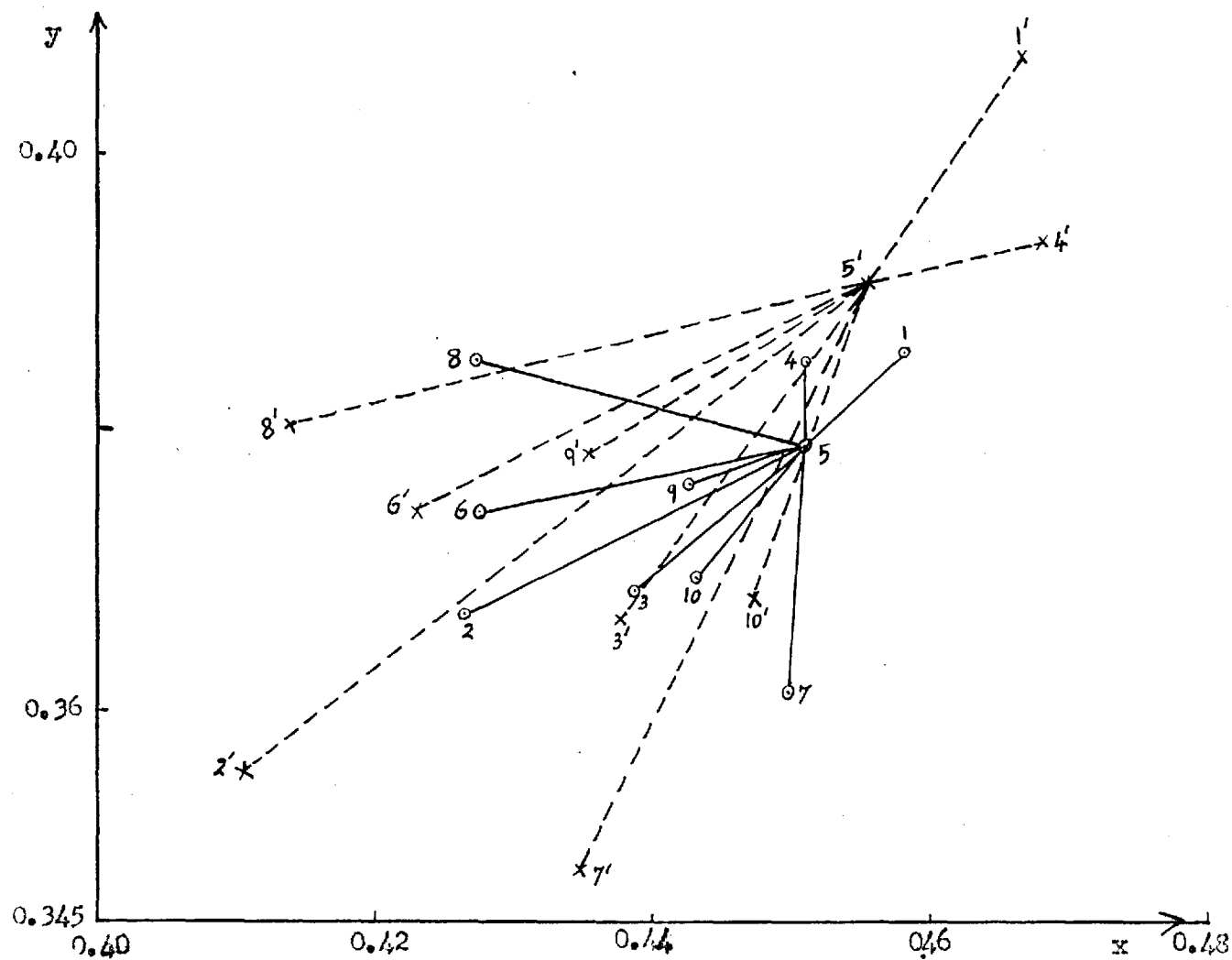


Figure (105) The effect of the Inclination, (—) for vertical, and (---) for 5° inclination, for the Grey Test Colour.

Figures (98-102) inclusive, show these effects for the orange, green, yellow, blue and grey test colours respectively on a larger scale.

Figures (103,104,100,101,105) show these effects for the same test colours in the simple pattern.

The following two general empirical rules can be deduced from the tables and figures just mentioned before for all the test colours.

As the Inclination is Reduced:

Rule (18): The separation between the points corresponding to different colour surround increases. This means that the smaller the inclination of the test patch, the bigger the difference in the colour appearance of the test colours, due to different surrounds.

Rule (19) The points in the chromaticity chart are shifted in the same order showing the following two obvious trends:

(a) Change in hue (or dominant wavelength) away from the yellow and towards  $0.59 \mu$  in the case of the yellow test colour.

(b) Change in saturation:

(1) For the compound surround towards more saturation for the orange, green and grey and towards desaturation for the blue (except the case of white surround).

(2) For the cases of orange, green, yellow in the simple pattern (and the case of yellow in the compound pattern also) there is no change in saturation shown. This is because all their points lie on the straight line (R) (G) since no blue component was needed in these matches.

THE LIGHTNESS OF THE TEST COLOUR.

-- The results did not show any obvious trend in the change of the lightness of the test colour with the change of viewing angle. This

may be partly due to the greater difficulty in measuring the lightness than the chromaticity because of the separation of the test and comparison patches, and partly because the cases of the vertical and the inclined test patch (which ought to show the biggest effect), were different in luminance, so the test colours can not be compared directly in apparent brightness.

The luminance of the test patch (for white paper) was 158.3 and 57.9 ft. lambert in the cases of the inclined and vertical test patches respectively. This big difference was overlooked until the end of the work, when it was too late to correct for this by using a suitable neutral density filter in the path of the illuminating beam for the former system. This difference was due to the accumulating effect of the following three factors:

(1) Normal incidence in the former case and  $45^\circ$  incidence in the latter.

(2) The distance between the illuminating source and the test patch in the former case is greater than in the latter. This is due to the mechanism of the rotating system of the former case.

(3) The illuminating sources in the two cases being of different types (as mentioned in Chapter III), The working voltage to give standard source  $S_A$  was higher for the former than the latter case.

This may lead to the result that the cases of vertical and inclined test patch (on which the last analysis was based for some of the test colours) can not be compared with each other. But according to the conclusions of the analysis on the effects of the luminance of the test patch (pages 104-5), the effects of the two rules (18) and (19), just

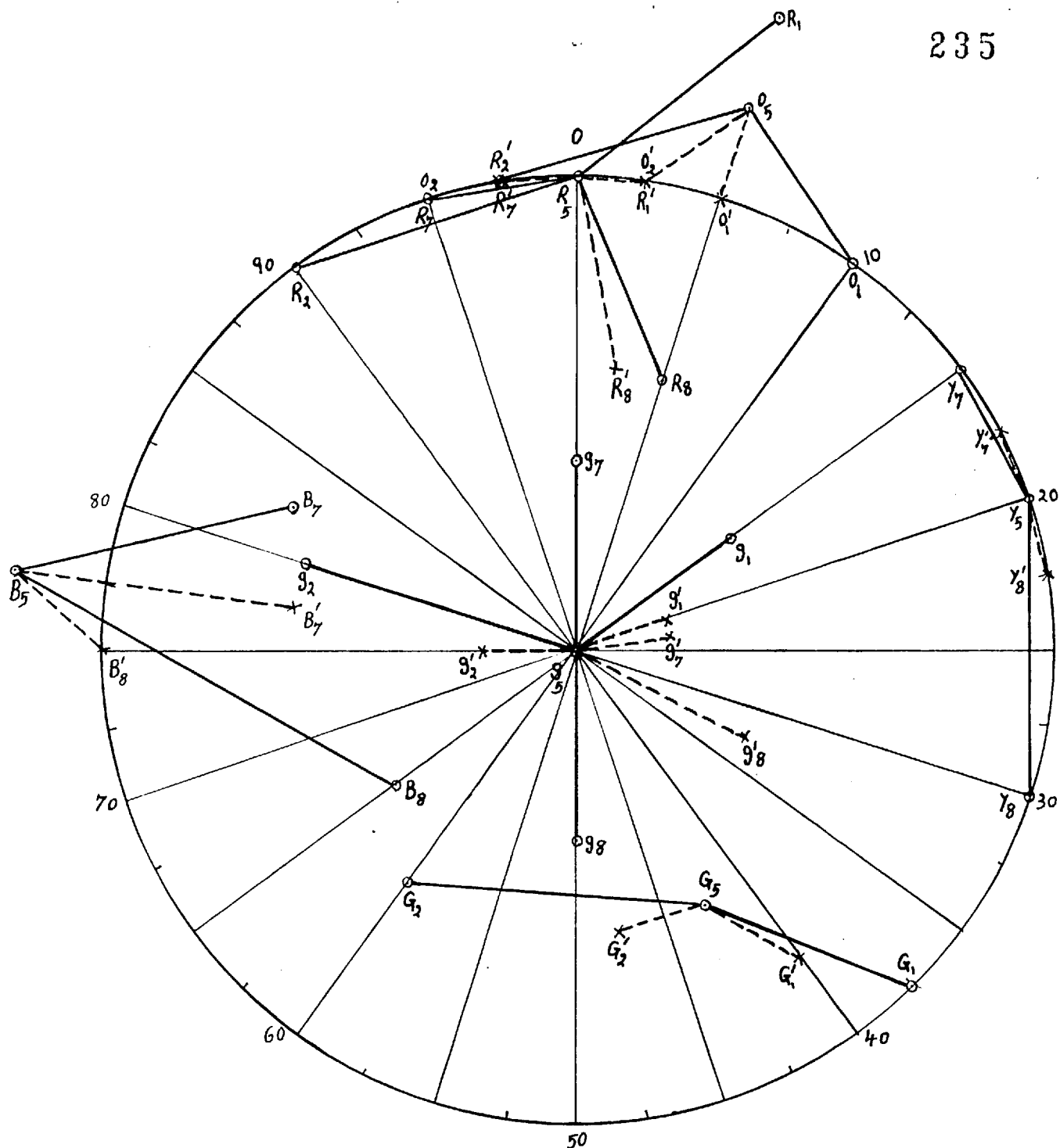


Figure (106) The effect of the orientation of the stripes of the charts as obtained by using the samples of the Munsell book of colour for comparison, and shown in the hue chart. (—) for horizontal stripes and (---) for vertical stripes.

mentioned before ought to be enhanced, if the two luminances were equal:

If the luminance of the test patch in the inclined case was reduced the following results will occur.

(1) The differences in the colour appearance due to different surrounds would have been bigger than they are.

(2) The shifts of the points in the same order showing the change in hue (away from the yellow), and the increase of saturation ought to be bigger than they are.

(3) The brightness of the test colour ought to be decreased. It is not likely that the decrease in brightness is proportional to the decrease in the luminance, but it is most probable that the brightness in this case will be lower than that in the vertical case.

#### (F) THE ORIENTATION OF THE STRIPES:

It was noticed that when the stripes of the charts are horizontal, the differences in the appearance of the test colours in the two patterns are greater than those when the stripes are vertical. This shows that the colour contrast phenomena depend on the orientation of the stripes. The comparison between these two cases was done by the two methods used in this investigation.

Tables (22) and (23) show the comparative results obtained by using the Munsell Book of Color, in the Munsell and C.I.E. systems.

Rows XIX and XX in Tables (8-12) inclusive, show the comparative results obtained by using the colorimeter.

Figure (106) shows in a hue chart the effect of the orientation of the stripes in the horizontal and vertical cases as measured by using the Munsell Book of Color. Obviously the points corresponding to the white



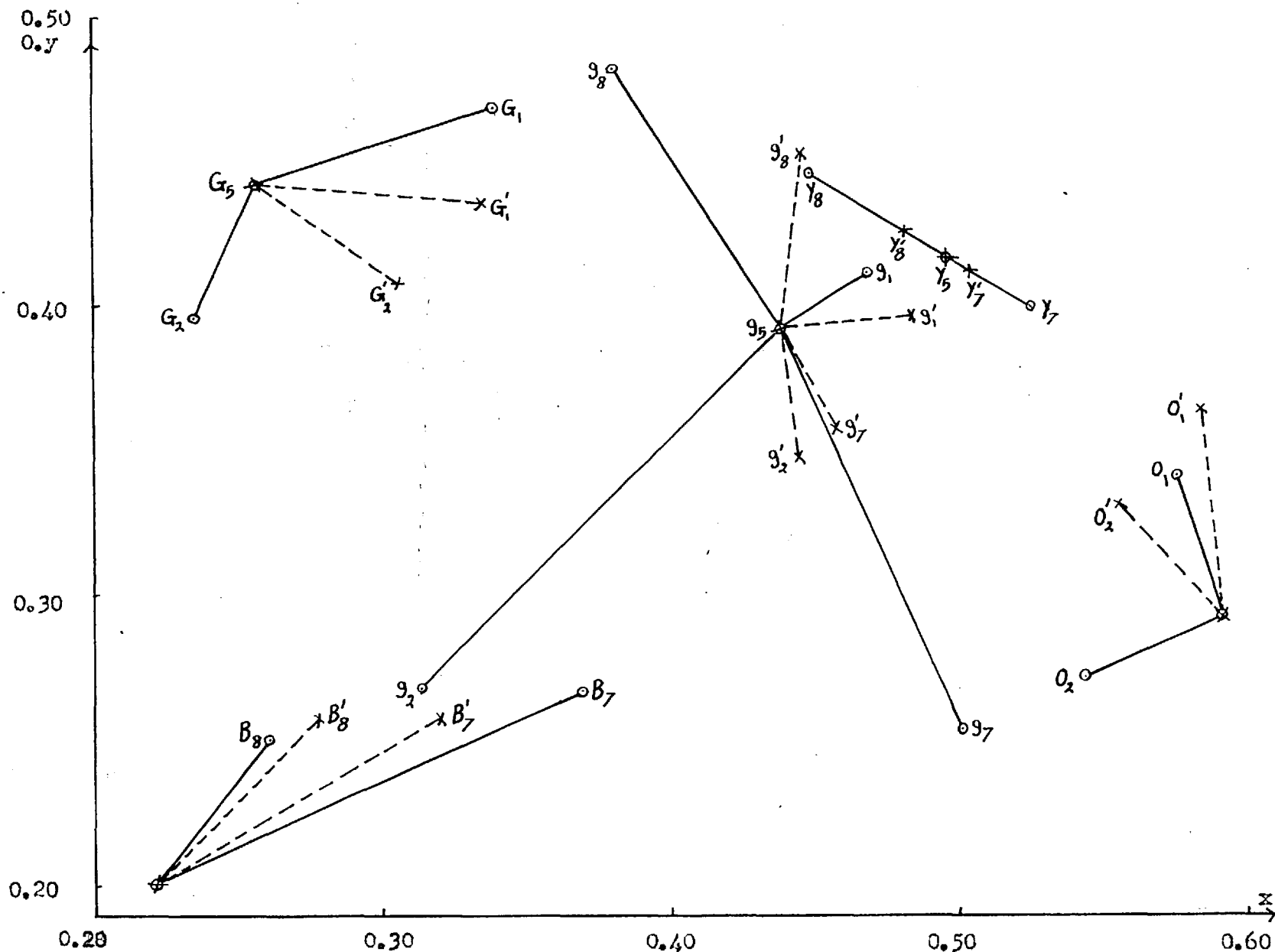


Figure (108) The effect of the orientation of the stripes in the charts obtained by the colorimeter.  
 (—) for horizontal stripes, and (---) for vertical stripes.

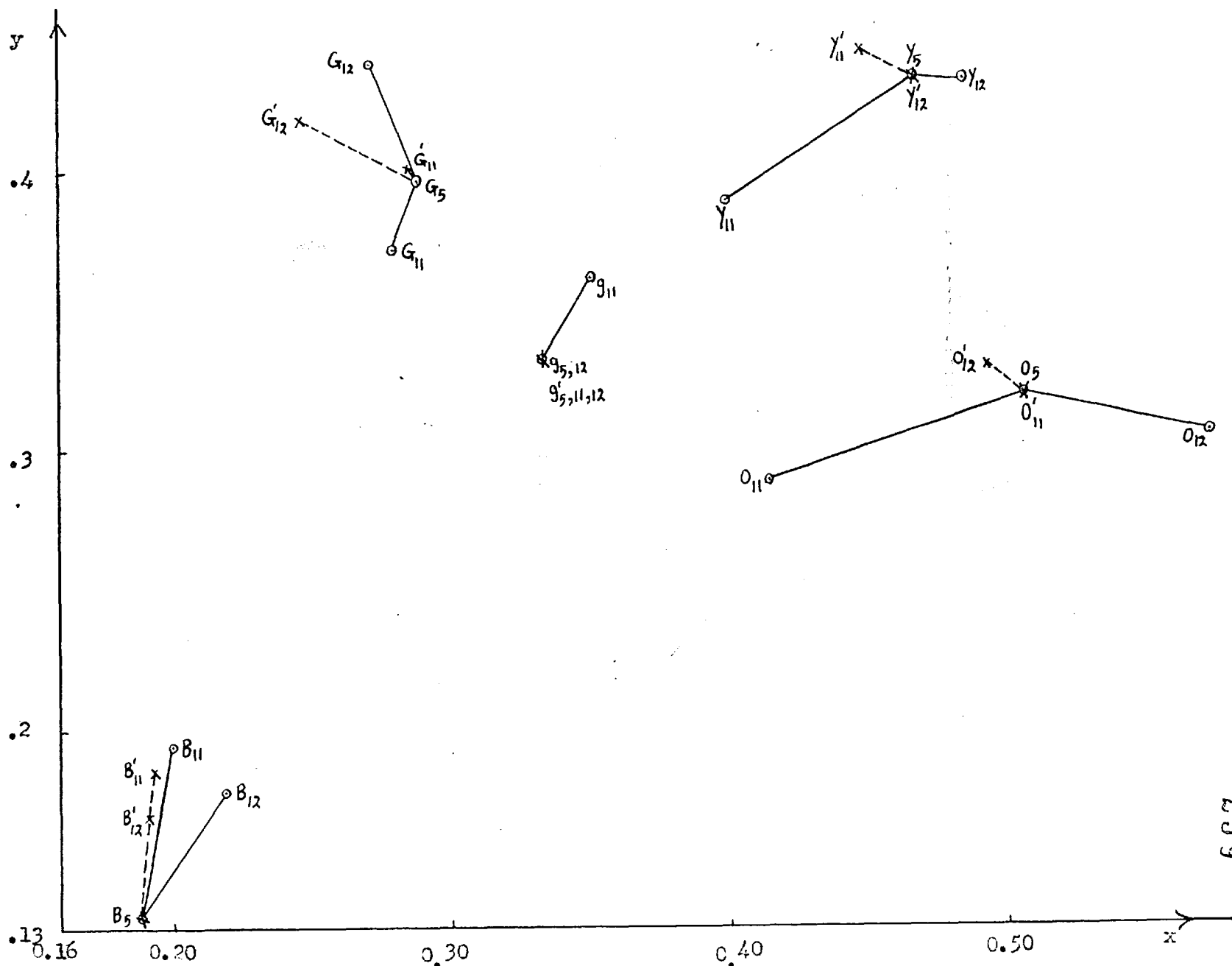


Figure (109) The effect of the orientation of the stripes (Black and White), (—)horizontal & (---)vertical.



surround are the same in the two cases.

Figure (107) shows the same results, in the chromaticity chart, after being transformed to the C.I.E. system.

Figure (108) shows in the chromaticity chart the effect as measured by using the colorimeter. Figures (87-91 b & c) inclusive, shows the same effect in larger scale.

The following two general empirical rules can be deduced from the tables and figures just mentioned before for all the test colours:

Rule (20) The separation between the points in the chromaticity chart corresponding to the two patterns in the case of the vertical stripes is smaller than that for the horizontal stripes.

Rule (21) In general the lightness of the test colours for vertical stripes is higher than that for horizontal stripes (with three exceptions).

Although cases of other orientations of the stripes in between the vertical and horizontal directions were not studied quantitatively, yet the following qualitative experiment was carried on by a number of observers.

A chart with patterns of small size was viewed at a grazing angle such that the maximum difference in the appearance of the test colour in the two patterns can be seen clearly. It was then rotated in its plane (about an axis normal to it) keeping nearly the same inclination. It was found by all the observers, for the yellow and blue stripes that when the viewing direction was perpendicular to the orientation of the stripes, the patterns on surround (1) figure (4) looked much yellower and those on surround (2) much bluer than the corresponding colours on white surround. When the viewing direction was along the stripes, patterns on surround (1) were slightly bluer than those on surround (2). When the

chart was rotated gradually in between these two directions, it was found by all observers, that there is a critical orientation in which the two patterns appeared to be nearly of the same colour, with a sudden comparative change from yellower to bluer or vice-versa, when it is rotated around this orientation. The viewing direction in this critical orientation is nearer to the direction of the stripes than to the normal to them, but it varies slightly from one observer to the other. This is clear since the difference in the colour appearance between the two patterns when the viewing direction is perpendicular to the stripes is greater than, and in opposite direction to, that when they are parallel, hence the bigger rotation from the former orientation towards the latter to get the case of equilibrium of the effects of the two cases. Also, the apparent colour of the squares of the two patterns in that critical orientation seems to be different (more desaturated) from the original apparent colour on the white surround.

This experiment confirms Rule (3), namely; the subtractive effect of the colour of the stripes on which the test colour is mounted and the additive effect of the colour of the side stripes. In this case, this rule can be expressed slightly different: namely: The subtractive effect of the colour of the stripe in the direction perpendicular to the viewing direction and the additive effect of the colour of the stripe in the direction parallel to that of viewing (since the chart is viewed at a grazing angle). Hence the pattern in surround (1) looks yellower than that in surround (2) for viewing at a perpendicular direction to the stripes, and bluer for viewing along the stripes.

This experiment shows also that the colour appearance depends on

the orientation of the resultant eye movements of the observer which varies from one person to the other, and hence the various critical orientations. The additive effect of the colours along the direction of vision may show that the vertical component of the eye movements is more than the horizontal one (This was confirmed by a private communication from Professor R. Ditchburn.) The subtractive effect of the colours perpendicular to the direction of vision may be mainly due to direct contrast effect.

The bigger differences when the viewing direction is normal to the stripes than when they are parallel may be explained as follows: In the former case, the squares of the test colour are considered by the eye as a part of the stripes on which they are mounted (perpendicular to viewing direction), and hence the subtractive contrast effect. This is added to the additive effect of the side stripes due to the eye movements. The addition of these two effects takes place since the two colours of the stripes are in opposite directions with respect to that of the test colour in the chromaticity chart. While in the latter case, the first factor is missing since the stripes are along the viewing direction, and hence the eye movements alone produce the additive effect of the colours of these stripes. The effect of the other intermediate stripes is highly reduced since, psychologically, the observer may not be aware of them other than as separating stripes to the squares of the test colours on which he is concentrating and the stripes on which they are mounted. However, this explanation is an over-simplification to what happens since eye movements may be accompanied also with successive contrast effect (usually subtractive).

(G) THE DYNAMIC COLOUR CONTRAST EFFECTS.

The chart was placed on a mechanical vibrator to vibrate it up and down on a vertical plane to study the effect of the vibration on the appearance of the test colour. It was found that:

(1) For horizontal stripes: the effect is enhanced by vibration. The difference between the appearance of the two patterns increases as the frequency of the vibration is increased. This is clear since in the stationary case, the resultant effect of the two colour surround is a shift towards the colour of the separating stripes (as previously mentioned). The effect of the vibration of the chart is to stimulate a certain area of the retina alternately by the test colour and the colour of the separating stripes and hence more mixture takes place, which enhances the effect. This may be an over-simplification to the effect of the movement since successive contrast and local adaptation (generally subtractive) may play their role on the effect. However the additive effect may be bigger than the subtractive one.

(2) For vertical stripes: In the chart of yellow and blue stripes, and in the stationary case, the patterns of surround (1) look yellower and those of surround (2) look bluer than the corresponding colours on the white surround in the cases of the horizontal and vertical stripes. But the difference in the appearance of the two patterns in the former case is larger than in the latter. Now when the chart is set into vibration, there is hardly any change in the appearance of the two patterns in the stationary case when seen at a long viewing distance. But when the viewing distance is decreased, a critical viewing distance is reached when the two patterns look nearly the same. For a smaller distance, the pattern on surround (1) looks bluer than that on surround

(2). This last observation in itself, can be easily explained in the same way as in the case of the horizontal stripes: The blue and the yellow are mixed with the test colour in the two patterns of surrounds (1) & (2) respectively. It seems that this mixing effect increases with the decrease of the viewing distance i.e. it is almost nil at a long distance and just compensates the stationary colour contrast effect at the critical viewing distance, and overcomes it and gives a reverse colour contrast effect for a shorter distance. This may be due to the fact that for longer distance and hence smaller angular amplitude of the vibration, the eye can easily follow the vibrating pattern (without the observer being aware) and hence the mixing effect of the colour of the vertical stripes on which the squares of the test colour are mounted, on the appearance of the test colour is very small. For shorter distance and hence larger angular amplitude of the vibration, the eye can not follow the vibrating pattern and hence the higher mixing effect.

As for the case of the horizontal stripes, the mixing effect enhances the difference in colour appearance of the two patterns (does not oppose it as in this case), and hence it shows itself in an increase in the difference as the viewing distance is decreased.

## CHAPTER VIII

### SOME POSSIBLE CAUSES FOR THE COLOUR CONTRAST PHENOMENA.

#### (A) INTRODUCTION:

It seems that successive colour contrast phenomena have been known for a long time and many attempts have been made to explain their origin.

Helmholtz theory<sup>(5)</sup> was that colour contrast is purely psychological and is due to an uncertainty of judgement or "mental illusion". The same as a medium sized man appears tall when standing with short men, and short when standing with tall men. Differences are enhanced and exaggerated by perceptual processes. Hering<sup>(42)</sup> suggested a strictly physiological explanation in terms of his opponent-colours theory. He said that colour contrast is due to interaction between different parts of the retina; the external stimulus evokes a certain chemical reaction in one region and induces the opposite reaction in adjacent regions. This means that the coloured surround induces the complementary colour on the coloured patch under test.

Van Bezold<sup>(27)</sup> discovered what he called "the spreading effect" which acts in an opposite sense to simultaneous colour contrast (Chapter I). In case of very thin elements in juxtaposition, the effect is additive and not subtractive.

Libney,<sup>(25)</sup> in his study of simultaneous colour contrast, proved that the contrast effect of a coloured surround in a white stripe is not complementary to this colour. The following are the ideas of some modern writers:

Evans<sup>(15)</sup> suggests that the colour adaptation of the eye is responsible for both successive and simultaneous colour contrast phenomena.

Viewing a bright spot of colour depresses, not only the sensitivities of the receptors of the retina on which it is imaged (causing successive colour contrast), but also those in the immediate neighbourhood (causing simultaneous colour contrast). He calls the former effect "Local Adaptation", and the latter "Lateral Adaptation". That is why, from his point of view, the colours of the after images appear complementary to the original stimuli causing them and the test patches look tinged with the complementary colour of the surround. Nevertheless, this explanation does not allow for the positive after images and the spreading effect.

According to the Committee on Colorimetry of the Optical Society of America,<sup>(1)</sup> simultaneous colour contrast produces an enhancement or intensification of perceived difference between neighbouring colours in luminance, purity and hue. This enhancement may be due to successive contrast caused by the movements of the eye in scanning from one colour to the other during perception. It may be due to neural interaction either in the retina or neural pathways and is likely to be rapid in operation and recovery.

Wright,<sup>(90)</sup> showing a chart similar to plate (1a) says "No completely satisfactory explanation of these colour changes is yet available. Simultaneous contrast resulting from neural interactions between neighbouring retinal and cortical areas is likely to be one major influence at work. Something in the nature of colour 'spreading' must also be involved to which eye movements, light scatter in the eye, and physiological spreading in the neural processes may contribute. Perhaps the psychological interpretation of the pattern has also to be considered".

Le Grand<sup>(16)</sup> says that the various regions of the retina are inter-

dependent. Such interaction constitutes simultaneous contrast and can assume two opposite forms:

(1) Summation Effect: where the flux falling on a region is partially added to that in the neighbouring regions (i.e. integration of flux distribution). This occurs more with sources which do not differ very greatly, especially if their intensities are low.

(2) Inhibition Effect: i.e. the excitation of one area of the retina counteracts that of others. This occurs when very unequal sources are present at the same time in the visual field.

Warburton and Lund<sup>(28)</sup> concluded from their qualitative study of simultaneous colour contrast that the effect of the surround on the appearance of the test colour is additive. Dr. Edridge Green in a private communication to the authors, suggested that this additive effect is due to: (1) The chromatic aberration of the eye causing an overlapping of the test and surrounding colours. (2) The flooding effect due to the film of the retina being liquid and eye movements cause the colours to spread. (3) The irradiation affecting the edge of contact of the two colours producing their mixture.

Jameson and Hurvich,<sup>(29)</sup> concluded from their quantitative study of colour contrast that the perceived colour changes can be interpreted in terms of assumed physiological mechanisms of opponent neural interactions. The changes are due to systematic chromatic induction effects, opponent in nature and proportional in magnitude to the strength of the related chromatic response aroused by the inducing stimulus.

#### (B) THE PRESENT INVESTIGATION:

This survey shows the complexity of the simultaneous colour contrast



phenomena and the variety of the hypothesis put forward to explain them. However some of these hypotheses deal only with the subtractive effect of the surround colour and the others deal with the additive effect. Yet all the experimental results of this investigation lead to a common conclusion, that both the subtractive and additive effects of the surround play a role in the appearance of the test colour.

Some of the hypotheses mentioned before, were suggested independently by the author. All the factors which may be causing the colour contrast phenomena can be divided into three main categories: physical, physiological and psychological, which can be subdivided as follows:

(A) Physical Causes:

- (1) The scattering of light within the eye.
- (2) The chromatic and spherical aberration of the refracting system of the eye.

(B) Physiological Causes:

- (1) The interaction between adjacent retinal areas.
- (2) The continual movements of the eye.

(C) Psychological Causes:

- (1) The psychological interpretation of the pattern as a whole.
- (2) The enhancement of the effects which may take place in the perceptual processes in the brain.

These factors suggest either additive or subtractive mixing processes of the test and surrounding colours. They are possibly acting together at the same time, and their complex interaction produces the striking effects of colour contrast studied in this investigation.

(1) Physical Defects of the Eye.

In spite of the many functions that the human eye performs successfully, which place it in a unique position unapproached by the finest optical instrument, the optical correction of its refracting system cannot be rated as high. Being a living organ it is subject to anatomical imperfections and inhomogeneity producing irregularities in the retinal image. Emsley<sup>(91)</sup> summarises the defects of the eye as:

(1) Chromatic and spherical aberrations, (2) lack of centering (3) irregularities in the surface curvatures of the cornea and crystalline lens, (4) diffuse scattering of light by its media which consist of cellular tissue, and are hence not perfectly transparent and homogenous. As a result of these defects the retinal image of each point of the object is spread over a larger area within which the distribution of light is irregular. These aberrations depending upon anatomical structure vary considerably in form and extent among individuals.

The diffuse scattering of light within the eye (the crystalline lens, the humours and the retina), in spite of being an important factor in producing colour contrast, yet it seems that it has not been yet satisfactorily studied. Chromatic and spherical aberrations of the eye will now be discussed in detail.

(1) Chromatic Aberration of the Eye,

The eye suffers from complete absence of any correction of the chromatic aberration.<sup>(18)</sup> In normal vision we are quite unaware of its effects perhaps because they may be ignored during the visual perception, either in the retina or in the brain. Light of shorter wavelengths is brought to a focus nearer to the eye lens than that of longer wavelengths.

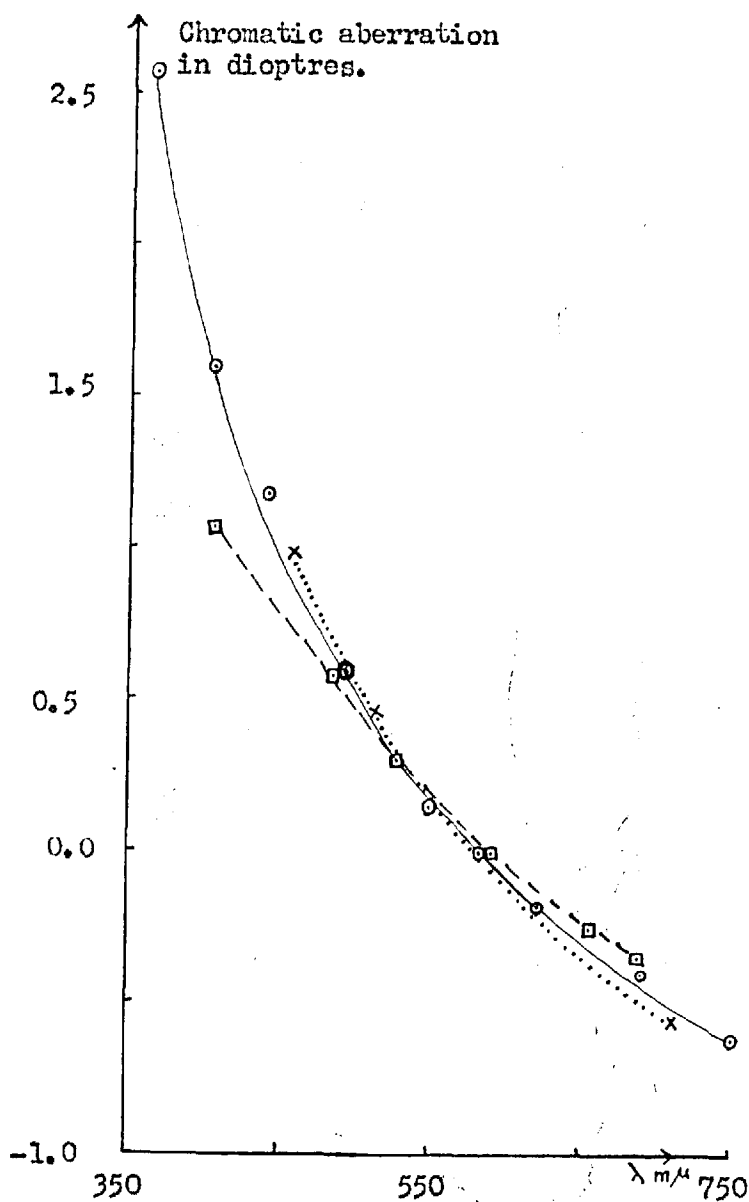


Figure (110) The Chromatic Aberration of the eye  
 (.....) Ivanoff (11 eyes)  
 (—) Wald and Griffen (14 observers)  
 (---) The calculated values (Ivanoff).

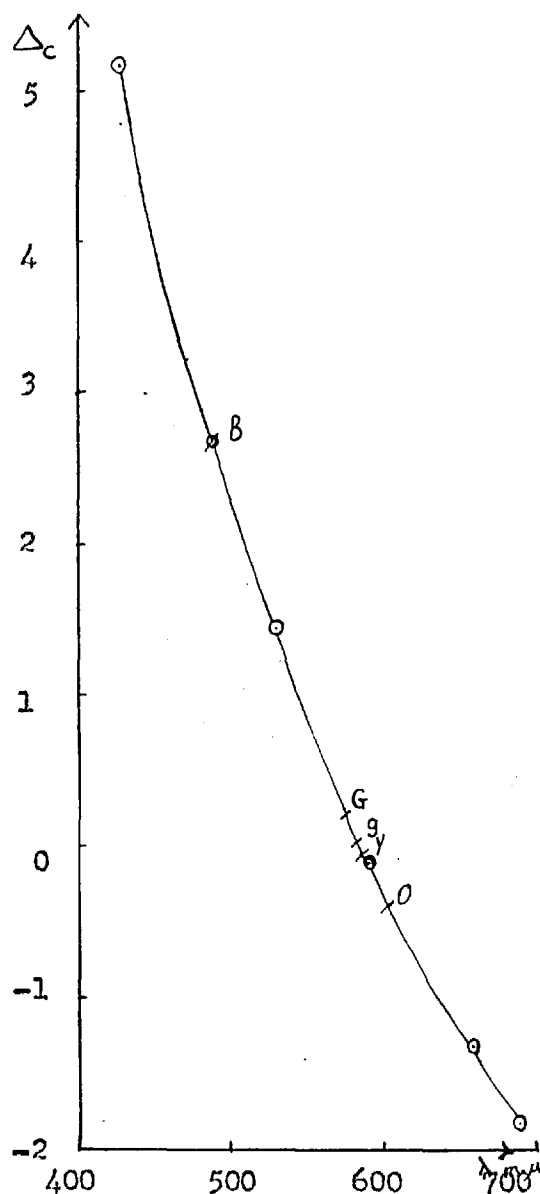


Figure (115) The calculated relation between the percentage overlapping of the surround on the test colour, and their dominant wavelength.

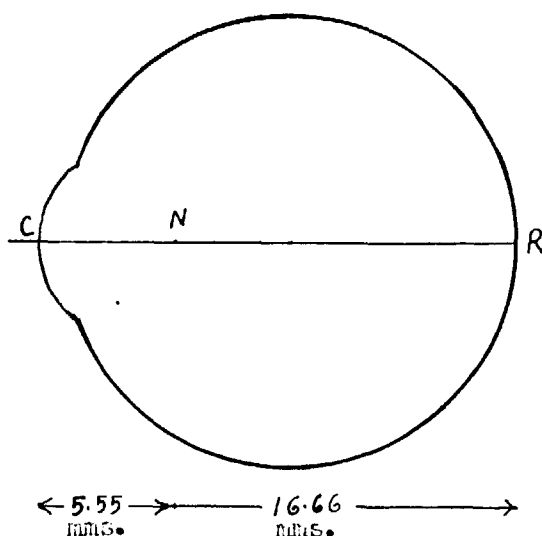


Figure (111) The reduced eye (Emsley)

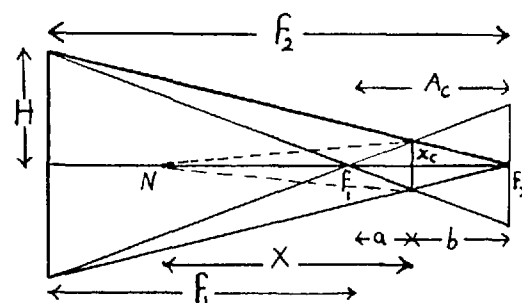


Figure (112) The effect of the chromatic aberration of the eye (not to scale).

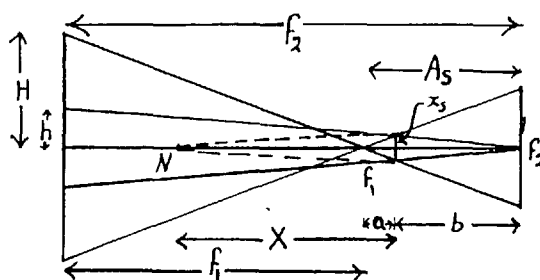


Figure (113) The effect of the spherical aberration of the eye (not to scale).

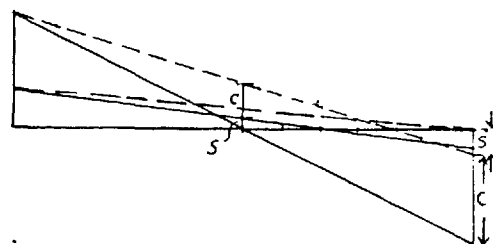


Figure (114) The combined effect of the chromatic and spherical aberrations.

Looking at the test patch, as used in this investigation the images of the test and surround colours will partially overlap on the retina.

The chromatic aberration of the eye was investigated by Newton,<sup>(2)</sup> Young<sup>(4)</sup> and Helmholtz<sup>(5)</sup>. Recently it was measured by Ivanoff<sup>(92)</sup> (using 11 eyes), and Wald and Griffen<sup>(93)</sup> (using 14 eyes). According to Ivanoff, <sup>(92)</sup> the average of his results is in a very good agreement with the average of the others, and does not vary much from the calculated values, as shown in figure (110). From this graph, the dioptric power of the refracting system of the eye varies from - 0.62 dioptre (at  $\lambda = 750 \text{ m. }\mu$ ) to + 2.63 dioptries (at  $\lambda = 365 \text{ m. }\mu$ .) These values are referred to the case of  $\lambda = 578 \text{ m. }\mu$ , where the chromatic aberration is considered zero and the power of the refracting system of the eye = 60 dioptries.

The following is a simple quantitative study of the effect of the chromatic aberration on the simultaneous colour contrast phenomena, (figure 112) based on the reduced eye (Emsley) (Figure 111).

Assume that  $f_1$  and  $f_2$  are the focal lengths of the eye system for the dominant wavelengths  $\lambda_1$  and  $\lambda_2$  of the test and surrounding colours respectively.

$F_1$  and  $F_2$  are the corresponding dioptric powers of the refracting system of the eye,  $n_1$  and  $n_2$  are the corresponding refractive indices of the vitreous humour,  $A_c$  is the axial chromatic aberration,  $x_c$  is the radius of disc of least confusion,  $H$  is the radius of the eye pupil and  $X$  is the distance between the nodal point of the eye system and the retina. Then:

$$A_c = f_2 - f_1 = n_2/F_2 - n_1/F_1 = a + b \quad (1)$$

$$\text{where } x_c/a = H/f_1 \quad (2)$$

$$\text{and } x_c/b = H/f_2 \quad (3)$$

Therefore  $b/a = f_2/f_1$  (4)

$$A_c = a + b = a (f_2 + f_1) / f_1 \quad (5)$$

Substituting from (1) into (5) we get:

$$a = f_1 (f_2 - f_1) / (f_2 + f_1) \quad (6)$$

Substituting from (2) ~~and~~ (6) we get:

$$x_c = H (f_2 - f_1) / (f_2 + f_1) \quad (7)$$

Element angle subtended by  $x_c$  at the nodal point =  $\delta\theta_c$  given by:

$$\begin{aligned} \delta\theta_c &= x_c / X = H (f_2 - f_1) / X (f_2 + f_1) \\ &= H (n_2 F_1 - n_1 F_2) / X (n_2 F_1 + n_1 F_2) \end{aligned} \quad (8)$$

Considering that the disc of least confusion is a measure of the amount of overlapping of the surround on the test colour, then  $\delta\theta_c$  represents the angular overlapping in radians.

$$\text{The relative overlapping} = \delta\theta_c / \theta \quad (9)$$

where  $\theta$  is the angle of subtense of the test colour in radians.

The relative overlapping shows the effectiveness of the chromatic aberration in the simultaneous colour contrast phenomena. Since  $X$  is constant and  $H$  is determined by the viewing condition, the relative overlapping depends on the dominant wavelengths,  $\lambda_1$  and  $\lambda_2$  of the test and surround colours, and on the angle of subtense of the test colour ( $\theta$ ). It increases with the increase of the difference between  $\lambda_1$  and  $\lambda_2$  (i.e. with the increase of the separation between the test and surround colours in the hue chart) and with the decrease of the element angle of subtense.

Now  $\delta\theta_c / \theta$  shows the overlapping per radian of angle of subtense. Therefore the relative overlapping per  $1^\circ$  element angle of subtense can be obtained by substituting  $\theta = 1^\circ = 1/57.3 \text{ radian} = 1/(180/3.14) \text{ radian}$ .

TABLE (25) REFRACTIVE INDEX OF THE VITREOUS HUMOUR ( $n$ ) (IVANOFF), AVERAGE CHROMATIC ADAPTATION ( $F$ ) (WALD, GRIFFEN AND IVANOFF) AND CALCULATED PERCENTAGE OVERLAPPING  $\Delta_c$  FOR  $1^\circ$  ANGLE OF SUBTENSE, (REFERRED TO  $\lambda = 578 \text{ m}\mu$ )

| $\lambda \text{ m}\mu$ | $n$    | $F$     | $\Delta_c$ |
|------------------------|--------|---------|------------|
| 687                    | 1.3314 | - 0.425 | - 1.83     |
| 656.3                  | 1.3321 | - 0.310 | - 1.30     |
| 589.3                  | 1.3340 | - 0.030 | - 0.10     |
| 527.0                  | 1.3364 | +0.330  | + 1.54     |
| 486.1                  | 1.3384 | + 0.625 | + 2.70     |
| 430.8                  | 1.3421 | + 1.200 | + 5.17     |

TABLE (26) PERCENTAGE OVERLAPPING ( $\Delta_c$ ) FOR THE COLOUR SAMPLES USED, REFERRED TO  $\lambda = 578 \text{ m}\mu$  FOR  $1^\circ$  OF SUBTENSE.

| Colour Sample | $\lambda \text{ m}\mu$ | $\Delta_c$ |
|---------------|------------------------|------------|
| Orange (O)    | 601                    | - 0.40     |
| Yellow (Y)    | 588                    | - 0.05     |
| Green (G)     | 576                    | + 0.20     |
| Blue (B)      | 489                    | + 2.68     |
| Grey (G)      | 583                    | + 0.05     |

TABLE (27) THE PERCENTAGE OVERLAPPING DUE TO CHROMATIC ADAPTATION ( $\Delta_c$ ) AND THE TOTAL PERCENTAGE OVERLAPPING ( $\Delta$ ), FOR THE COLOUR COMBINATIONS USED, FOR  $1^\circ$  ANGLE OF SUBTENSE.

| Colour Combination | $\Delta_c$ | $\Delta$ |
|--------------------|------------|----------|
| O <sub>B</sub>     | 3.08       | 4.42     |
| O <sub>Y</sub>     | 0.45       | 1.79     |
| G <sub>B</sub>     | 2.48       | 3.81     |
| G <sub>Y</sub>     | 0.25       | 1.59     |
| B <sub>O</sub>     | 3.08       | 4.42     |
| B <sub>G</sub>     | 2.48       | 3.81     |

| Colour Combination | $\Delta_c$ | $\Delta$ |
|--------------------|------------|----------|
| Y <sub>O</sub>     | 0.45       | 1.79     |
| Y <sub>G</sub>     | 0.25       | 1.59     |
| B <sub>B</sub>     | 2.63       | 3.97     |
| G <sub>Y</sub>     | 0.10       | 1.44     |
| B <sub>O</sub>     | 0.45       | 1.79     |
| B <sub>G</sub>     | 0.15       | 1.49     |

TABLE (28) THE CALCULATED MIXING COEFFICIENTS OF THE ONE COLOUR AND TWO COLOUR SURROUNDS DUE TO THE COMBINED EFFECT OF THE SPHERICAL AND CHROMATIC ABERRATIONS OF THE EYE, FOR  $15'$  ELEMENT ANGLE OF SUBTENSE.

| SURROUND    | 3              | 4              | 1 or 2              |
|-------------|----------------|----------------|---------------------|
| TEST COLOUR | a <sub>3</sub> | a <sub>4</sub> | a <sub>1 or 2</sub> |
| Grey        | 0.792          | 0.430          | 0.395               |
| Orange      | 0.372          | 0.278          | 0.286               |
| Green       | 0.384          | 0.158          | 0.192               |

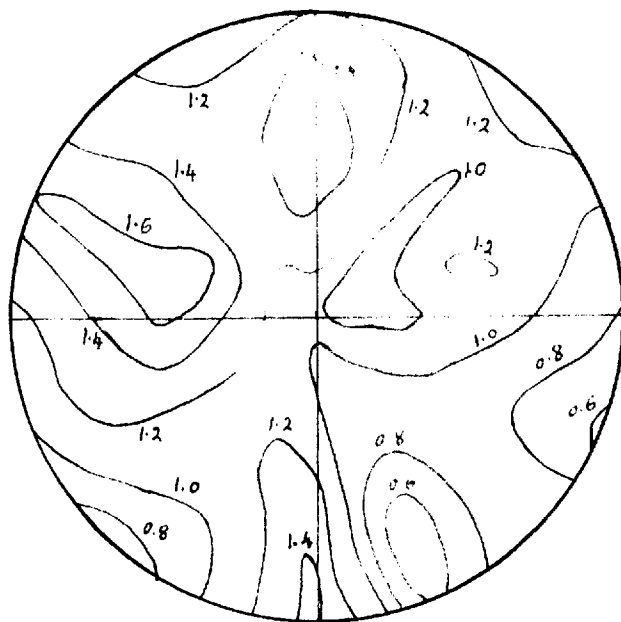
| SURROUND    | 9              | 10              | 7 or 8              |
|-------------|----------------|-----------------|---------------------|
| TEST COLOUR | a <sub>9</sub> | a <sub>10</sub> | a <sub>7 or 8</sub> |
| Grey        | 0.620          | 0.492           | 0.310               |
| Yellow      | 0.192          | 0.144           | 0.096               |
| Blue        | 2.358          | 1.802           | 1.180               |

The percentage overlapping per  $1^\circ$  element angle of subtense ( $\Delta_c$ ) can be calculated. Applying the average chromatic aberration given by Wald and Griffen <sup>(93)</sup> and Ivanoff <sup>(92)</sup> as shown in figure (110), the refractive indices of the vitreous humour given by Ivanoff,  $X = 16.66$  mm according to Emsley, <sup>(91)</sup> and  $H = 2.15$  mm from the average results of Crawford and Reeves <sup>(94)</sup> for one of the levels of adaptation used in this work, (2.9 ft. lambert) the values of the percentage overlapping  $\Delta_c$  can be calculated for different wavelengths. Table (25) shows these values referred to the case of  $\lambda = 578$  m. $\mu$ . where  $\Delta_c = 0$ . Figure (115) shows the calculated relation between the percentage overlapping ( $\Delta_c$ ) of any colour surround on yellow test colour ( $\lambda = 578$  m. $\mu$ ) and the dominant wavelength of the surround. To calculate the percentage overlapping for any test and surrounding colours, the values of  $\Delta_c$  corresponding to their dominant wavelengths have to be subtracted from each other. For example if the test and the surround colours are blue and red (or vice-versa) of dominant wavelengths 430.8 and 6.87 m. $\mu$ , then  $\Delta_c = 5.17 - (-1.83) = 7.0\%$  ( for  $1^\circ$  element angle of subtense)

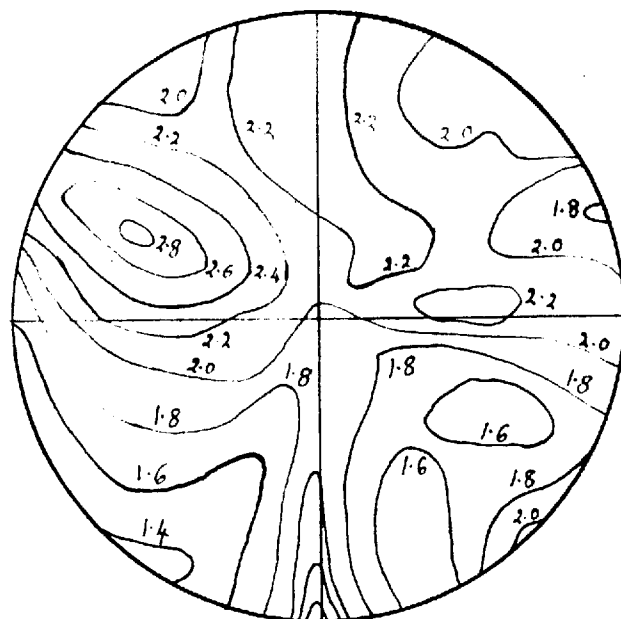
## (2) Spherical Aberration of the Eye.

Young was the earliest to measure the spherical aberration of the eye. Ivanoff, <sup>(92)</sup> using a similar method, showed that the spherical aberration of the eye varies with different states of accommodation. In a very recent paper, with a more elaborate technique, Brink <sup>(95)</sup> showed that: (1) The refracting system of the eye has an optically inhomogeneous structure, (2) the accommodation causes an irregular change of the dioptric power over the area of the eye lens, (3) At the state of accommodation giving maximum visual acuity of the eye, the homogeneity





(a) At 0.0 dioptre accommodation.



(b) At 1.0 Diopetre accommodation.

Figure (116) The isodiptic lines in the refracting system of the eye. (Brink).

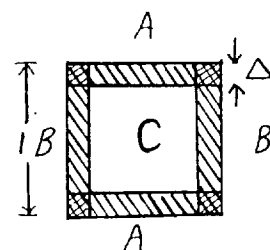


Figure (118) The image of the test colour(C) on the retina with the relative overlapping of the surround. (A&B).

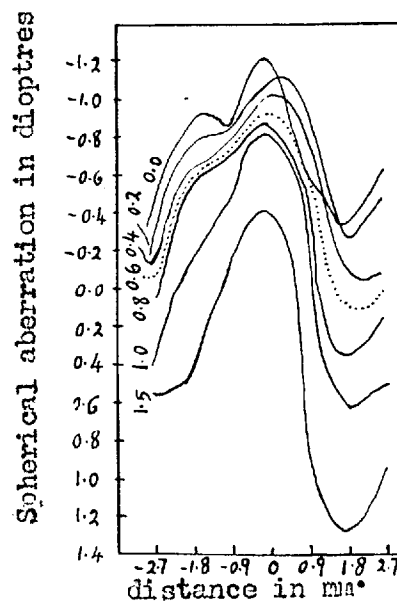


Figure (117) The spherical aberration in dioptres and the distance from the centre at different states of accommodation (Brink).

is better than the surrounding states of accommodation. The paper includes maps of the eye lens with iso-diopetre curves (locus of points of equal power) which show this inhomogeneity and its change with accommodation. Figure (116) shows two of these maps, at states of accommodation 0 and 1 diopetre. Also figure (117) shows the relation between the spherical aberration and the distance from the centre of the eye lens along the horizontal meridian, at different states of accommodation.

Due to the spherical aberration of any uncorrected lens, the marginal rays are focused at a point nearer to the lens than that of the paraxial rays. When a wide beam of light falls on such a lens, the image produced is blurred due to the overlapping of images of central and peripheral parts of the field of view. Now for such inhomogeneous case of the eye system, the overlapping produced is more complex. Even in the central part of the eye lens the dioptric power varies considerably.

The following is a simple quantitative study of the effect of the spherical aberration on the simultaneous contrast phenomena (Figure 113).

Assume that  $f_1$  and  $f_2$  are the focal lengths of the eye system for paraxial and marginal rays,  $F_1$  and  $F_2$  are its corresponding dioptric powers,  $n$  is the average refractive index of the vitreous humour,  $A_s$  is the axial spherical aberration,  $x_g$  is the radius of disc of least confusion,  $H$  is the radius of eye pupil,  $h$  is the height of the eye pupil giving paraxial rays (this is arbitrary since the difference in dioptric power can be referred to it. It is considered in this analysis that  $h = \frac{H}{10}$ ) and  $X$  is the distance between the nodal point of the eye system and the retina, then:

$$A_s = f_2 - f_1 = n/F_2 - n/F_1 = a + b \quad (10)$$

$$\text{where } x_s/a = H/f_1 \quad (11)$$

$$\text{and } x_s/b = h/f_2 \quad (12)$$

$$\text{assume } H = 10h \quad (13)$$

$$\therefore b/a = (H/f_1)/(f_2/h) = 10 f_2/f_1 \quad (14)$$

$$A = a + b = (10 f_2 + f_1) a/f_1 \quad (15)$$

Substituting from (10) into (15) we get:

$$a = f_1 (f_2 - f_1) / (10 f_2 + f_1) \quad (16)$$

Substituting from (11) into (16) we get:

$$x_s = H (f_2 - f_1) / (10 F_2 + F_1) \quad (17)$$

Element angle subtended by  $x_s$  at the nodal point =  $\theta_s$  given by

$$\begin{aligned} \theta_s &= x_s/X = H (f_2 - f_1) / X (10 f_2 + f_1) \\ &= H (F_1 - F_2) / X (10 F_2 + F_1) \end{aligned} \quad (18)$$

As a first approximation, we can take:  $F_1 = F_2 = F = 60$  dioptries.

$$\therefore \theta_s = H (F_1 - F_2) / 11 XF \propto (F_1 - F_2) \quad (19)$$

Since  $X$  is constant and  $H$  is determined by the viewing condition used.

Considering that the disc of least confusion is a measure of the amount of overlapping of the surround on the test colour, then  $\theta_s$  represents the angular overlapping in radians.

$$\text{The relative overlapping} = \theta_s / \theta \quad (20)$$

where  $\theta$  is the angle of subtense of the test colour in radians.

The relative overlapping shows the effectiveness of the spherical aberration in the simultaneous contrast phenomena. It depends on the amount of spherical aberration in diptres and hence on the radius of the eye pupil, and on the angle of subtense of the test colour ( $\theta$ ). It increases with the radius of the eye pupil and with the decrease of

angle of subtense.

Following the same method used in the case of the chromatic aberration, the percentage overlapping per  $1^\circ$  element angle of subtense ( $\Delta_s$ ) can be calculated. Assuming the same values of H and X considered in the previous case, and taking  $F_1 - F_2 = 1.23$  dioptre (from figure 117) for  $H = 2$  mms,  $h = 0.2$  mm and a case of accommodation 1.5 dioptre (the nearest to the viewing condition used in this work for the experiments on the colorimeter), then  $\Delta_s = 1.34\%$  for  $1^\circ$  element angle of subtense.

### (3) The Combined Effect of the Chromatic and Spherical Aberrations:

The chromatic and spherical aberrations of any optical system are independent of each other, and they occur simultaneously. The corresponding values of percentage overlapping can be added together as shown in figure (114). The total percentage overlapping  $\Delta$  can be written as:

$$\Delta = \Delta_s + \Delta_c \quad (21)$$

Now  $\Delta_c$  depends on the test and surround colours, the more these colours are separated from each other in the hue chart, the more effective is their chromatic aberration. Both  $\Delta_c$  and  $\Delta_s$  (and hence their sum  $\Delta$ ) increase as the angle of subtense is reduced.

### APPLICATION TO THE COLOUR SAMPLES USED IN THIS INVESTIGATION.

Table (27) shows the values of percentage overlapping  $\Delta_c$  and  $\Delta$  for the different colour combinations of the test patterns used in this investigation for  $1^\circ$  element angle of subtense determined from the previous analysis and assumptions. Taking the case of  $6'$  element angle of subtense (used in the case of charts (1 a' and 2 a')), the values given in table (27) have to be divided by 0.1. The percentage overlapping will range from 88.4% (in the case of orange and blue combination) to 24.8%

(in the case of grey and green combination) for any two opposite sides of the square test patch. This means that the effect of this factor is considerable.

It must be remembered that the combined effect of spherical and chromatic aberrations is one of the factors producing the positive mixing process in the simultaneous colour contrast. The following two conclusions can be drawn:

(1) Since the combinations of the blue with any other colour have relatively higher values of percentage overlapping ( $\Delta_c$ ) than those of other combinations. This may be responsible for the tendency of the blue test colour, contrary to all other test colours used, to show the positive mixing process as shown in Chapter V and as will be shown in the mathematical analysis in Chapter IX. This does not mean that the negative mixing process is missing, but the positive mixing process in this case is bigger.

(2) Since the blue and yellow colours used are complementary, this may be responsible for the desaturation of the test colours when seen against the blue-yellow surround.

#### Quantitative analysis:

The area of the surround overlapping the test colour is a border square frame as shown in figure (118). The percentage overlapping area in any two opposite sides of the square test colour =  $(L \cdot \Delta L + L \cdot \Delta L) / (L)^2 = 2\Delta$ , (where  $L$  is the side of the test colour square). In the case of two colour surround ( $2\Delta$ ) represents the percentage overlapping area of each surround and in the case of one colour surround the percentage overlapping area will be  $4\Delta$ .

The total luminous flux falling on the area (S) of the retina on which the test square colour (C) is imaged, in the case of two colour surround (A) and (B), consists of:

$$(1) \text{ Luminous flux due to the test colour (C) } = K Y_C S$$

$$(2) \text{ Luminous flux due to the colour surround (A) } = 2 (K Y_A \Delta_A S) / 100$$

$$(3) \text{ Luminous flux due to colour surround (B) } = 2 (K Y_B \Delta_B S) / 100$$

where K is a constant,  $Y_C$ ,  $Y_A$  and  $Y_B$  are the relative luminances of colours (C), (A) and (B) respectively. The relative luminous fluxes are:

$$1 : 2(Y_A/Y_C)\Delta_A : 2(Y_B/Y_C)\Delta_B :: 1 : a : b \quad (22)$$

In the case of one colour surround (A), the relative luminous fluxes are:-

$$1 : 4(Y_A/Y_C)\Delta_A :: 1 : a_2$$

Table (28) shows the calculated values of the mixing coefficients  $a$  &  $b$  for one and two colour surrounds, for  $15'$  element angle of subtense. From this table the following conclusions can be drawn:

(1) The effect of one colour surround is additive, which is in contradiction to the empirical rule (2).

(2) The effect of one colour surround is bigger than the effect of two colour surrounds, since  $a_2 = 2a_1$  and the effect of  $b$ , is opposite to that of  $a$ , (since the surround colours (A) and (B) are in opposite sides of the test colour (C) in the chromaticity chart). This conclusion is in contradiction to the empirical rule (1).

(3) There is no difference between the positive mixtures of the two colour surround, whether the test colour (C) is mounted on stripes of colour (A) or colour (B). This conclusion is in contradiction to the actual appearance of the test colour in the two patterns (plates 1 - a and 2 a) and to the empirical rule (3).

From these conclusions we can deduce that although the positive

mixing process of the combined effect of the spherical and chromatic aberrations is a considerable factor in producing the simultaneous colour contrast phenomena, but it cannot by any means, be the only factor.

(B) PHYSIOLOGICAL CAUSES:

(1) THE INTERACTION BETWEEN ADJACENT RETINAL AREAS:

It is well-known that adjacent areas of the retina are interdependent. This may be due to the complex neural system joining the receptors to the optic nerve fibres. A number of electrophysiological investigations were done by Granit, Rubstein and Therman<sup>(96)</sup> and Brindley<sup>(97)</sup> on frog's retina, Barlow, Fitzburgh and Kuffler<sup>(98)</sup> on cat's retina, Hartline and Ratcliff<sup>(99)</sup> on limulus eye, Motokawa, Yamashita and Ogawa<sup>(100)</sup> on carps retina, and others, and these yield evidence for such interaction.

Granit and his co-workers projected two points of light 0.3 mm apart on the retina of an open frog's eye, the potentials (showing the responses) were added if the excitations were simultaneous. This shows directly the physiological spreading of the excitation over the retina.

Brindley found that if a retinal region is stimulated with a small spot of light, a micro-electrode within the stimulated area records large negative charges at "on" and at "off" (i.e. at the start and cessation of the stimulus respectively). This response continued but decreased gradually as the electrode is moved along a straight line away from the centre of the light spot. If, instead of the light spot, an annulus surround was illuminated with the electrode at its centre, it often happens that similar responses, but of opposite sign, are obtained. Then he recorded the response due to simultaneous illumination of a small spot centred on the electrode and of an annulus surround. The response was far from being

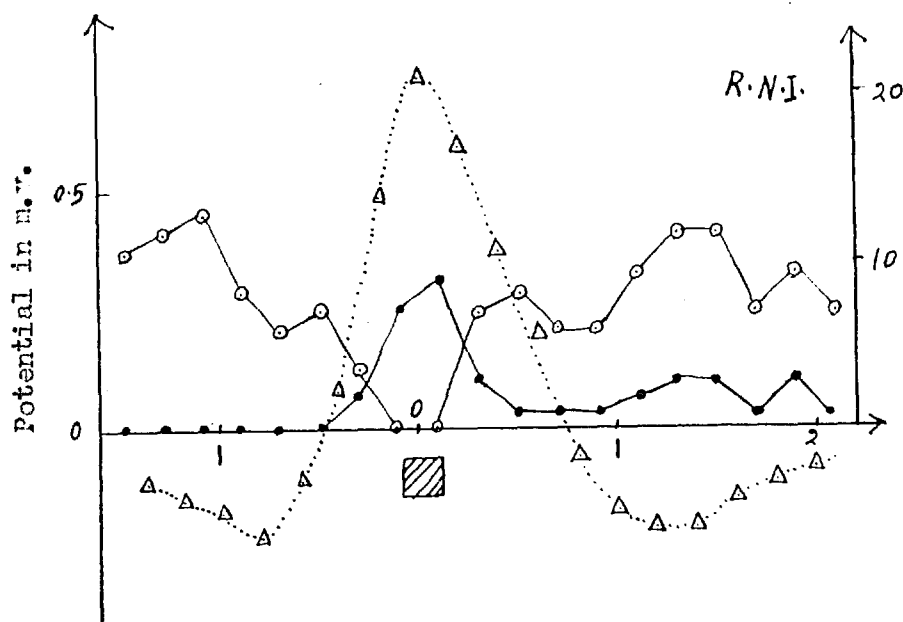
equal to the sum of those produced by the spot and the annulus separately. He suggests that this ~~was~~ due to the retinal interaction whose physiological basis seems to be complex.

Barlow and his co-workers report that the receptors are interconnected in a complicated way so as to form overlapping fields. When a large area is stimulated, each receptor exerts an inhibitory action on those of its neighbours to which it is connected. Weak signals come from its centre and stronger signals from the edges where the receptors ~~are~~ subject to inhibition from one side only. They conclude that lateral inhibition is the cause of simultaneous contrast phenomena.

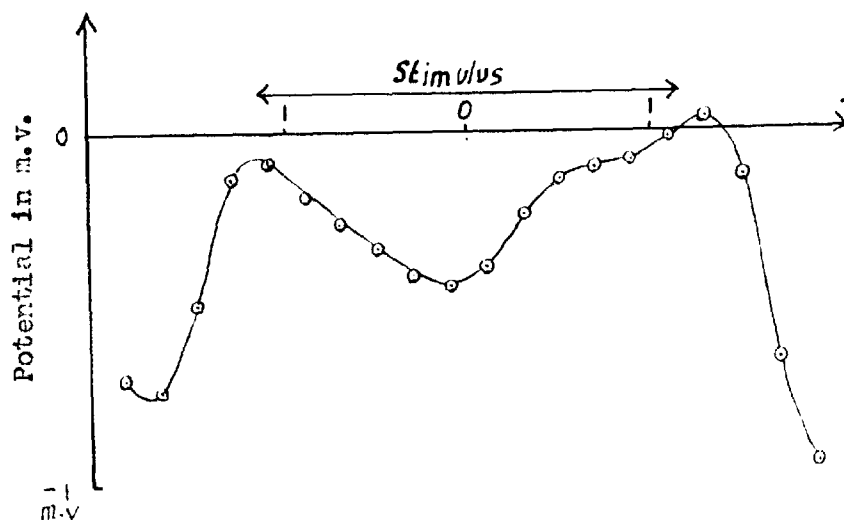
Hartline and Ratliff's investigation led to the following conclusions: The amount of inhibition exerted mutually between any two single receptor units is less the further they are apart. If two groups of receptors are illuminated together, the total inhibition on a test receptor near them depends on the combined inhibitory influences exerted by the two groups. If the two groups are widely separated, their total inhibitory effect on the test receptor equals the sum of the inhibitory effects they each produce separately. If they are close enough together to interact, their effect when acting together is usually less than the sum of their separate effects, since each group inhibits the activity of the other and hence reduces its inhibitory influence. They concluded that the pattern of optic nerve activity is not an exact reproduction of the pattern of the various stimulus intensities distributed over the retinal receptor mosaic, it is modified by the inhibitory interaction.

In a very recent paper, Motokawa and his co-workers recorded simultaneously the slow potentials and spike activity of ganglion cells. They





Figure(119) Magnitudes of slow responses ( $\Delta \dots \Delta$ ) & relative numbers of impulses (R.N.I.) are plotted as a function of distances between electrode tip and centre of light spot, ( $\circ \rightarrow \circ$ ) for "on" and ( $\bullet \rightarrow \bullet$ ) for "off" discharges.  $\square$  is the stimulus in size and position. Intensity and duration of the stimulus were 1250 lux and 0.4 sec. respectively. (Motokawa and coworkers).



Figure(120) The potential field within and without a wide retinal image ( $2.5 \times 2.5$  mm) in size. Magnitude of response was measured from base line to steady level of response and plotted against distance between electrode tip and centre of illumination. (Motokawa and coworkers).

summarised their results as follows:

(1) The slow potentials within a small illuminated area ( $0.2 \times 0.2$  mm) were positive in polarity relative to an electrode placed at the back of the retina. In the surrounding area there appeared negative potentials which had maximum amplitude at a short distance from the margin of the illuminated area<sup>a</sup> and extended as far as few millimeters (as shown in figure 119).

(2) When the retina was exposed to stimuli larger than a certain limit (area used is  $2.5 \times 2.5$  mm), the positivity of slow potentials was maximum at the margin of the illuminated area. They interpreted this result as physiological evidence of border contrast (as shown in figure 120 )

(3) The positive slow potential is a local process, while the negative one is a propagating process. On the basis of these properties, the spatial distribution characteristics for border contrast was accounted for in terms of interaction between positive and negative potentials.

It is clear from this survey of some of the work done in electrophysiology, that retinal interaction exists and that its function is complicated. It may be argued that all these experiments were done on animal retinas which may be different in structure and function from the human retina. This is true to a certain extent. We are mainly concerned, in colour vision, with the human fovea, which is mainly populated with cones, while those retinas studied may be mainly populated with rods. Also in the human fovea, histological evidence indicates that there are small ganglion cells, each of which is connected only to a single cone, while the usual situation throughout the vertebrates is that each ganglion

serves many receptors. (3) However that one to one connection between the cones and the optic nerve fibres have been found by Polyak, (101) to occur primarily in the very centre of the fovea. Outside the central pit of the fovea, more diffuse forms of connection become evident and the possibility that the impulses from neighbouring cones may intermingle, is greatly increased; this gives rise to lateral interaction between adjacent foveal areas. (12)

#### THE ROLE PLAYED BY RETINAL INTERACTION IN PRODUCING SIMULTANEOUS COLOUR CONTRAST PHENOMENA.

If we assume that the results of the study of retinal interaction, just mentioned before, apply, more or less, to the human fovea, the following conclusions can be drawn:

(1) The mutual inhibition between adjacent areas of the retina is an important factor in the effect of the surround on the appearance of the test colour. It produces the negative mixing process which was mentioned in the analysis of the results in Chapter V, and which will be seen in the mathematical analysis in Chapter IX.

(2) Since the inhibitory effects decrease with the increase of distance apart, then it must be expected that the change in the appearance of the test colour is smaller for bigger angles of subtense. This is shown to be true from the results of Chapter VII.

(3) For big angles of subtense, the retinal interaction gives no more than a boundary contrast effect which gives a small change in the overall appearance of the test colour.

(4) The total effect of different parts of the surround is equal to, or a little smaller than the sum of their individual effects for big or

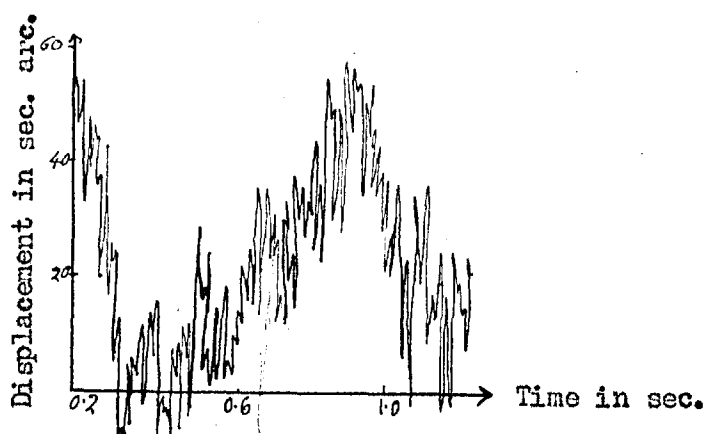


Figure (121) Record of Tremor (Fender).

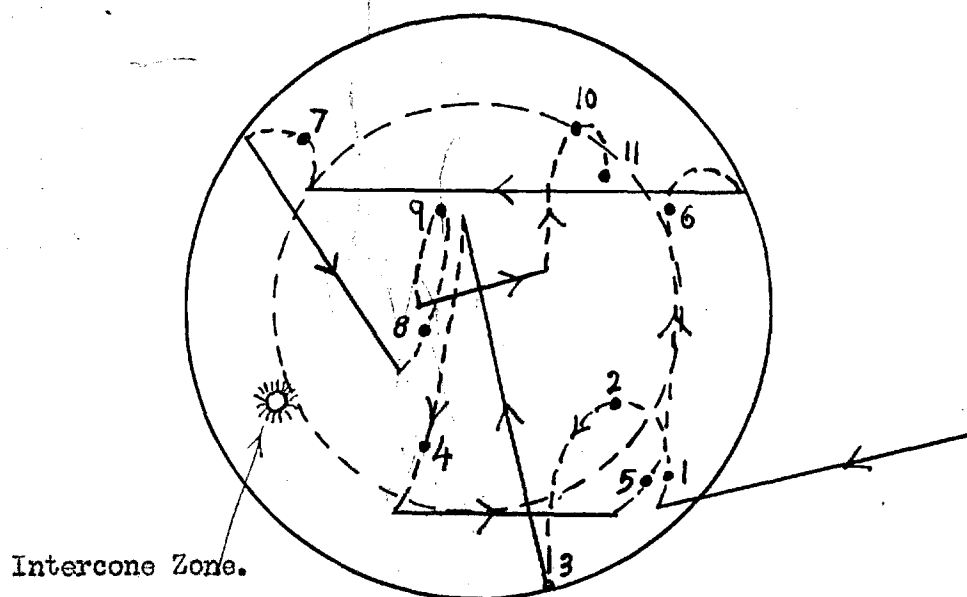


Figure (122) The movements of retinal image, the diameter of the circle is 10 minutes of arc. The numbered dots indicate positions at intervals of 0.2 sec. The Tremor is not shown. (Ditchburn).

small angles of subtense respectively.

## (2) THE EYE MOVEMENTS.

It has long been known that small involuntary rotations of the eye-ball exist even when the observer tries to fixate as steadily as possible on a well defined target. These rotations cause movements of the image across the retina, which prove to be essential in visual perception. Lord and Wright, (102), (103) investigated the eye movements and surveyed the different subjective and objective techniques of their recording. Ratliff and Riggs, (104) Barlow, (105) Ditchburn and Ginsborg, (106) and Ditchburn, (107), (108) studied the eye movements during fixation and their effect on vision.

The methods used in these studies fall into two main groups :

(a) Those depending on reflection of light on the cornea, and (b) Those using a contact lens with a plane mirror. Most of the results showed that there are three types of eye movements.

(1) An irregular rapid oscillatory movement called a "Tremor". The corresponding movements of the image relative to the retina are of the order of the diameter of a foveal cone (24 sec. arc.) of frequency 30-150 C.P.S. Figure (121) shows an amplified record of tremor by Fender. (109)

(2) Sharp saccadic movements called "Flicks", up to 60 min. arc, lasting for about 0.03 second and occurring at intervals which vary from 0.03 to 5 seconds.

(3) A slow "Drift" at a rate of about 1 min. arc. per second during the interflick periods.

These values (which agree fairly well with the results of others), together with figure (122) showing the movement of the image of a fixation

point across the retina, are quoted from Ditchburn,<sup>(107)</sup> He reports that there is a considerable day-to-day variation for one subject and a variation between subjects, but the movements are always of the same order of magnitude. He also suggests that these movements assist normal vision perception in the following way:

(1) The tremor oscillates the boundaries between light and dark areas in the visual image across certain retinal receptors. This causes rapid variations of stimulus of these receptors producing their "on-off" action and bursts of potential spikes travel along the associated nerve pathway to the cortex.

(2) If the tremor were the only movement, certain receptors would be strongly stimulated all the time and others which were subjected to steady illumination would be weakly stimulated. The drift moves the boundaries on to new sets of receptors, which have not been subjected to the "on-off" stimulation.

(3) Since the drifts are predominantly in one direction, the flicks operate to restore the image to the central fovea.

Ditchburn and others,<sup>(110), (111)</sup> developed a technique in which the eye movements of the observer controlled the movement of a target such that its image remains accurately on the same part of the retina all the time. Such an image is called a stabilised retinal image. He found that by stabilising the image in this way, the main functions of visual and colour discrimination (especially in the blue green region) fail intermittently, partial vision being restored from time to time. This shows the important function of the eye movements in visual perception.

THE EFFECT OF EYE MOVEMENTS ON SIMULTANEOUS COLOUR CONTRAST PHENOMENA.

It is obvious that eye movements play an important role in the phenomena of simultaneous colour contrast. Although the observer concentrates on the test colour, yet his eye, through its involuntary drifts and flicks, surveys the whole test pattern. The tremor, being rapid and of small amplitude, affects the appearance of the boundaries of the test and surrounding colours. This effect is enhanced as the angle of subtense is decreased.

The eye movements may be responsible for two opposite effects:

- (1) The persistence of vision and (2) the successive colour contrast.

The persistence of vision, <sup>(3)</sup> describes the fact that the effect of the stimulus on the retina remains for a short time after the cessation of the stimulus. The tremor being rapid and of speed above the critical frequency of flickering may cause the mixing of the sensations due to the test and surrounding colours at their boundaries. On the other hand, the different types of eye movement cause the same area of the retina to be alternately stimulated by the test colour and different parts of the coloured surround. Hence the appearance of the former may be affected by the after-image of the latter.

The first effect results in simple addition of the test and surrounding colours. The second effect depends on the nature of these colours and mostly produces the overlapping of the complementary colours of the surround and test colour. A private communication from Professor Ditchburn showed that for both the flick and drift eye movements, the amplitude of the vertical component is in general greater than that of the horizontal component. This may throw a light on the positive mixing effect of the side stripes.

If Ditchburn's theory that the brain in some way fills in a region such as the blind spot, from which it receives no signals whatever, (112) is true and general all over the retina, then the boundary effects (due to the tremor eye movement and chromatic and spherical aberrations), become generally very important not only for very small angles of subtense. However this theory needs more investigation to be well established.

### (C) PSYCHOLOGICAL EFFECTS.

It has been mentioned in Chapter I that colour perception is of three phases: physical, physiological and psychological. The physical phase is concerned with the spectral energy distribution of the light falling on the eye from the coloured object, and the image formed on the retina by the refracting system of the eye. The physiological phase is concerned with the absorption of the spectral energy distribution of the light energy by the light receptors of the retina (cones and rods) and sending a message to the visual cortex in the form of nervous pulses of a definite code through the neural system and the optic nerve fibres. The psychological phase is concerned with the decoding of the neural message received by the visual cortex and interpreting it as the subjective image of the coloured object we actually see.

This chapter, has, so far, dealt with the role played in simultaneous colour contrast phenomena by the physical defects of the eye system and the complicated physiological factors. We are left now with the psychological causes of such phenomena which tend to lie outside the scope of physical interpretation.

The application of psychology (21) in colour vision deals with the study of the relation between the colour as calculated for the standard



observer (the objective phase of colour), and the colour actually perceived by the mind of a real observer under certain viewing conditions ( the subjective phase of colour). The word perception is used in psychology to show what an observer does see, which is different from the physical nature of light reaching his eye. Perception includes the psychological factors of attention, attitude and feeling which affect the subjective image seen. Also, the mental faculties of any person are a part of his learning and everyday experience. That is why the interpretive reaction of the mind to any coloured scene is purely subjective. There are two possible psychological factors in colour contrast.

(1) Psychological interpretation of the test pattern as a whole and its effect on the appearance of the test colour. Tenant,<sup>(113)</sup> expressed this idea as "The principle of the relativity of our perception of visual effects". The whole test pattern may be psychologically interpreted as consisting of two main parts: The stripes on which the squares of the test colour are mounted and the other stripes, and perhaps more importance may be given to the former, since the observer is concentrating on the test colour. Also the squares of the test colour may be looked at as belonging to the stripes on which they are mounted and hence their contrasting effect. This affects the judgement made by the observer in adjusting the R-G-B mixture in the comparison patch in the colorimeter, or choosing the coloured chip in the Munsell Book of Color, to match the test colour in its surround.

(2) Perceptual processes in the brain may enhance the changes in the appearance<sup>(13)</sup> of the test colour against its background.

## CHAPTER IX

### SIMPLE LINEAR ANALYSIS OF THE COLOUR CONTRAST PHENOMENA BASED ON THE MIXTURE EFFECTS OF THE SURROUNDING COLOURS ON THE APPEAR- ANCE OF THE TEST COLOUR.

The different possible factors that may be responsible for producing the colour contrast phenomena, which were discussed in the last chapter, suggest some additive and subtractive mixture of the test colour and the colours of the surround. It is very difficult at this stage of work, to tell the actual form of these mixing processes. This needs:-

- (1) More knowledge of the visual processes which is incomplete up to the present date.
- (2) a statistical analysis of large number of results obtained by many observers using the colorimeter.

For simplification, the following analysis is suggested as a preliminary study of these mixing processes:

#### (A) The Case of Two Colour Surround:

Assume that the appearance of the test colour in its surround ( $C_{AB}$ ) is a linear function of the test colour (C) and the surrounding colours (A) and (B) as seen on a white surround i.e.

$$(C_{AB}) = f \{ (C), (A), (B) \} \quad (I)$$

Where ( $C_{AB}$ ), (C), (A) & (B) are given in the corresponding C.I.E. unit trichromatic equations obtained by colour appearance measurement i.e. by matching each of these stimuli against the equations obtained by R.G.B. mixture under the defined surround conditions which can be written as follows:-

$$(C_{AB}) \equiv x_{C_{AB}} (X) + y_{C_{AB}} (Y) + z_{C_{AB}} (Z) \quad (1)$$

$$(C) \equiv x_C (X) + y_C (Y) + z_C (Z) \quad (2)$$

$$(A) \equiv x_A (X) + y_A (Y) + z_A (Z) \quad (3)$$

$$(B) \equiv x_B (X) + y_B (Y) + z_B (Z) \quad (4)$$

The coefficients  $x_{CAB}$ ,  $y_{CAB}$ ,  $z_{CAB}$ ;.... &  $x_B$ ,  $y_B$ ,  $z_B$  are experimental values.

Now assume that the linear function (I) can be written as:-

$$(C_{AB}) \equiv c (C) + a (A) + b (B) \quad (5)$$

Where  $c$ ,  $a$  &  $b$  are constants which can be called mixing coefficients.

Substituting from (1), (2), (3), and (4) into (5), and equating coefficients of (X), (Y) & (Z) in both sides of the equation we get:-

$$x_{CAB} = c x_C + a x_A + b x_B \quad (6)$$

$$y_{CAB} = c y_C + a y_A + b y_B \quad (7)$$

$$z_{CAB} = c z_C + a z_A + b z_B \quad (8)$$

Equations (6), (7) and (8) can be solved and the values of the mixing coefficients  $c$ ,  $a$  &  $b$  can be determined.

Equation (5) is applied to the case of compound pattern, of 15' element angle of subtense for all the test colours used in this investigation at normal and 20° viewing angle. The compound pattern was chosen because it represents bigger effects of colour contrast than in the case of the simple pattern. Also the orange, red and green test colours show more limited colour contrast effects in the case of simple pattern (no perceived change in saturation), than in the case of the compound pattern.

Tables (29, a & b) show the mixing coefficients that have been calculated from experiments with the two colour surrounds: (1), (2), (7) & (8) for all the test colours, at normal and 20° viewing angle, normalised

for unit mixing coefficient of the test colour (i.e.  $c = 1$ )

: It can be easily seen from these tables that:

(1) For all the cases (except the case of surround (1) for grey test colour at normal vision), the mixing coefficients of the colour of the stripe on which the test colour is mounted is negative and that of the colour of the two side stripes is positive. The blue proved to be an exception to this rule since the two mixing coefficients are positive. The exceptional case of grey on surround (1) must not be over estimated, since it is most probably due to experimental error. This is clear since the same case (the grey on surround (1) for  $20^\circ$  viewing angle — which shows bigger effect than from normal viewing) follows this rule (No 3).

The exceptional case of the blue test colour may be due to (1) the relatively high positive mixing process due to the chromatic aberration (Chapter VIII) or (2) the darkness of the blue on white surround, and hence the inaccuracy of measuring it (Chapter V). Carrying out the same calculations referring the shifts to the case of the black surround instead of white (i.e. where it looks brighter), it was found that the blue test colour obeys this rule. This is shown numerically in Table (29b) and graphically in figure (47) and verifies the analysis on the blue test colour in Chapter V.

(2) The effect of the stripe on which the test colour is mounted (the -ve mixing coefficient) is smaller than that of the two side stripes (the + ve mixing coefficient) for all the test colours (including the blue), except for the grey test colour on surrounds (1) and (2) and also (7) for normal viewing only, where the reverse takes place. I can not give any reason for these exceptional cases of the grey.

These two conclusions are shown graphically in the case of  $20^\circ$  viewing angle (where the effects are bigger than in the case of normal viewing), in Chapter V .

(3) The mixing coefficients for all the test colours are bigger in the case of the inclined test patch than that in the case of normal test patch (except in the exceptional case of grey test colour on surround (1)) and hence the bigger shifts noticed in the former case than in the latter one.

#### (B) The Case of One Colour Surround.

It was found that the case of one colour surround can not be taken as a special case of the two colour surround, by eliminating the effect of the other surround. That is to say equation (5) for two colour surround does not apply for one colour surround by equating the mixing coefficient of the other surround to zero. If that was the case, expanding equation (5) and equating the coefficients of (X), (Y) & (Z) in both sides we get three linear simultaneous equations in two unknowns only. This does not give unique roots except in a special case when the point representing the appearance of the test colour in its surround, lies on the straight line joining the two points representing the test and the surrounding colours against a white background. This is not, by any means, the case for any test colour.

So it seems necessary to add another factor to this equation which gives the usual case of three equations in three unknowns. Since all the points representing the appearance of the test colour on one colour surround as shown in figure (42) (and other similar figures for different viewing conditions), are shifted a little from the case of white surround

towards desaturation, i.e. more or less towards the white point, so it was thought of adding to the R.H.S. of the equation a fraction of equal energy standard white  $S_E$ . This addition represents a desaturating factor in the equation.

So we can assume that the appearance of the test colour  $C$  in one colour surround  $A$  i.e.  $(C_A)$  is a linear function of the test colour  $(C)$  on a white surround and the equal energy white  $(W)$ . This can be written in the form:-

$$(C_A) = F \{ (C), (A), (W) \} \quad (II)$$

Where  $(C_A)$ ,  $(C)$  and  $(A)$  are given by the corresponding C.I.E. unit trichromatic equations obtained by the actual matching.  $C_A$  can be written in the form:-

$$(C_A) \equiv x_{C_A}(X) + y_{C_A}(Y) + z_{C_A}(Z) \quad (9)$$

where  $x_{C_A}$  &  $y_{C_A}$  &  $z_{C_A}$  are experimental values.

and  $(C)$  &  $(A)$  are given in equations (2) & (3) respectively

$$\text{and } (W) \equiv 0.333 (X) + 0.333 (Y) + 0.333 (Z) \quad (10)$$

Now assume that the linear function (II) can be written as:-

$$\begin{aligned} (C_A) &\equiv c (C) + a (A) + \bar{b} (W) \\ &\equiv c (C) + a (A) + b \{ (X) + (Y) + (Z) \} \\ b &= 0.333 \bar{b} \end{aligned} \quad (11)$$

where  $c$ ,  $a$  &  $b$  are constants called the mixing coefficients.

Substituting equations (9), (2) & (10) into equation (11) and equating coefficients of  $(X)$ ,  $(Y)$  and  $(Z)$  in both sides we get:-

$$x_{C_A} = c x_C + a x_A + b \quad (12)$$

$$y_{C_A} = c y_C + a y_A + b \quad (13)$$

$$z_{C_A} = c z_C + a z_A + b \quad (14)$$

This means that the addition of the equal energy white (W), is no more than adding a constant (b) to the R.H.S. of the last three equations.

Equations (12), (13) & (14) can be solved and the values of the mixing coefficients c, a and b can be determined.

Equation (11) is applied to the case of one colour surround in compound pattern of 15' element angle of subtense for all the test colours used at normal and 20° viewing angle for the same reasons mentioned in the case of two colour surrounds.

Tables (29, a and b) show the mixing coefficients of the one colour surrounds (3), (4), (9) and (10) for all the test colours at normal and 20° viewing angle, normalised for unit mixing coefficients of the test colour (i.e. c = 1).

It can be easily seen from these tables that:

(1) For all the cases (including the blue), the mixing coefficient of the surround colour is negative. There are two exceptions to this rule: (1) case of orange test colour on yellow surround for normal viewing, and (2) case of blue test colour on orange surround for 20° viewing angle. These exceptions are most probably due to experimental errors since the same cases for the other viewing condition follow this rule.

This is a good verification to Rule (2) in Chapter V namely the subtractive effect of one colour surround.

(2) For all the cases (without any exception), the mixing coefficients of the white is positive. This shows the desaturating effect of the one colour surround compared with the case of white surround which was just mentioned in the argument about adding the equal energy white (W)

TABLE (2g) THE MIXING COEFFICIENTS FOR THE COMPOUND PATTERN 15' ELEMENT ANGLE OF SUBTENSE (a) VERTICAL TEST PATCH (b) 20° VIEWING ANGLE. (1) THE MIXING COEFFICIENTS NORMALISED FOR UNIT MIXING COEFFICIENT OF THE TEST COLOUR. (2) THE SAME DIVIDED BY THE RELATIVE LUMINOSITIES. (3) THE SAME DIVIDED BY THE RELATIVE LUMINOSITIES AND AREAS.

[illegible]



TABLE (29) (CONTD.)

B.

[illegible]

| SURROUND    |        | 9              |                | 10              |                 | 7              |                | 8              |                |
|-------------|--------|----------------|----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| TEST COLOUR |        | a <sub>9</sub> | b <sub>9</sub> | a <sub>10</sub> | b <sub>10</sub> | a <sub>7</sub> | b <sub>7</sub> | a <sub>8</sub> | b <sub>8</sub> |
| BLUE        | (a) 1- |                |                |                 |                 | +              | -              | -              | +              |
|             | 2-     |                |                |                 |                 | 0.1562         | 0.1348         | 0.0711         | 0.1129         |
|             | 3-     |                |                |                 |                 | 0.0613         | 0.0480         | 0.0279         | 0.0293         |
|             |        |                |                |                 |                 | 0.0116         | 0.0150         | 0.0087         | 0.0055         |
|             | (b) 1- |                |                |                 |                 | +              | -              | -              | +              |
|             | 2-     |                |                |                 |                 | 0.2339         | 0.0960         | 0.1621         | 0.00044        |
|             | 3-     |                |                |                 |                 | 0.0173         | 0.0078         | 0.0199         | 0.00002        |

to equation (11)

These two results justify the suggested form of the linear function (II) for one colour surround.

(3) As for the effect of the viewing angle on these mixing coefficients, it can be said after examining table (29 a & b), that there is no definite trend as in the case of the two colour surrounds. This may be due mainly to the wide range of variation of the mixing coefficient of the white (W).

(C) THE POSSIBILITY OF PREDICTING THE APPEARANCE OF ANY TEST COLOUR  
AS SEEN AGAINST ANY BACKGROUND.

Predicting the appearance of any test colour seen against any background, must be the aim of such quantitative study of the colour contrast phenomena. This would have been easy if the mixing coefficients could be calculated successfully by other means than the actual matching. Once these mixing coefficients, together with the unit trichromatic equations of the test and surrounding colours are known, they could be substituted in equations (5) and (11) or similar equations for different patterns, and hence the appearance of the test colour on its surround could be calculated.

It can be seen from the possible causes of colour contrast phenomena, as discussed in the last Chapter, and the conclusions mentioned in this Chapter, that there are two opposite processes acting simultaneously to produce such phenomena, namely the negative and positive mixing effects. Whenever the former is larger than the latter, the mixing coefficient is negative, as for example, in the case of one colour surround, or the effect

**TABLE (30) THE TRICHROMATIC COEFFICIENTS OF THE COMPOUND PATTERN**  
**15' ELEMENT ANGLE OF SUBTENSE, 20° VIEWING ANGLE, TRANSFORMED TO**  
**MACADAM UNIFORM CHROMATICITY CHART.**

$$U = \frac{4x}{x + 15y + 3z}$$

$$V = \frac{6y}{x + 15y + 3z}$$

GREY TEST COLOUR

| SURROUND | U     | V     |
|----------|-------|-------|
| 1        | 0.286 | 0.357 |
| 2        | 0.246 | 0.313 |
| 3        | 0.280 | 0.343 |
| 4        | 0.276 | 0.350 |
| 5        | 0.278 | 0.346 |
| 6        | 0.253 | 0.339 |
| 7        | 0.354 | 0.341 |
| 8        | 0.210 | 0.349 |
| 9        | 0.253 | 0.341 |
| 10       | 0.293 | 0.342 |

GREEN

| SURROUND | U     | V     |
|----------|-------|-------|
| 1        | 0.150 | 0.359 |
| 2        | 0.126 | 0.341 |
| 3        | 0.141 | 0.353 |
| 4        | 0.143 | 0.355 |
| 5        | 0.138 | 0.356 |
| 6        | 0.161 | 0.359 |

YELLOW

| SURROUND | U     | V     |
|----------|-------|-------|
| 5        | 0.263 | 0.353 |
| 6        | 0.236 | 0.358 |
| 7        | 0.289 | 0.357 |
| 8        | 0.229 | 0.359 |
| 9        | 0.244 | 0.359 |
| 10       | 0.276 | 0.357 |

ORANGE

| SURROUND | U     | V     |
|----------|-------|-------|
| 1        | 0.387 | 0.350 |
| 2        | 0.417 | 0.327 |
| 3        | 0.415 | 0.340 |
| 4        | 0.404 | 0.342 |
| 5        | 0.424 | 0.341 |
| 6        | 0.375 | 0.343 |

BLUE

| SURROUND | U     | V     |
|----------|-------|-------|
| 5        | 0.139 | 0.257 |
| 6        | 0.232 | 0.287 |
| 7        | 0.253 | 0.269 |
| 8        | 0.201 | 0.275 |
| 9        | 0.202 | 0.269 |
| 10       | 0.217 | 0.273 |

WHITE POINT

|  |       |       |
|--|-------|-------|
|  | 0.211 | 0.316 |
|--|-------|-------|

of the stripe on which the test colour is mounted, in the case of ~~two~~ two colour surrounds, when the former is smaller than the latter the mixing coefficient is positive as the effect of the two side stripes for a two colour surround.

The nature of the positive and negative mixing coefficients is rather complicated, since each of them depends on more than one factor. Most of these factors and their interaction among each other are not fully understood up until now.

The mixing coefficients should depend on the relative light fluxes reflected from the test and surrounding colours i.e. on their relative areas and luminances. They may depend also on the relative locations of their corresponding points in the chromaticity chart. But it does not seem likely that there is any linear relation between the mixing coefficients and these factors.

For further simplification, we are going to assume that this relation is linear. So the mixing coefficients of the test and surrounding colours are divided by their corresponding areas and luminances. The results are contained in rows (1,b) and (3,b) in Table (29 a & b)

No obvious relation was found between the final results and the distances between the points corresponding to the test and surrounding colours in the chromaticity chart. This conclusion in itself is not surprising, but it has been expected since the C.I.E. chromaticity chart is non uniform i.e. the distance apart of two colours in the chart is not a measure of their subjective difference (the perceived sensory difference). That is why the C.I.E. unit trichromatic coefficients were transformed into those of a uniform chart (MacAdams Uniform Chart was chosen for the simplicity of transformation). Table (30) shows the

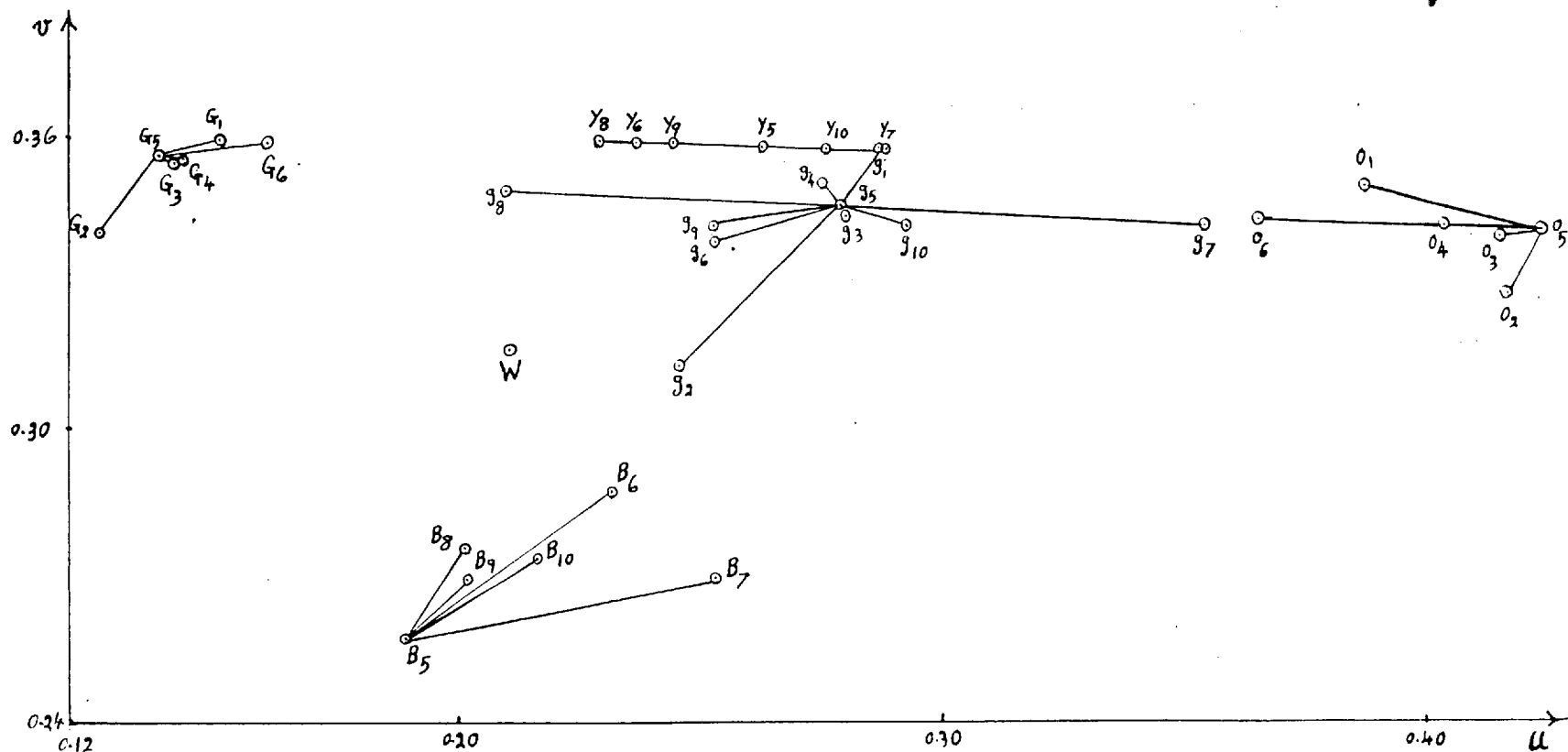


Figure (123) The chromaticities of the appearance of all the test colours against their backgrounds used in the case of the compound pattern of 15 element angle of subtense and 20° inclination shown in MacAdam uniform chromaticity chart.

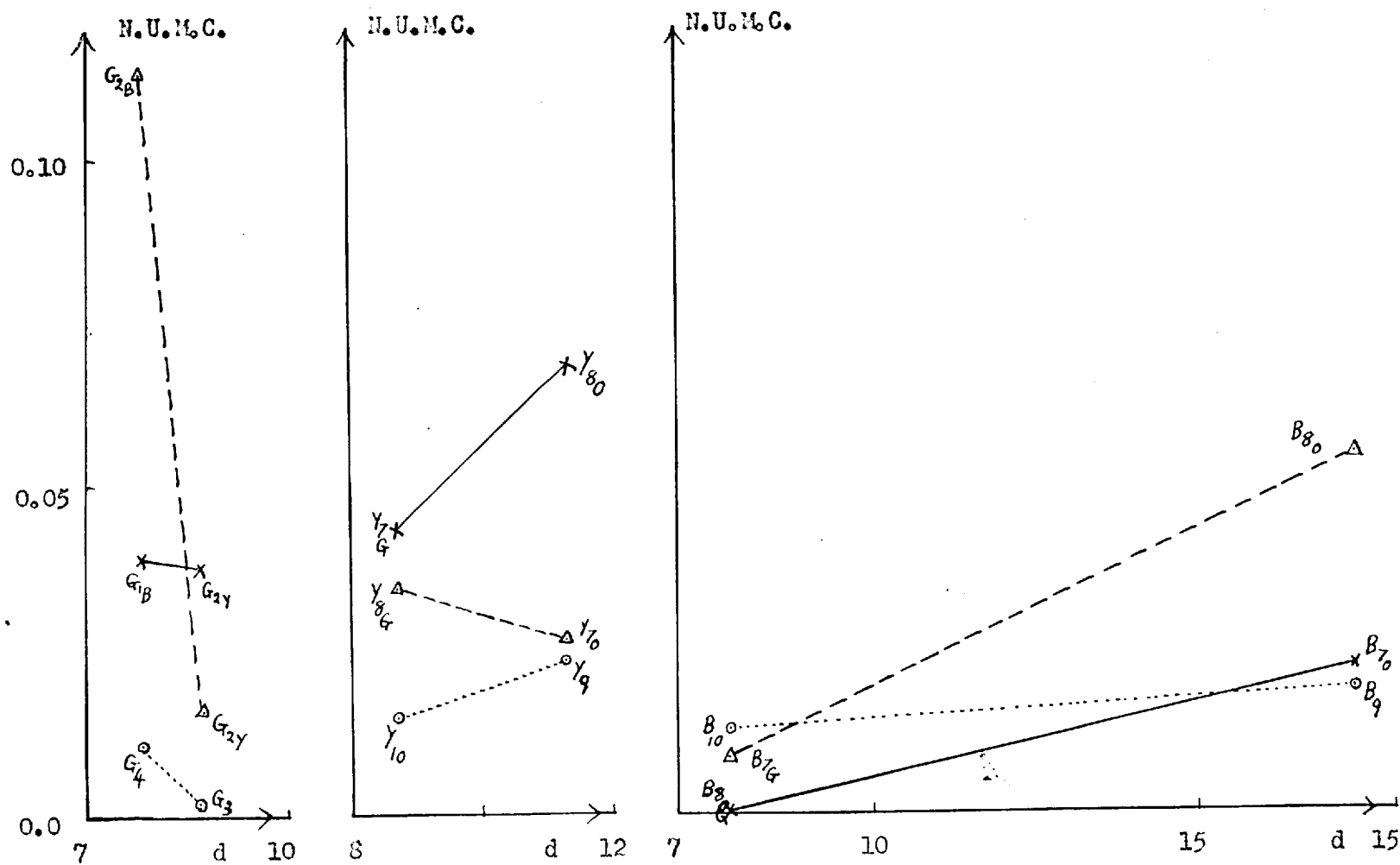


Figure (124) The relation between the normalised unit mixing coefficient (N.U.M.C.) and the distance (d) apart in MacAdam uniform chromaticity chart for Green, Yellow and Blue test colours in their surrounds.



TABLE (31) THE MIXING COEFFICIENTS, FOR THE COMPOUND PATTERN 15' ELEMENT  
 ANGLE OF SUBTENSE, 20° VIEWING ANGLE, AFTER TRANSFORMATION TO MACADAM'S  
 UNIFORM CHROMATICITY CHART. (1) THE MIXING COEFFICIENTS NORMALISED FOR UNIT  
 MIXING COEFFICIENT OF THE TEST COLOUR. (2) THE SAME DIVIDED BY THE RELATIVE  
 LUMINOSITIES. (3) THE SAME DIVIDED BY THE RELATIVE LUMINOSITIES AND AREAS  
 THE SECOND CASE OF THE BLUE REFERRED TO BLACK SURROUND.

| SURROUND    |    | 3              |                | 4              |                | 5              |                | 6              |                |
|-------------|----|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| TEST COLOUR |    | a <sub>3</sub> | b <sub>3</sub> | a <sub>4</sub> | b <sub>4</sub> | a <sub>5</sub> | b <sub>5</sub> | a <sub>6</sub> | b <sub>6</sub> |
| GREY        | 1- | -              | +              | -              | +              | +              | -              | -              | +              |
|             | 2- | 0.1816         | 0.0116         | 0.1059         | 0.1739         | 0.1045         | 0.1076         | 0.0436         | 0.5639         |
|             | 3- | 0.0529         |                | 0.1568         |                | 0.0305         | 0.1593         | 0.0127         | 0.8349         |
| ORANGE      | 1- | 0.0060         |                | 0.0178         |                | 0.0055         | 0.0498         | 0.0040         | 0.1575         |
|             | 2- | 0.0100         | 0.0514         | 0.0581         | 0.1674         | 0.3959         | 0.0613         | 0.1473         | 0.1303         |
|             | 3- | 0.0050         |                | 0.1480         |                | 0.1985         | 0.1561         | 0.0738         | 0.3319         |
| GREEN       | 1- | 0.0006         |                | 0.0168         |                | 0.0354         | 0.0488         | 0.0231         | 0.0626         |
|             | 2- | 0.0213         | 0.0775         | 0.0239         | 0.0374         | 0.1195         | 0.0324         | 0.1589         | 0.1558         |
|             | 3- | 0.0162         |                | 0.0921         |                | 0.0906         | 0.1248         | 0.1205         | 0.6002         |
|             |    | 0.0018         |                | 0.0105         |                | 0.0162         | 0.0390         | 0.0377         | 0.1132         |

| SURROUND    |    | 9              |                | 10              |                 | 7              |                | 8              |                |
|-------------|----|----------------|----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| TEST COLOUR |    | a <sub>9</sub> | b <sub>9</sub> | a <sub>10</sub> | b <sub>10</sub> | a <sub>7</sub> | b <sub>7</sub> | a <sub>8</sub> | b <sub>8</sub> |
| GREY        | 1- | -              | +              | -               | +               | +              | -              | -              | +              |
|             | 2- | 0.0985         | 0.1823         | 0.1416          | 0.0785          | 0.0925         | 0.3233         | 0.2599         | 0.1750         |
|             | 3- | 0.0573         |                | 0.5442          |                 | 0.0538         | 0.1243         | 0.1511         | 0.0673         |
| YELLOW      | 1- | 0.0065         |                | 0.0618          |                 | 0.0096         | 0.0388         | 0.0472         | 0.0127         |
|             | 2- | 0.1026         | 0.0207         | 0.0995          | 0.0140          | 0.0718         | 0.1042         | 0.1095         | 0.1392         |
|             | 3- | 0.2047         |                | 0.1312          |                 | 0.1432         | 0.1374         | 0.2184         | 0.1836         |
| BLUE        | 1- | 0.0233         |                | 0.0149          |                 | 0.0270         | 0.0429         | 0.0683         | 0.0346         |
|             | 2- | 0.0490         | 0.1742         | 0.4397          | 1.2328          | 0.2999         | 0.1118         | 0.0952         | 0.1464         |
|             | 3- | 0.0192         |                | 0.1141          |                 | 0.1177         | 0.0290         | 0.0374         | 0.0380         |
| BLUE        | 1- | 0.0022         |                | 0.0130          |                 | 0.0222         | 0.0091         | 0.0117         | 0.0072         |
|             | 2- | 0.1656         | 0.1238         | 0.3871          | 1.0972          | 0.1625         | 0.2133         | 0.1740         | 0.0011         |
|             | 3- | 0.0188         |                | 0.0440          |                 | 0.0307         | 0.0667         | 0.0544         | 0.0002         |



new unit trichromatic coefficients in this system of all the test colours used in the case of the compound pattern viewed at  $20^\circ$  angle<sup>of inclination</sup>. Table (31) shows the corresponding mixing coefficients normalised for unit mixing coefficient of the test colour (i.e.  $c = 1$ ). The negative and positive mixing coefficients follow exactly the same system explained earlier in this chapter. They are then divided by their corresponding areas and luminance and normalised for unit coefficient of the test colour. These final results can be called the normalised unit mixing coefficients (N.U.M.C.) Their values are plotted (as ordinates) against the distance between the corresponding test and surrounding colour in the uniform chromaticity chart (as abscissa) figures (121, 122). Straight lines are joined between the two points corresponding to the two surrounding colours in identical cases (e.g. 0...0 for one colour surround, x---x for the colour of the stripe on which the test colour is mounted and <---< for the colour of the two side stripes, in the two colour surrounds.) These straight lines have no significance but they serve as indicator for comparison. From these figures it can be seen that:

(1) The N.U.M.C. are the smallest for one colour surrounds (except in the cases of the grey and blue test colours on green surround).

(2) The N.U.M.C. are the biggest for the colour of the two side stripes in the two colour surrounds (except in the cases of grey test colour on orange and green surround and green test colours on yellow and blue surround).

(3) The longer the distance apart between the test and surrounding colours in the uniform chromaticity chart, the bigger the N.U.M.C. This means that the bigger the apparent difference between the test and the surrounding colours, the bigger the colour contrast effects produced.

This is shown clearly in the cases where there are big differences between the distances apart of the test colour and the two surrounding colours e.g. for the grey and orange test colours on yellow and blue ~~surrounds~~ and yellow and blue test colours on orange and green surrounds with one exception the side stripes of the yellow test colour. This conclusion does not apply for the cases where the distances apart of the test colour and the two surrounding colours are almost equal e.g. for the grey test colour on orange and green surrounds and green test colour on yellow and blue surrounds. This can not be taken as an evidence against this conclusion which is logical but can be explained as due to the fact that even in this uniform chromaticity chart, there is no exact equality of colour steps (which is particularly noticeable for small differences).

There is no obvious direct relation between the N.U.M.C. for any test and surrounding colours and the distance between the corresponding points in the uniform chromaticity. No wonder, because all the last treatment was over simplification of a rather complicated case and the uniform chromaticity is not actually as uniform as could be understood from its name. This means that knowing the locations of the test and surrounding colours in the uniform chromaticity chart, their N.U.M.C. can not be estimated. Hence, in this stage of work, it can be said that the appearance of any test colour as seen against any background can not be predicted. This may be achieved in the future after more investigations are done in this field. This needs more understanding of the actual causes of the colour contrast phenomena and their interaction with each other to produce the final colour appearance.

Even then, it must be remembered that different observers perceive colour contrast effects differently, so the average values of a number of observers must be taken.

Nevertheless, before reaching this stage of generalisation, it is useful to apply the same analysis used in this investigation for the average results obtained by several observers for different combinations of test and surrounding colours arranged in different patterns used in our everyday life: in nature, industry and artistic colour designs.

This work is no more than an introduction to the study of colour contrast phenomena using five test colours, namely, orange, yellow, green, blue and grey, on one colour and two colour surrounds, in simple and compound patterns. The surrounds used are these colours together with (almost) neutral white and black.

## CHAPTER X.

### SUMMARY AND CONCLUSIONS.

In this investigation the effect of the surround on the appearance of a selection of test colours was studied in a limited number of cases at a limited number of viewing conditions, as an introduction to the study of simultaneous colour contrast phenomena.

A part of the study was done by a number of observers on two charts similar to plates (1,a) and (2,a) illuminated by natural daylight and using the Munsell Book of Color for comparison. In addition, the author made the same study on the 4 charts similar to plates (1) and (2) in different conditions. The other part was done by the author on these charts and on simple and compound patterns of one and two colour surrounds illuminated by standard source  $S_A$ , using a modified form of Donaldson colorimeter.

In the first part: (1) The observers passed the Ishihara test and hence can be considered as having normal colour vision. (2) The matching was done only when the sky was clear which gives roughly fairly constant illumination. (3) The angle of subtense of the whole pattern was  $42'$  giving big changes in colour appearance. (4) The observers were fairly consistent with themselves. (5) The corresponding shifts according to different observers, referred to the case of white surround, were roughly in the same general direction, but they varied amongst them in magnitude and direction. This shows that, although there is a general tendency among the observers to perceive a certain change in the appearance of any given test colour, as seen against any given background, yet they expressed this change differently. This may be partially due to experimental factors ((a) small changes in the quality and brightness of natural daylight and

(b) difficulty of matching among untrained observers), but mainly due to personal factors ( (a) different sensitivities of colour receptors, (b) different densities of macular pigment, (c) different retinal interaction, and (d) different psychological interpretation of colour appearance, among the observers). (6) The average shifts show in general, a subtractive effect of the stripe on which the test colour is mounted, and an additive effect of the two side stripes.

In the second part: The following effects were studied: (All the shifts were referred to the case of white surround).

(A) THE EFFECT OF DIFFERENT COLOUR SURROUNDS: The results showed the following:

(1) The shifts due to two colour surrounds are bigger than those due to one colour surround.

(2) The effect of one colour surround is in general, subtractive.

(3) In the case of two colour surround, the effect of the stripe on which the test colour is mounted is, in general, subtractive and that of the two side stripes is generally additive.

(4) The shifts due to black surround are generally towards desaturation.

These conclusions were shown for different cases graphically and analytically.

The Effect of the Compound Pattern:

(1) The shifts in the case of the compound pattern are generally bigger than those in the case of the simple pattern (except for the orange and green test colours).

(2) The test colour looks more desaturated in the case of the

compound pattern than in the case of the simple pattern (except in the case of the grey, where bigger shifts show themselves in higher saturation).

The Effect of Surround on the Apparent Brightness of the Test Colour.

(1) For one colour surround, the darker the background the lighter the test colour looks.

(2) For two colour surround, the test colour seems to follow the stripe on which it is mounted. The darker this stripe, the lighter the test colour appears.

(B) THE EFFECTS OF DIFFERENT VIEWING CONDITIONS: It was found that:

(a) Reducing the luminance of the surround of the comparison patch.

(b) Reducing the luminance of the whole test patch.

(c) Reducing the angle of subtense of the test patch.

(d) Reducing the inclination of the test patch.

produce the following general effects to different extents:

(1) The recorded differences in chromaticities of the appearance of the test colours due to different surrounds were enhanced.

(2) The set of points in the chromaticity chart corresponding to any test colour due to different surrounds were shifted in the same order showing two general trends: (a) change in hue away from the yellow, and (b) towards more saturation.

(3) Decrease in the lightness of the test colour.

At the same time (a) reducing the luminance of surround of the test colour (by using black instead of white surround); (1) produces shifts towards desaturation and (2) increases the lightness of the test colour. This result is not contradictory to the case (a) of reducing the luminance of the surround of the comparison patch. In case (a), the effects

measured are the attempt of the observer to compensate for the change in the appearance of the comparison patch caused by the change of the luminance of its surround, when matching the test colour. This means that the effects of the luminance of the surround on the comparison patch and the test colour are the same.

Also the (f) orientation of the stripes plays its role on the effect. The effect is more pronounced when the stripes are horizontal than when they are vertical. (g) Vibrating the charts up and down: enhances the effect when the stripes are horizontal (this may be mainly due to the increase of the additive effect of the side stripes). When the stripes are vertical no change was noticed (from the stationary case) at a long viewing distance, getting nearer, a critical distance was attained when almost no difference was seen in the appearance of the test colours in the two patterns, and for a shorter distance still, the difference in appearance between the two patterns were reversed. This may be due to the additive effect of the stripes on which the test colour is mounted, which is opposite to the original situation before vibration. The additive effect is enhanced as the viewing distance decreases where the angular amplitude of vibration becomes more than can be followed by the eye movements.

Different factors were suggested to explain these colour contrast phenomena (physical, physiological and psychological). These can be summarised as follows:

(1) The blurring of the image formed on the retina due to the physical defects of the eye (scattering and spherical and chromatic aberrations), causes additional mixture of the test and surround colours

due to partial overlapping.

(2) The continuous involuntary eye movements means that an area of the retina which at one moment receives light from the test colour, is at the next, stimulated by the surround causing successive contrast giving rise mainly to subtractive mixture, but also to pure addition due to persistence of vision. In general, the additive mixing process of the side stripes may be explained as due to the additive factor of the eye movements whose vertical component is reported to be higher than the horizontal.

(3) Through the physiological interaction between adjacent retinal areas, (mainly producing inhibition), the nervous impulses carried by the nerve fibres partially modulate each other, such that the final message received by the visual cortex is a modified reproduction of the retinal image.

(4) Psychologically the mental decoding of this message as a whole, affects the appearance of the test colour and may enhance its change. Perhaps the test colour is considered psychologically as a part of the stripe on which it is mounted, and the whole set is separated by the other stripes, and hence the contrasting effect of the former.

In the light of these possible factors which suggest both additive and subtractive mixing processes between the surround and the test colours, a simple mathematical analysis was done. It was assumed that the unit trichromatic equations representing the appearance of the test colour against its surround, and that of the test and surround colours as seen on a white background may be related by a linear function. In general, the mixing coefficients of this function for one colour surround was



found to be negative. In the case of two colour surround, the mixing coefficient of the stripe on which the test colour is mounted was negative and that of the two side stripes was positive.

A trial was done to find some way of predicting the appearance of any test colour as seen against any background. It was assumed that the relation between the mixing coefficients, on one hand, and the relative luminance and areas of the test and surround colours on the other, are linear. The normalised unit mixing coefficients in some of the cases increase with the increase of the distance between the test and surround colours in MacAdam uniform chromaticity chart, but no obvious relation could be drawn. This failure of this trial was not surprising, since all this procedure was an over-simplification to this complicated phenomena of colour contrast.

It is hoped that this introductory study of the simultaneous colour contrast phenomena may stimulate other people to investigate the phenomena from other different angles. This field is wide and fruitful. Its study may lead to a better understanding of colour perception and its physical, physiological and psychological phases and their interaction to produce the mental image of colours we actually see. Also it has its practical bearing in aesthetic, artistic and industrial uses of colour, since the background is everywhere and affects everything.

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