# FACTORS AFFECTING BRIGHTNESS AND COLOUR VISION UNDER WATER

by

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## ABSTRACT

Both theoretical and practical importance can be attached to attempts to model human threshold and supra-threshold visual performance under water. Previously, emphasis has been given to the integration of visual data from experiments conducted in air with data of the physical specification of the underwater light field. However, too few underwater studies have been undertaken for the validity of this approach to be assessed. The present research therefore was concerned with the acquisition of such data.

Four experiments were carried out: (a) to compare the predicted and obtained detection thresholds of achromatic targets, (b) to measure the relative recognition thresholds of coloured targets, (c) to compare the predicted and obtained supra-threshold appearance of coloured targets at various viewing distances and under different experimental instructions, (d) to compare the predicted and obtained detection thresholds for achromatic targets under realistic search conditions. Within each experiment, observers were tested on visual tasks in the field and in laboratory simulations. Physical specifications of targets and backgrounds were determined by photometry and spectroradiometry.

The data confirmed that: (a) erroneous predictions of the detection threshold could occur when the contributions of absorption and scattering to the attenuation of light were not differentiated, (b) the successful replication of previous findings for the relative recognition thresholds of colours depended on the brightness of the targets, (c) the perceived change in target colour with increasing viewing distance was less than that measured physically, implying the presence of a colour constancy mechanism other than chromatic adaptation and simultaneous colour contrast; the degree of colour constancy also varied with the type of target and experimental instructions, (d) the successful prediction of the effects of target-observer motion and target location uncertainty required more than simple numerical corrections to the basic detection threshold model. It was concluded that further progress in underwater visibility modelling is possible provided that the tendency to oversimplify human visual performance is suppressed.

# CONTENTS

## APPENDICES

LIST OF FIGURES, TABLES AND PLATES Page

CHAPTER 3

CHAPTER 4

TABLES

CHAPTER 5

FIGURES

CHAPTER 6

APPENDICES

"But, to determine more absolutely, what Light is, after what manner refracted, and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie".

Sir Isaac Newton (1730)

# CHAPTER ONE - PROLEGOMENA

The underlying aim of the experiments to be reported was to examine the possibility of predicting the human visual response to targets of varying brightness and colour from the physical specification of the target and the putative performance characteristics of the eyes. The desire to conduct the investigation in the underwater environment might appear rather unusual. However, the fact that water bodies are rarely spectrally neutral encourages the view that they can provide an ideal 'natural' laboratory for the study of colour vision. In addition, the increasing attention now being given to human underwater performance (for example Adolfson and Berghage, 1974) seems to merit the study of underwater vision in its own right.

Underwater research is not without its problems. Of particular concern are the practical limitations imposed by the operating environment. Godden (1975) has provided an illuminating account of the type of conditions under which many underwater scientists must work. The description dispels the myth that "diving is usually associated with wafting effortlessly through faerie grottos, while lunch driftspast in technicolour shoals (Godden, 1975, p. 423)". More realistically, the researcher can anticipate that most tasks will be at least an order of magnitude more difficult to perform than in the land based laboratory, even under optimal conditions. Equipment must be simple and robust. Experimental design must be planned judiciously around the safety of the divers and an increasing body. of government regulations. Finally, the researcher will require considerable powers of persuasion to encourage the assistance of colleagues for more than a handful of test sessions.

Within psychology, data obtained from field research does not yet appear wholly acceptable. As Ross (1974) has indicated, psychologists seem to suffer from a chronic doubt as to the type of research they should undertake, and the field tradition has never been strong, despite the efforts of Galton, Brunswik, Gibson and others. Most of the available data for human underwater vision are due to the researches of a small group of workers, who have also appreciated the potential importance of attempting to replicate the findings under land based laboratory conditions. In the present study, it was hoped to replicate in the laboratory as many as possible of the field experiments. If reliable, useful data could be obtained without the need to conduct all of the experiments in the field, a considerable saving of effort could be made in any future studies.

The dichotomy over field and laboratory research also embraces a more specific problem for the vision researcher, namely the appropriate level of explanation of the data. Clearly, the recognition of a coloured object, for example, can be described in terms of the activity at several sites along the visual pathway, or indeed, of cognitive mechanisms without reference to specific anatomical structures or physiological mechanisms. Vigorous debates over an appropriate paradigm for perception continue, and seem to be set to do so for some time to come. For present purposes the data from specific experiments will be discussed in terms of whichever approach appears to be most appropriate.

The first experimental section of the thesis (Chapter 3) examines the largely untested model of underwater visibility developed by Duntley and his colleagues at the Scripps Institute of Oceanography, California. As the model is based on hydrological optical theory, which may not be familiar to the non specialist reader, a detailed appendix has been given (Appendix A) in which some of the important concepts to be discussed in the main body of text are outlined. The second experimental section (Chapter 4) attempts to describe some of the likely difficulties that might be involved in the extension of the basic Duntley model to include the visibility of coloured targets. Chapter 5 is the most ambitious section of the study. It seeks to examine the possibility of predicting the supra-threshold appearance of coloured objects underwater at different distances. In the final section (Chapter 6), the current limits to visibility modelling are examined by reference to the problem of predicting the detection threshold of a dynamic observer or target.

Throughout the thesis, the background literature has been referred to frequently and sometimes in detail. This was because some of the most relevant papers are not easily accessible. It is hoped that the patience of the reader familiar with the less accessible research is not stretched to excess.

# CHAPTER TWO - A MODEL OF VISIBILITY BASED ON HYDROLOGICAL OPTICS

## 2.1. INTRODUCTION

### 2.1.1. Preliminary remarks.

The adequacy of a model of underwater visibility based on hydrological optics is determined by how accurately it can predict the visibility of various objects from the characteristics of both the water and the detector. The present discussion is an attempt to describe the characteristics outlined in the visibility model proposed by Duntley (1952).

In the past, the development of a visibility model has been impaired not so much by the conceptual difficulty of forming hypotheses as by the practical problems of testing them. It is not surprising, therefore, that theory has been inextricably linked with the state of technology. For brevity, however, comments on instrumentation will here be omitted where they do not contribute significantly to the argument. Jerlov (1976) has summarized recent advances in this field.

The discussion is in two parts. First, working from basic principles, an outline will be given of the radiative transfer model developed at the Scripps Institute of Oceanography. Because the radiance model contains mainly background information, it has been set out in an appendix (Appendix A). The second part of the discussion is a description of a visibility model developed from the radiance model, and is presented below. It is intended that the latter part of the discussion can be read independently of the former, if the reader is willing to accept the formulae given below without detailed explanation. In neither section are new formulae presented. Consequently derivations have been largely omitted.

To prevent the description from being too abstract, hypothetical values of some of the important hydrological optical parameters are given in Appendix A (Figure A.1) for turbid inshore coastal water (such as might be found around the British coast) and, where relevant, corresponding values for clear oceanic water. The figure is intended to show the approximate shapes of the relevant functions. The plethora of terms used to describe the concepts of underwater optics is a potential source of confusion. Consequently, definitions of the principal concepts are given, together with their units and symbols, in Appendix A (Table A.1).

### 2.1.2. The visibility model of S.Q. Duntley.

#### 2.1.2.1. Introduction.

Research on vision through the atmosphere, summarized in Middleton (1952), provides a strong theoretical background to the study of visibility under water. In both media, the most important determinant of visibility (to the human observer) is the visual contrast between an object at a given distance and its background. For each contrast level, there is an associated threshold, beneath which the object becomes invisible, although, as Blackwell (1946) showed, the threshold also varies with the shape and size of the object, together with the overall adaptive state of the observer.

The starting point for Duntley's model was the qualitative similarity between light transmission in the atmosphere and under water. On this basis it seemed reasonable to expect that contrast reduction would also take a similar form in the two media. In this context, Duntley's analysis of contrast reduction in the atmosphere can be regarded as seminal, even if, as Middleton (1952) pointed out, the equations were erroneously derived. It is interesting to note that some of Duntley's conclusions are similar to those of Le Grand (1939), who used alternative derivations of the fundamental equations. Le Grand's paper will not be discussed here, however.

2.1.2.2. Theory. Detailed expositions of the theory are given in Duntley (1952, 1963). The following description is based on the compendious statement published in 1962 (Duntley, 1962).

The visual contrast (C) was defined in terms of an object emitting a radiance L against a background $L_b$ :

$$C = \frac{L - L_b}{L_b} \quad . \tag{2.1}$$

If the object and background have radiances $L_0$ and $L_{b0}$ when observed at zero distance, and $L_r$ and $L_{br}$ at distance r, the inherent contrast $C_0$ and apparent physical contrast $C_r$ become :

$$C_0 = \frac{L_0 - L_{b0}}{L_{b0}} \tag{2.2}$$

$$C_r = \frac{L_r - L_{br}}{L_{br}} \tag{2.3}$$

Assuming that natural waters are composed of horizontal strata with uniform properties, the attenuation of the daylight radiance along a pathsight from a point $(z, \theta, \phi)$ is given by :

$$\frac{dL(z,\theta,\phi)}{dr} = -K(z,\theta,\phi)L(z,\theta,\phi) \cos \theta \ , \tag{2.4}$$

which assumes that $K(z,\theta,\phi)$ is constant for the path of sight. A detailed explanation of this equation is given in Appendix A.

For an object at depth $z_t$, at distance r from an observer at depth z, with path of sight $\theta$, (zenith) $\phi$, (azimuth), and where $z - z_t = r \cos \theta$, the equation for the transfer of field radiance can be applied to the apparent target radiance $L_t$ :

$$\frac{dL_t(z,\theta,\phi)}{dr} = -cL_t(z,\theta,\phi) + L^*(z,\theta,\phi) \quad . \tag{2.5}$$

Combining equations (2.4) and (2.5) with equation (A.26) in Appendix A and integrating throughout the path of sight gives the relation between the inherent radiance $L_{tO}$ and the apparent object radiance $L_{tr}$ :

$$L_{tr}(z,\theta,\phi) = L_{tO}(z_t,\theta,\phi)e^{-cr} + L(z_t,\theta,\phi)e^{-Kr\cos\theta} \cdot (1-e^{-cr + K\cos\theta}) \quad , \tag{2.6}$$

wherein the first term on the right represents the attenuation of image-forming light from the object, and the second indicates the gain by backscattering of ambient light throughout the path of sight. Replacement of the subscript $_t$ by $_b$ in equation (2.6) results in an analagous expression for the background:

$$L_{br}(z,\theta,\phi) = L_{bO}(z_b,\theta,\phi)e^{-cr} + L(z_b,\theta,\phi)e^{-Kr\cos\theta} \cdot (1-e^{-cr + K\cos\theta}) \quad . \tag{2.7}$$

Subtracting the apparent background radiance from the apparent target radiance gives the relation :

$$L_{tr}(z,\theta,\phi) - L_{br}(z,\theta,\phi) = [L_{tO}(z_t,\theta,\phi)-L_{bO}(z_t,\theta,\phi)]e^{-cr} , \tag{2.8}$$

which shows that the radiance differences between the target and background follow the attenuation law of a beam, because the relation $T_r = e^{-cr}$ is the beam transmittance along the path of sight.

Using equations (2.2) and (2.3) to define contrast, the ratio of apparent to inherent contrast is :

$$\frac{C_r(z,\theta,\phi)}{C_O(z_t,\theta,\phi)} = T_r(z,\theta,\phi)\frac{L_{bO}(z_t,\theta,\phi)}{L_{br}(z,\theta,\phi)} \qquad (2.9)$$

which holds true for non-uniform water and different levels of ambient light.

Two special cases are mentioned. First, for an object in deep water, $L(z_t,\theta,\phi) = L_{bO}(z_t,\theta,\phi)$, so that :

$$\frac{C_r(z,\theta,\phi)}{C_O(z_t,\theta,\phi)} = e^{-cr + K(z,\theta,\phi)r\cos\theta} . \qquad (2.10)$$

For horizontal paths of sight $\cos\theta = o$, and the equation reduces to :

$$\frac{C_r(z,\pi/2,\phi)}{C_O(z_t,\pi/2,\phi)} = e^{-cr} \qquad (2.11)$$

or, in its more usual form, as $z = z_t$ :

$$C_r = C_O\, e^{-cr} \qquad (2.12)$$

<u>2.1.2.3. Applications of the model</u>. Duntley (1960) has constructed a series of nomograms for the prediction of underwater visual ranges by substituting measured optical quantities into the foregoing equations. Theoretically, for an object differing in brightness from its background (the problem of colour is not considered), knowledge of the adaptation luminance, the inherent object contrast, and the total and diffuse attenuation coefficients enables the prediction of apparent

visual contrast at any distance. The size of the object is also relevant, but is rarely a limiting factor, due to the generally short viewing distances compared with the situation in air.

Duntley (1960) emphasized that the nomograms applied strictly to the case where the viewer was experienced in the underwater environment, acquainted with the object (but not specifically trained for the task), and had perfect vision. Further, the object was assumed to be at a known, fixed location, so that visual search and vigilance were not involved. At the same time, however, the general model was considered applicable to variations of the standard viewing situation through the use of alternative 'field factors'. No details were given as to how the original or modified field factors were calculated.

No method was given for the <u>in situ</u> determination of inherent contrast, although by definition a black target has an inherent contrast of -1. In good light, the contrast detection threshold for a diver with a facemask is usually taken as 0.02 (Le Grand, 1939; Lythgoe, 1971), so that for a horizontal viewing path the accurate measurement of c enables the prediction of the distance at which the apparent contrast between target and background is reduced to threshold.

Several rules of thumb have been formulated (Duntley, 1960). For a black target :

$$C_r = |-1|e^{-cr} = \frac{1}{e^{cr}} \quad . \tag{2.13}$$

Assuming that $C_r = 0.02$ :

$$0.02 = \frac{1}{e^{cr}} \quad , \qquad (2.14)$$

hence :

$$r = \frac{\log_e 50}{c} \quad , \qquad (2.15)$$

which implies that large dark objects can be seen at approximately the distance 4/c when viewed horizontally. Equation (2.13) makes it clear that for this model it is irrelevant whether the contrast is positive or negative. Secondly, most objects were expected to be sighted at four to five times the distance :

$$\frac{1}{(c(z) - K(z) \cos \theta)} \quad . \qquad (2.16)$$

Thirdly, for some natural waters :

$$c(z) = 2.3\ K(z) \qquad (2.17)$$

Finally, the downward visual range of most objects was estimated to be 0.875 of the horizontal range for large dark objects.

2.1.2.4. Conclusion. The semi-empirical approach to the underwater visibility problem presented in the foregoing discussion is both comprehensive and intuitively appealing. Furthermore, it readily lends itself to practical use - visibility can be determined simply by lowering appropriate instruments into the water. Such considerations do not guarantee the validity of the model, however. In the following chapters the model will be confronted with criticism of some of its assumptions and empirical tests of some of its predictions.

# CHAPTER THREE - BRIGHTNESS CONTRAST AND HORIZONTAL VISUAL RANGE - A TEST OF THE DUNTLEY MODEL

## 3.1. INTRODUCTION

### 3.1.1. The relationship between luminance contrast and brightness contrast.

In the first empirical test of the Duntley visibility model, Duntley, Tyler and Taylor (1959) confirmed the predicted log-linear relationship between apparent contrast and distance for a black target in the horizontal plane of a submerged photometer. The visual threshold of the target, calculated from the visual observations of a young, well trained observer, also agreed with the photometric data. The important conclusion from this study was that the value of contrast determined with a hydrophotometer could be used to predict apparent contrast along horizontal paths of sight.

A crucial assumption of the Duntley model was that measured photometric contrast is equivalent to the contrast perceived by the human eye. The methodology of Duntley et al. (1959), for example, was based on photometric techniques widely used in the investigation of the relationship between contrast reduction and viewing distance in the atmosphere (Löhle, 1929; Duntley, 1948.) The general view, expressed by Middleton, was that "the fundamental experiment to test the theory of the reduction of contrast by the atmosphere consists of the telephotometry ... of a number of similar screens at various distances, ... and also of the sky adjacent to them". (Middleton, 1952, p. 37).

Evidence from vision research, however, suggests that this assumption might be too simplistic, because it is well known that a change in the brightness of light imaged on one region of the retina can be caused by simultaneous illumination of other regions (Heinemann, 1972). Indeed, Heinemann referred specifically to the problem of relating the brightness difference between two areas to their luminance contrast. In the case where each field depresses the brightness of the other, it was concluded that "it is not possible to say how the brightness difference changed unless an assumption is made concerning the form of the relation between luminance and brightness" (Heinemann, 1972, p. 147).

Heinemann (1972) reported that several factors contribute to such an effect. First, the value of an inducing field luminance is of crucial importance for determining the brightness of a test field in a typical matching situation. Second, although contrast ratios can remain constant with changes of luminance, the appearance of contrast may change. Third, an increase in the area of the inducing field can lead to a reduction in the required matching luminance. Finally, the brightness of the centre of a relatively large test field can be altered by peripheral portions of the field.

Furthermore, spatial relations within the visual field are also involved in the brightness constancy theory of Gilchrist (1977). It was argued that perceived brightness depends on the luminance relations between surfaces perceived to lie in the same plane and not between surfaces that are merely adjacent on the retinal images. Although some of the formal aspects of Gilchrist's theory have been challenged (Frisby, 1979, p. 154), his experiments would seem to suggest that lareral inhibition might not be a fully adequate explanation of brightness constancy. The lateral inhibition interpretation, which was strongly suggested by Hartline's (1942) discovery that the presence of light on a receptor could decrease the response of a nearby receptor, has been thoroughly developed by Cornsweet (1970).

A further potential difficulty concerns the relationship between positive and negative contrast. A fundamental assumption of Blackwell (1946) was that for a given contrast level it was irrelevant whether the contrast was positive or negative (an exception was the case of large stimuli at low luminance levels). However, in their study of the visibility of objects from an underwater habitat, Kinney and Miller (1974) reported that targets of negative contrast were more visible than targets of equal contrast but opposite sign. Sexton, Malone and Farnsworth (1952), on the other hand, found that positive contrast was superior. Clearly, further research is merited.

A rather more fundamental reason why luminance might not correlate highly with the psychophysical dimension of brightness is the possibility that even without complications arising from spatial relations within the visual field, the V (λ) function, which is used to estimate brightness, contains inherent defects (Alman, 1977). For example, the suggestion that the CIE photopic luminosity values in the blue region of the spectrum were too low resulted in a proposed correction (the "Judd correction"). Graham (1965, p. 355) considered that the CIE luminosity curve for the Standard Observer "is a representational scheme that by no means represents all the data of cone luminosity", and that the shape and position of the function depended on factors such as stimulus size, retinal location (even within the fovea) and adaptation luminance. When the highly artificial conditions under which the CIE function was established are absent, a different function is obtained. In particular, under the normal viewing conditions of steady state brightness matching (rather than flicker type methods), addivity has been repeatedly shown to fail (Harrington, 1954; Kaiser, 1971; Guth and Graham, 1975). More recent evidence has confirmed that not all types of cone contribute to the luminosity function (Eisner and Macleod, 1980), that it is a poor predictor of perceived brightness when stimuli of different chromaticities are being compared (Booker, 1981), and that cortical colour channels also contribute to the brightness sensation (Bauer and Röhler, 1977). Finally, for mesopic or extra foveal vision, brightness perception may be influenced by the action of the rod system (Stabell and Stabell, 1973, 1975, 1976).

Of particular importance in contrast perception is the nature of the border between an object and its background (Lamar et al., 1947; Yund and Armington, 1975). Under appropriate conditions, paradoxical brightness sensations can be experienced that are not unequivocally correlated with luminance (Ripps and Weale, 1976). In addition to the well known Mach-band phenomenon (Ratliff, 1965), it has been demonstrated that even if two adjacent regions have the same luminance, perceived brightness can be altered by the presence of a luminance discontinuity along the border (the Craik-Cornsweet-O'Brien illusion). For this case also, the lateral inhibition explanation has been challenged (Van den Brink and Keemink, 1976). Indeed, Van Esen and Novak (1974) suggested that different visual functions are probably involved in the production of contrast within a central field and at its edge.

Because of its possible effects on contrast perception in the atmosphere, the research effort directed towards the problem of target edge blur merits special consideration. The phenomenon was well known to artists after Leonardo da Vinci (who gave it the name "sfumato") and employed to stimulate the viewer's projective faculty by making objects appear less visible. Barbaro, for example, a contemporary of Titian, spoke of "the soft disappearance of objects from our view, ... delighting those who do not understand it better and stunning those who do" (Barbaro, 1556, cited in Gombrich, 1977). It was also familiar to Gestalt psychologists, who demonstrated marked changes in contrast between adjacent colours whose borders were covered with tracing paper (Osgood, 1953, p. 234).

Blurring the image of an object by defocusing to a sufficient degree raises the threshold intensity necessary for detection (Enoch, 1958; Ogle, 1960, 1961a, 1961b; Hood, 1973; Rentschler and Arden, 1974; Fry and Somers, 1974) and decreases perceived brightness (Enoch, 1958). Similar changes occur for the detection threshold (Middleton, 1937; O'Brien, 1958; Thomas and Kovar, 1965) and perceived brightness (Thomas and Kovar, 1965; Thomas, 1966) if the edge is artificially blurred by the addition of light. Ogle (1961) further reported that the effect of blur is reduced as the stimulus size increases.

The visual consequences of target edge blur are commonly explained in terms of lateral inhibition, although specific models have favoured slightly different forms for the proposed network of neural interaction. Thomas and Kovar (1965), for example, favoured the Von Békésy model, whereas Hood and Whiteside (1968) supported that of Fry

(1948). More recently, it has also been proposed that different systems are involved in the detection of different degrees of edge blur (Rentschler and Arden, 1974). An additional effect has been reported that complicates these types of interpretation. Frome, Buck and Boynton (1981) found that the visibility of a border increased with an increase in overall luminance and suggested that at low levels of luminance there is less lateral inhibition. It was suggested that chromatic and luminance systems make independent contributions to the visibility of borders.

### 3.1.2. Visual Resolution in turbid media.

**3.1.2.1. Resolution in a foggy atmosphere.** If artists are correctly interpreting Nature in attempting to convince the beholder that distant objects produce blurred images when viewed through atmospheric haze, it would follow that in fog this effect should be greater and that even nearby objects might appear to have blurred edges. However, Middleton (1952) considered that such edge diffusion in either fog or haze - 'ground-glass plate effect' - was largely founded on popular belief. Contrary to the findings of Löhle (1929) and Bennett (1930), Middleton's own research and that of Fry, Bridgman and Ellerbrock (1947) supported the view that nearly all of the luminance changes between an object and a foggy background occurred exactly at their boundary. For example, Middleton (1937) found that the diffusion would need to be in the order of seven minutes of arc to produce a noticeable effect; whereas the actual diffusion experienced was likely to be in the order of less than one minute. Furthermore, Langstroth et al., (1947), Duntley (1948) and Barber (1950) reported equal resolution of photographs of distant objects in clear and hazy weather. In weighing the evidence, therefore, Middleton (1952) concluded that if a ground-glass plate effect existed, it was seldom of importance.

3.1.2.2. Resolution under water. The formulation of an underwater visibility model was considerably simplified by the assumption that Middleton's comments on edge diffusion in the atmosphere were also valid for the underwater situation. Nonetheless, Duntley (1963) pointed out a special case. Where a strongly lighted white object was observed against a dark background, the water immediately surrounding the object appeared to glow, due to intense small angle forward scattering of light reflected by the target in directions adjacent to the observer. In this case, there was a difference between the edge contrast and the absolute contrast. It was considered that normally few underwater objects would be white enough to produce a significant effect.Although most naturally occurring objects under water are not highly reflective, man-made equipment designed for underwater use is frequently highly reflective.

In more general terms, there are grounds for considering that attempts to minimise the differences between atmospheric and underwater visibility models are convenient but do not promote accuracy. In water, the minimum value of the total attenuation coefficient is larger than in air by a factor of 1000 or more (Luria and Kinney, 1970). In the atmosphere, also, the total attenuation coefficient is usually determined by the degree of scattering (an exception being industrial fogs). Under water the relative contributions of scattering and absorption can differ markedly, clear water often having a dominant absorption component and turbid water a dominant scattering component. Consequently, where attenuation is primarily caused by scattering, the presence of target edge blur is likely to result in a different visual range (the distance at which visual contrast falls to threshold level) for a highly reflective target than for the case where an identical total attenuation coefficient is obtained of which the main component is absorption. Of less significance, but nonetheless to be accounted for, is the fact that in the visual periphery, objects viewed under water become blurred irrespective of the scattering and absorption contributions. This is because oblique light rays striking the faceplate are refracted disproportionately more than those in the normal plane, producing a pincushion effect (a square appearing to be bowed inwards). In addition to being nearer, the optical location of peripheral points is imprecise, causing a blurred image (Ross, 1970). These considerations represent potential difficulties for the Duntley model, and in view of their likely importance to divers, it is unfortunate that the evaluation of optical resolution under water has largely neglected the human eye.

Duntley (1963) suggested that the principal cause of image degradation under water was light scattering at small forward angles. This is due to the presence of suspended particles such as transparent plankton which have a refractive index close to that of water, and scattering from refractive index variations in the water due to large scale thermal and saline variations (Yura, 1971). The thermal component, dominant at angles of less than half a degree, is considered to be of the order of a few hundredths to a few tenths of a degree Celcius, and to be additive with respect to the saline variations (Yura, 1971).

The consensus as to the cause of the phenomenon has not been accompanied by agreement about its effect. Laboratory studies have resulted in contradictory values for the range and frequency at which edge blur occurs. Mertens (1970) gave a value of one cycle/radian, whereas Duntley (1974) considered that under normal conditions 20 cycles/radian were necessary. The probable explanation for this discrepancy lies in the differences between experimental conditions (Lythgoe, 1979, p. 124). Thus, although Honey and Sorenson (1970) and Hodgson and Caldwell (1972) showed that turbulence can have considerable effects on the light field, it is unclear to what extent the studies have adequately reproduced the natural conditions under which turbulence occurs. For example, although Replogle and Steiner (1965) found evidence of optical degradation in 'natural' water, the experiment was undertaken at night when the water was thermally quiet. Similarly, in a series of carefully controlled laboratory experiments, Duntley (1974) found no significant degradation except when biological scatterers were present in abnormally high concentrations. However, this approach omits the effects of wind driven turbulence, which occurs under natural conditions and which stirs otherwise stratified density changes in the upper surface layers (Wells, 1973). Furthermore, Duntley photographed only black targets, which reflect little light and are therefore less likely to produce edge effects than highly reflective targets. Finally, it is by no means clear that the Fourier techniques used to interpret photographic data are valid, because thermal fluctuations have been found to call into question the basic assumption of linearity (Hodgson and Caldwell, 1972).

Even accepting that photographic experiments provide a valid estimate of image degradation, there remains the problem of how the information can be applied to human vision. Thus Lingrey (1968) reported that underwater resolution was 30 percent better for a television system than for a diver. Unfortunately, measurement of resolution in this experiment was insufficiently accurate to allow analysis of any edge degradation effect. In what appears to have been the only investigation directly concerned with diver vision, Muntz, Baddeley and Lythgoe (1974) measured modulation transfer functions of bar gratings under water and in air. However, the study was not specifically designed to investigate the edge degradation effect. Furthermore, the underwater transfer functions were obtained in a freshwater swimming pool, which cannot be considered to be optically equivalent to the marine environment.

### 3.1.3. An alternative approach to the visibility problem

3.1.3.1. Introduction. The Duntley visibility model uses the values of certain water parameters to determine apparent contrast as a function of viewing distance. An alternative approach is to treat the problem directly, by asking the viewer to determine contrast. Unfortunately, due to the practical problems of underwater research, this has not proved a popular avenue of investigation.

3.1.3.2. The Secchi disc. The direct approach has as its precedent the pioneering work of Secchi (Tyler, 1968). Briefly, a white circular disc is lowered vertically downward from above the water surface until it just disappears from view. The distance from the disc to the surface is then recorded. Tyler (1968) demonstrated that using Duntley's contrast reduction equation, the Secchi disc reading depended on the sum of the attenuation coefficients for collimated and diffuse light. From this, it followed that the determination of the latter component (for example with an irradiance meter) provided a measure of the former.

As an approximate guide to vertical visibility, the method is quite useful, particularly in view of its simplicity. As an alternative means of determining optical parameters of water it has the serious disadvantage that the value of the attenuation will vary with pathlength because of the water's selective absorption characteristics. In addition, it is difficult to ensure that the viewing conditions are sufficiently standardised. Estimates using this method therefore possess relatively large standard errors (Holmes, 1970). Due to the optical inhomogeneities frequently found in the vertical plane under water, such as thermoclines, errors are also possible in the prediction of horizontal visibility from Duntley's 'rule of thumb' that the downward visibility is approximately three quarters that of the horizontal visibility (Duntley, 1962).

3.1.3.3. Underwater visual estimates. In their experimental test of the Duntley model, Duntley et al. (1959) measured the visibility of a black target to an observer stationed in a viewing dome attached to a floating barge. The difficulty of interpreting data that exclude the assessment of highly reflective targets has been previously noted. Furthermore, the test was only conducted at a freshwater site. No precise data relating to the optical properties of the water were reported.

The only published data of diver estimates of brightness contrast appear to be those of Hemmings and Lythgoe (1965) and Lythgoe and Hemmings (1967). In both experiments a similar methodology was used. Grey tiles of different reflectance were attached at random orientation to a clear perspex board, suspended in midwater to provide an unobscured background. The divers approached the board along a tape measure extended perpendicularly to it and recorded the distance at which the orientation of each tile could be distinguished.

The method of data analysis in both studies is interesting because it allowed the Duntley model to be assessed. The reflectance in air of each tile was equated with the concept of object brightness. Consequently, by substituting these values into the contrast reduction equation, together with a blackbody estimate of the total attenuation coefficient and an estimate of the background brightness made from the reflectance of the nearest matching tile, it was possible to calculate the predicted visibility of each tile. Hemmings and Lythgoe (1965) found reasonable agreement between theory and data for tiles below about 30 percent reflectance. In the second experiment, however, using a wider range of greys, Lythgoe and Hemmings (1967) observed that for all targets whose reflectances exceeded 30 percent the measured visibility was less than predicted, and above about 60 percent reflectance all targets were approximately equally visible. It was also found that no tile could be camouflaged sufficiently to reduce its visibility to zero.

The results of the second experiment, which are incompatible with the Duntley model, have been discussed by Lythgoe (1971). In brief, it was suggested that the visual range of the more reflective tiles could be accounted for by edge blur caused by forward scattering at small angles. This suggestion is most interesting because the experiment was conducted in relatively clear water, which was unlikely to have exhibited the abnormally high concentrations of biological material considered by Duntley (1974) to be necessary for significant image blur to occur. The second result also merits attention because it implies that under some conditions luminance contrast differed from apparent brightness contrast. Lythgoe (1971) suggested that no tile could be perfectly camouflaged, because of the presence of slight imperfections on the tiles' surfaces and the glint of bright light reflected from their top edges. In addition, it was considered that the presence of a colour difference between the tile and its background would enable it to be detected through colour rather than brightness contrast. This is probably not a significant difficulty for the model at or near threshold for grey targets (Hemmings, 1966; Hemmings and Lythgoe, 1965), but might lead to incorrect predictions of brightness contrast for close viewing distances, where, for example, a white target might be expected to provide strong colour and brightness contrast with its background.

### 3.1.4. A proposed test of the model.

**3.1.4.1. Formulation of the hypothesis.** The preceding discussion highlights at least one potential limitation of the Duntley model. The single expression for the total attenuation coefficient in the contrast reduction equation contains two variables, namely the coefficients of scattering and absorption, that might affect vision in different ways. It was decided, therefore, to compare the visibilities of grey targets of different reflectances in water having a dominant scattering component with the visibilities of the same targets in water having a dominant absorption component. Specifically, it was considered that a high ratio of scattering to absorption would result in target edge blur and an increase in contrast threshold. It should be possible, therefore, for two different water bodies to have the same total attenuation coefficient but to result in different detection thresholds for a given target. In the laboratory, it is a relatively simple but time consuming task to produce the desired values for the two coefficients. For the complementary experiment in natural conditions, the water properties cannot be artificially manipulated, and a judicious choice of sites is required.

In the field experiment, it was also considered of interest to examine the relationship between luminance and brightness contrast. Lythgoe (1971) proposed that imperfections on target surfaces might prevent a grey target having an inherent contrast of zero. Such differences would not necessarily be detected by a photometer, which excludes the measurement of luminance at a target's edge. Furthermore, a single measurement (in this case of luminance), conveys the same amount of information as a single photopigment to a visual system, and is therefore unable to monitor colour contrast. The potential combination of these effects with the optical and psychophysical effects outlined in the previous sections made it impossible to predict the form of the relationship between the photometric and visual measurements.

3.1.4.2. A methodological consideration. In undertaking the proposed experiments the measurement of the total attenuation coefficient presents a significant practical problem. In principle the total attenuation coefficient of a water sample is best measured by calculating the attenuation of a collimated beam of light from a source over a given pathlength, a primary aim being the prevention of light scattering back into the beam. To measure the beam attenuation accurately, Williams (1970) considered that there were two minimum requirements. First, the meter must contain a filter to restrict the spectral responsiveness of the detector. If this was not done the selective absorption characteristics of water would produce an attenuation coefficient which varied with pathlength. Second, it was demonstrated mathematically that it was essential to have a dual beam unit, with identical optics in each beam and a very small ratio of beam width to beam length. The alternative solution, the standardisation of all meters, would almost certainly be impractical to achieve.

In view of these criticisms, it is surprising that the experimental validation of a meter incorporating both flaws has been reported (Briggs and Morris, 1966). One explanation of this result is that the effects discussed by Williams (1970) are sufficiently small to be of no practical significance. Jerlov (1976) considered that for ocean water, assuming that seven percent of the total scattering occurs in the interval zero to one degree, a typical instrument might produce an error of four percent for short wavelength light. This figure is highly unrealistic for coastal water, however; for oceanic surface water Jerlov himself gives a value of 22 percent (Jerlov, 1976, p. 40). Furthermore, this argument omits consideration of the problems of spectral changes with wavelength. It is also to be noted that although in the Briggs and Morris experiment there was a high correlation between visibility predicted from the meter and that predicted from a blackbody measurement, the latter was always less than the former, as Williams' argument would predict.

Perhaps the most surprising feature of this area of research is that Williams' ideas have not been closely examined. In a trenchant criticism of contemporary meter design, he concluded that "it appears that a beam transmittance meter of the conventional design, no matter what its dimensions, measures instrumental properties as much as it does the environment" (Williams, 1970, p. 104). Nonetheless meters continue to be constructed without regard to the possibility that he may be correct. At the present time, therefore, considerable caution should be applied in the interpretation of values for the total attenuation coefficient until it has been more clearly established exactly what is being measured. As a result of these difficulties, it was decided to use the blackbody method to estimate the total attenuation coefficient. The method is not without defects - for example, it provides no information about the wavelength dependency of the attenuation process, and relies on the visual detection threshold, which is itself an average value. Nonetheless, in a situation where both the attenuation meter and the blackbody estimate methods contain defects, the latter at least has the virtue of simplicity.

## 3.2. METHODS AND RESULTS

### 3.2.1. Experiment 3a - Laboratory study.

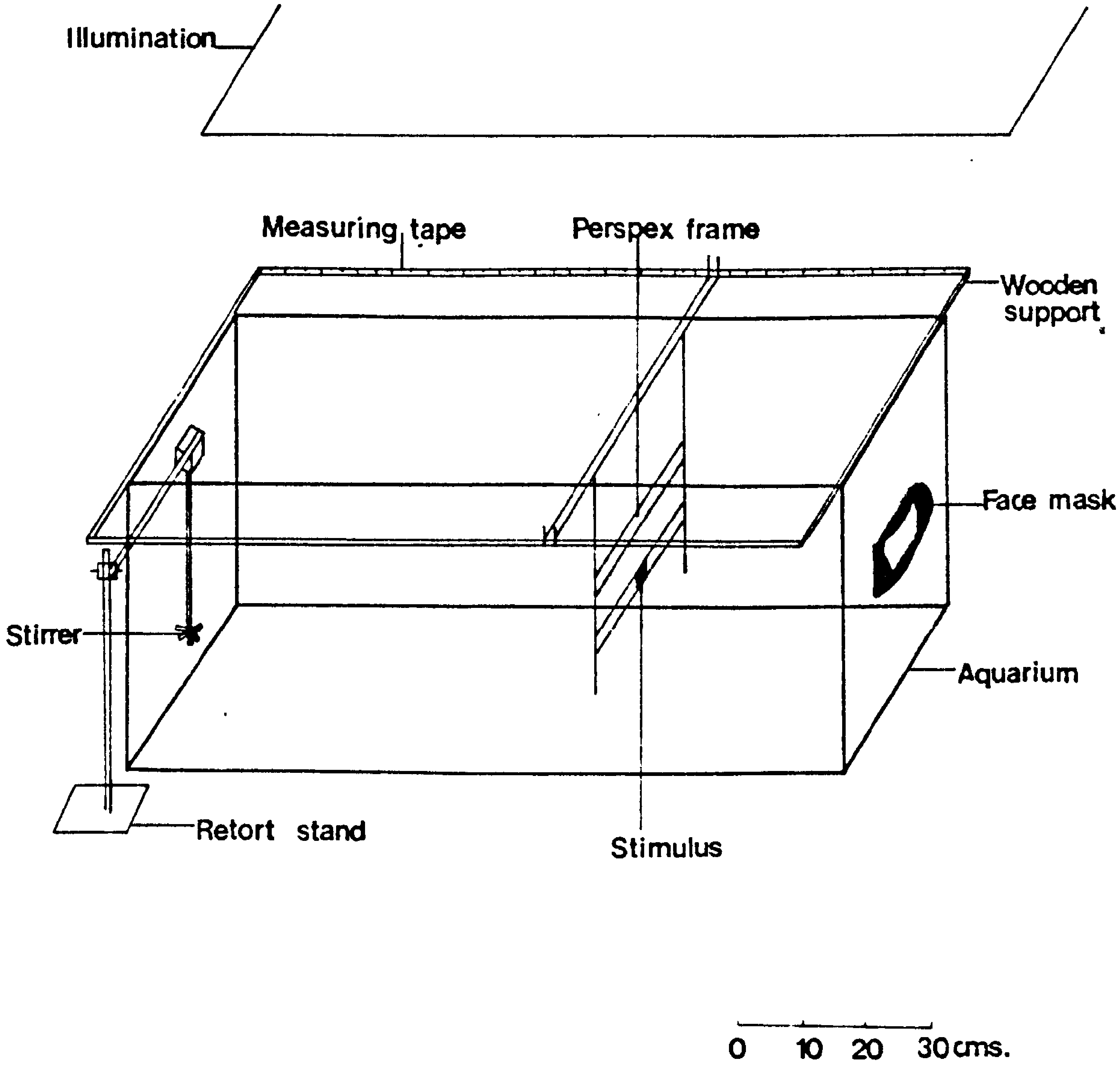
3.2.1.1. Observers. Nine unpaid volunteers, six males and three females, took part. Their age range was 23-28 years, with a mean of 25 years. All had normal or corrected visual acuity on the Snellen acuity chart and normal colour vision on the Ishihara Colour Test. They had all previously participated in psychophysical experiments.

3.2.1.2. Apparatus. The stimuli were nine grey aluminium tiles, each having a surface area of 6.45 sq. cm. The reflectance of each tile was determined by mixing matt black and white paint in different proportions. The reflectance data are given in Appendix B. The top edges of the tiles were bent at 120° to the vertical to allow them to be presented on a horizontal strut of a clear perspex frame (Figure 3.1.), which hung inside a clear perspex aquarium from a wooden support fixed to the aquarium's top. Two runners on the wooden support allowed the perspex frame to travel the length of the aquarium. A diving facemask (Scubapro Equinaso) was glued to one end of the aquarium, and the remaining outside surface area was covered with matte black card. A tape measure was attached to the wooden support to facilitate the measurement of the distance from the facemask to the stimulus. To reduce fogging of the facemask, the nosepiece was cut away, and the glass plate sprayed with an anti-mist liquid before each test session. To prevent changes in water turbidity due to the settling out of particulate matter, an electrically powered stirrer provided continuous agitation of the solutions which filled the aquarium.

Illumination was provided by 16 daylight fluorescent tubes (model No. T.L. 40W 55, Phillips Ltd), in four arrays of four tubes suspended 75 cm. above the aquarium. The tubes, each 125 cm. long, operated at a correlated colour temperature of 6250°K, with a colour rendering index of 0.94. Luminance was regulated with an XR regulator (Phillips Electrical Ltd) and manual (linear 10KΩ,10W) potentiometer. Luminance and illuminance inside the aquarium and at the water surface were monitored with a 40X Optometer (United Detector Technology). The blackbody in this and subsequent

Fig. 3.1. Apparatus for Experiment 3a.

The detection thresholds of various grey targets were established for observers viewing binocularly through the facemask by moving the perspex frame towards the observer until each target was just visible.



laboratory experiments was the inside of a small cylindrical tobacco tin, painted matte black.

3.2.1.3. Procedure. A repeated mesures design was employed, which involved each observer in three test sessions. In the first part (Condition I), the aquarium was filled with a solution of black ink (Quink) and tap water. The illuminance at the tank surface and the concentration of the solution were then adjusted until the blackbody distance for a pre-adapted observer (the Experimenter, E) viewing through the facemask was established at a distance approximately a quarter of the length of the aquarium away from the facemask. The background luminance and illuminance in the horizontal plane at the facemask were then measured and a water sample taken.

Following an adaptation period of five minutes, a modified method of limits was used to establish the visual ranges of the nine stimuli for each observer viewing binocularly through the facemask (to correspond with the method of Experiment 3b the ascending series was omitted). After ten practice trials, the observer was given ten test trials for each of the nine stimuli, in which the stimuli were presented singly, in random order, in a fixed position on the frame. On each trial, the frame was moved manually in increments of one centimetre along the wooden runners towards the observer, who was instructed to indicate verbally when the stimulus just appeared. Although the observers' adaptation levels were maintained as far as possible, rest periods were allowed at any time on request. These were followed by a further period of adaptation. Before each test session, which lasted approximately 75 minutes, the luminance in the aquarium was measured and a blackbody estimate made by E. No changes were reported during the experimental period.

In the second test session (Condition II), the aquarium was filled with a solution of Indian ink and tap water. The illuminance on the aquarium and concentration of the solution were then adjusted until the blackbody distance to E and the background luminance were as close as possible to the values in Condition I. The remainder of the procedure followed that described for Condition I.

In the final test session (Condition III), the Indian ink solution was used again. The illuminance on the aquarium and the concentration of the solution were then adjusted until the background luminance level and the visual range (for E) of the most reflective tile was equal to that for the same tile in Condition I. The procedure then followed that described for Condition I.

3.2.1.4. Results. The water samples were examined in a microscope, and were found to confirm that the Indian ink contained a higher proportion of particulate matter than the "Quink" ink. Photomicrographs of the solutions in Conditions I and II are shown in Plates 3(a) and (b). The solution in Condition II was not qualitatively different from that in Condition II and was therefore not photographed.

The mean visual ranges (in cm.) of the nine tiles for the nine observers in the three experimental conditions are presented, together with their standard deviations in Appendix C. The mean visual range for each stimulus is

Plates 3a and 3b. Water sample photomicrographs for Experiment 3a.

The photomicrographs (x400) are for the solutions used in Condition I (Plate 3a) and Condition II (Plate 3b). The plates confirm the predominance of absorption over scatter in Condition I, and of scatter over absorption in Condition II.

Plate 3a.

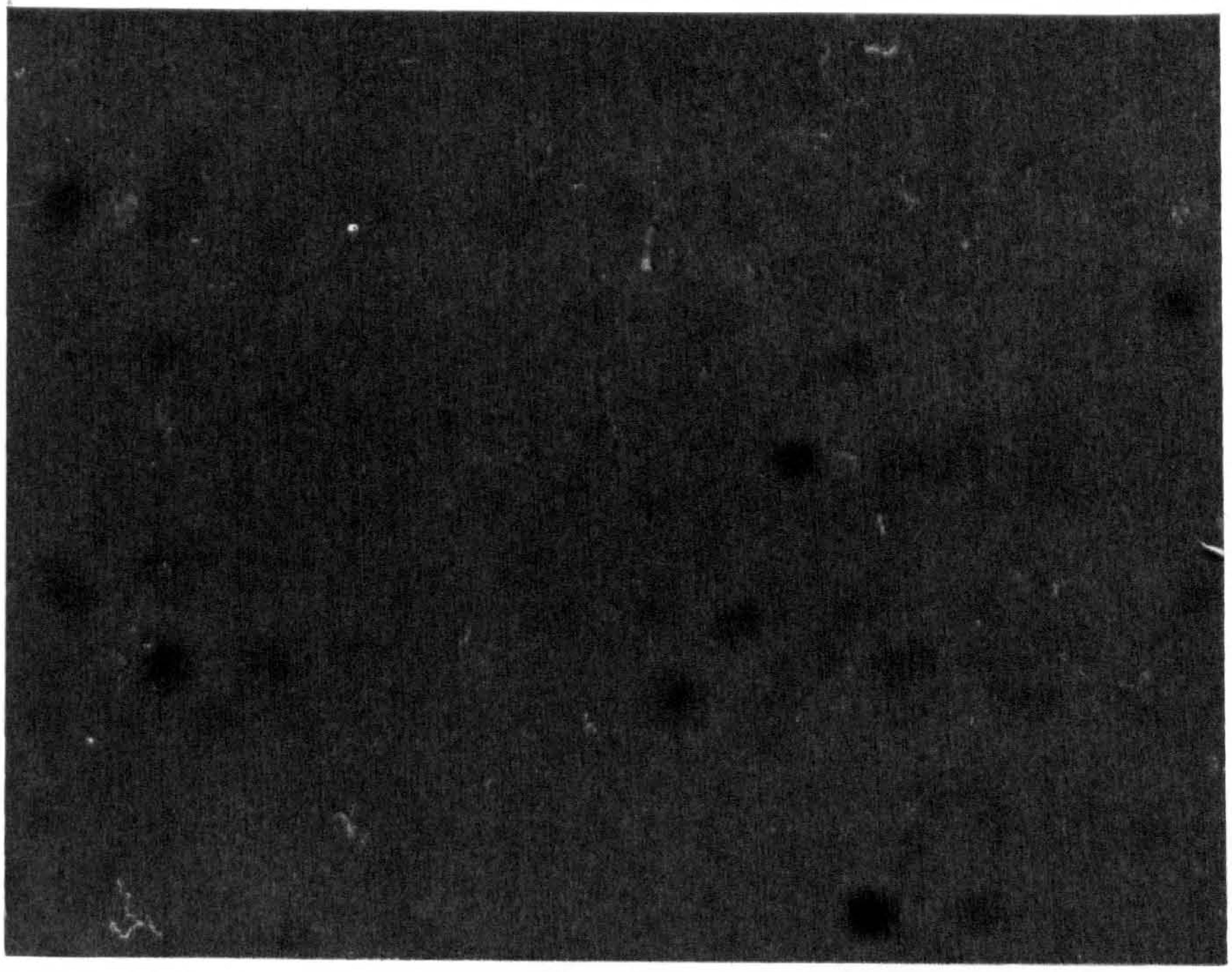
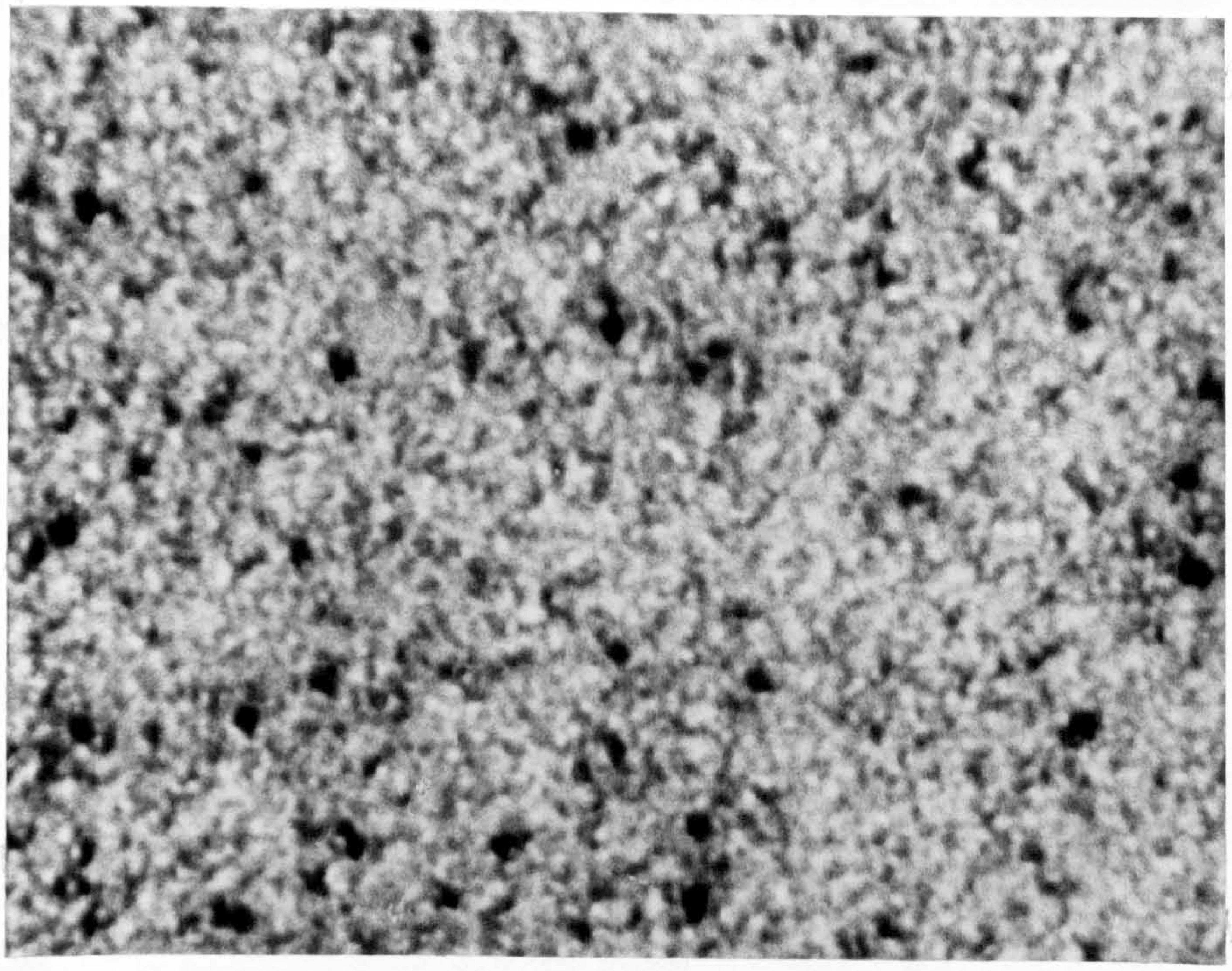


Plate 3b.



presented in Figure 3.2, as a function of stimulus reflectance in air. For clarity, standard deviations have been omitted. The figure confirms that for Conditions I and II the visual ranges for the least reflective tile are approximately equal. As reflectance increases, however, the stimuli are detected at increasingly discrepant distances in the two conditions. For Conditions I and III, on the other hand, there is first a region where the visual ranges decrease equally in the two conditions until, for tiles of low reflectance, they become increasingly discrepant.

In Figure 3.3 the data of Figure 3.2 are compared with those predicted from Duntley's theory. The latter values were calculated in the following way: the stimulus reflectance was taken as the object brightness, and the background reflectance assumed to be the reflectance of an object which would have a visual range of zero. From these data inherent contrast was calculated from equation 2.2. and, with the values of the total attenuation coefficient c and apparent contrast $C_r$, the visual range ($V_r$) was determined from the formula:

$$V_r = \frac{\log_e C_o - \log_e C_r}{c} \qquad (3.1)$$

where $C_o$ represents inherent contrast. In practice, because of the relatively small number of stimuli, it was not always clear from the data precisely which reflectance to select as being equivalent to the background, therefore maximum, minimum and intermediate values were computed.The figure shows that the predicted visual ranges are close to all the experimental values for the low scatter condition (I) and

Fig. 3.2. Visual ranges in the presence of low and high levels of light scatter (Experiment 3a).

The mean visual ranges (N=9) for each of nine grey tiles in Experiment 3a. The Conditions were : I - low scatter ( △ ), II - high scatter with blackbody distance equal to that in Condition I ( ▲ ), and III high scatter with the visual range of the most reflective tile equal to that for the same tile in Condition I ( ● ). The background adaptation luminance was 1.5 cd/m² in all three conditions.

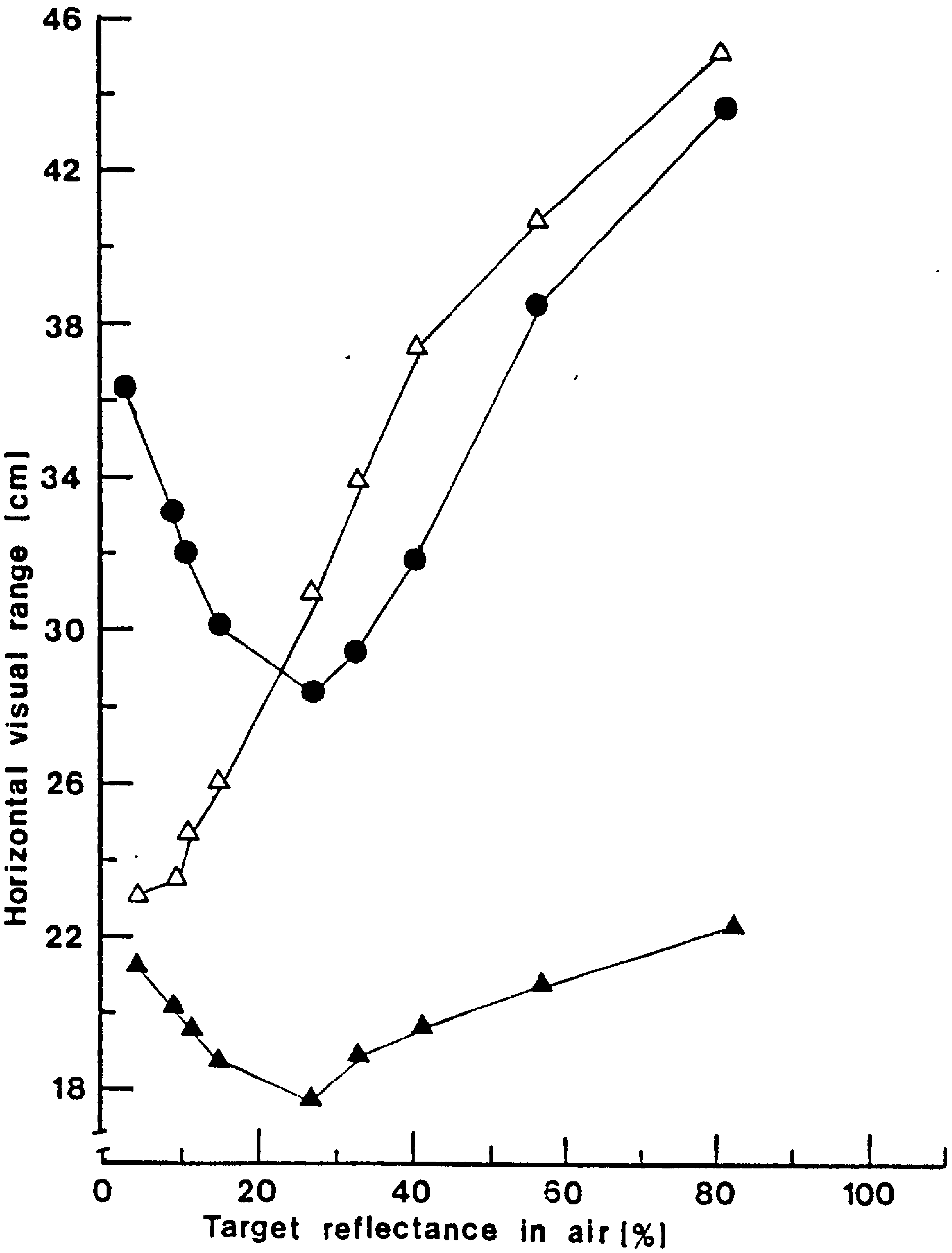


Fig. 3.3. Predicted and observed visual ranges with low and high levels of light scatter (Experiment 3a).

The mean (N=9) horizontal visual ranges (binocular viewing) of nine grey tiles ( ♦ ) in three types of water ( the low scatter and two high scatter conditions of Experiment 3a) have been replotted from Fig. 3.2 with values calculated from the Duntley visibility model (continuous line). The error bars indicate the probable lower and upper limits of the predicted values (details in text).


Condition I
low scatter
50
40
30
20
0
20
40
60
80
100
Condition II
high scatter
45
35
25
15
0
20
40
60
80
100
Horizontal visual range [cm]
Condition III
high scatter
55
45
35
25
0
20
40
60
80
100
Target reflectance in air [%]

the values for the stimuli of low reflectance (less than about 25 percent) in the high scatter conditions (II and III). For stimuli of higher reflectance, the predicted values are greater than the experimental values.

Analysis of Variance, summarized in Appendix D, performed on the experimentally obtained values revealed significant differences due to water type ($\underline{F} = 94.46$, $\underline{df} = 2/16$, $\underline{p} < .001$), and target brightness ($\underline{F} = 154.66$, $\underline{df}$ 8/64, $\underline{p} < .001$) and a significant interaction between target reflectance and experimental conditions ($\underline{F} = 35.11$, $\underline{df} = 16/128$, $\underline{p} < .001$).

### 3.2.2. Experiment 3b - Field study

3.2.2.1. Observers. Six trained and experienced[1] divers, five males and one female, volunteered for the experiment. Their age range was 23 - 33 years, with a mean of 25.3 years. Five observers had normal visual acuity on the Snellen chart. G.M. wore corrective lenses inside his facemask. All had normal colour vision on the Ishihara Colour Test except G.M., who was slightly deuteranomalous.

3.2.2.2. Apparatus. The stimuli were eight aluminium tiles, identical to those in Experiment 3a, but having a surface area of 300 sq. cm. They were suspended against an unobstructed background on the clear perspex cross-sections of a rigid free-standing aluminium frame (Figure 3.4.). The perspex cross-sections were enclosed within a rectangular frame, which was adjustable so that the stimuli could be

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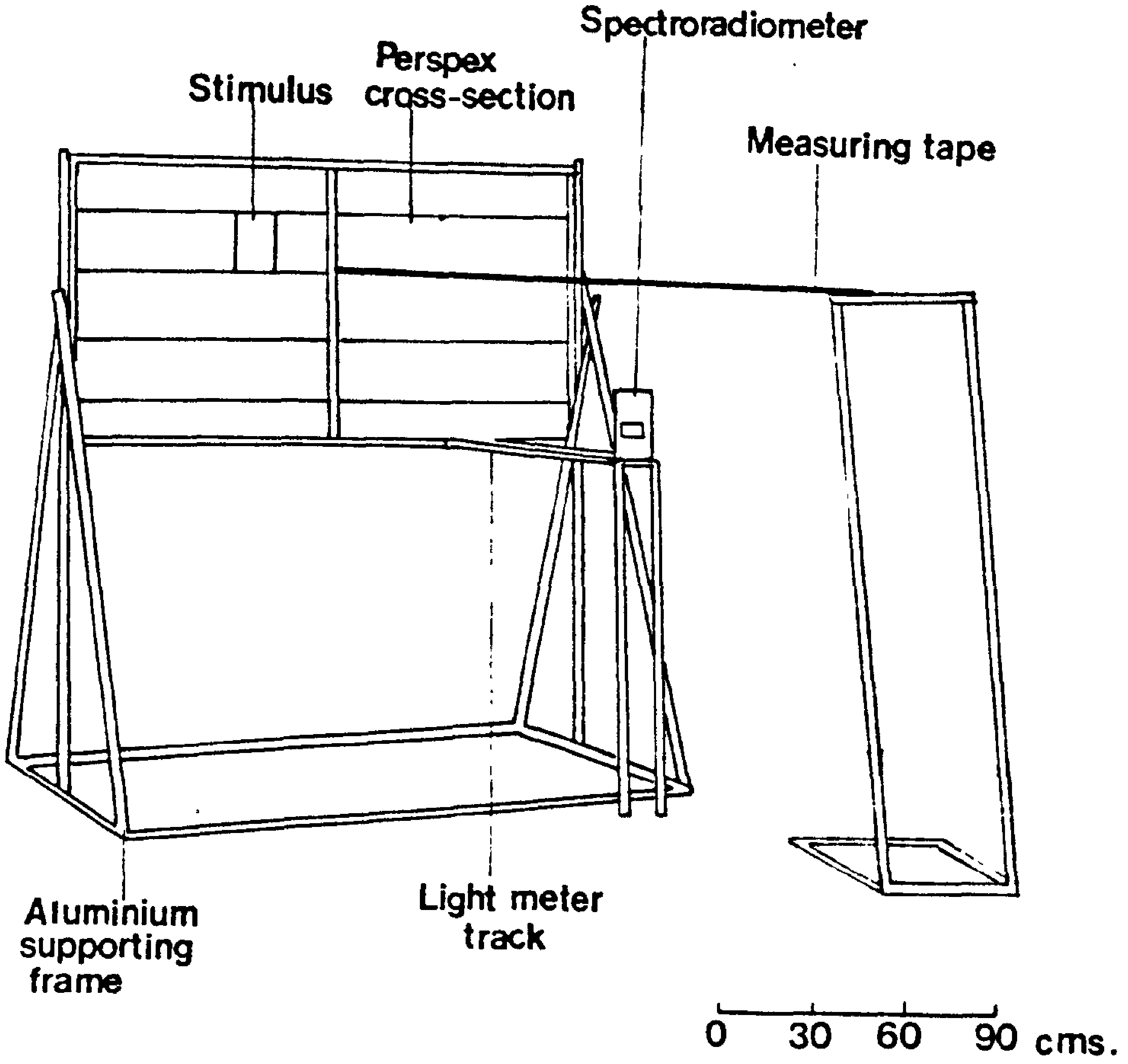
[1] 'Trained' and 'experienced' are relative terms. All of the divers in the present study were trained to a minimum of Third Class standard with the British Sub Aqua Club and had recorded a minimum of 50 dives.

Fig. 3.4. Aluminium frame for target presentation (field studies).

The upper section of the main frame was adjustable in the vertical plane, to suit the underwater conditions.



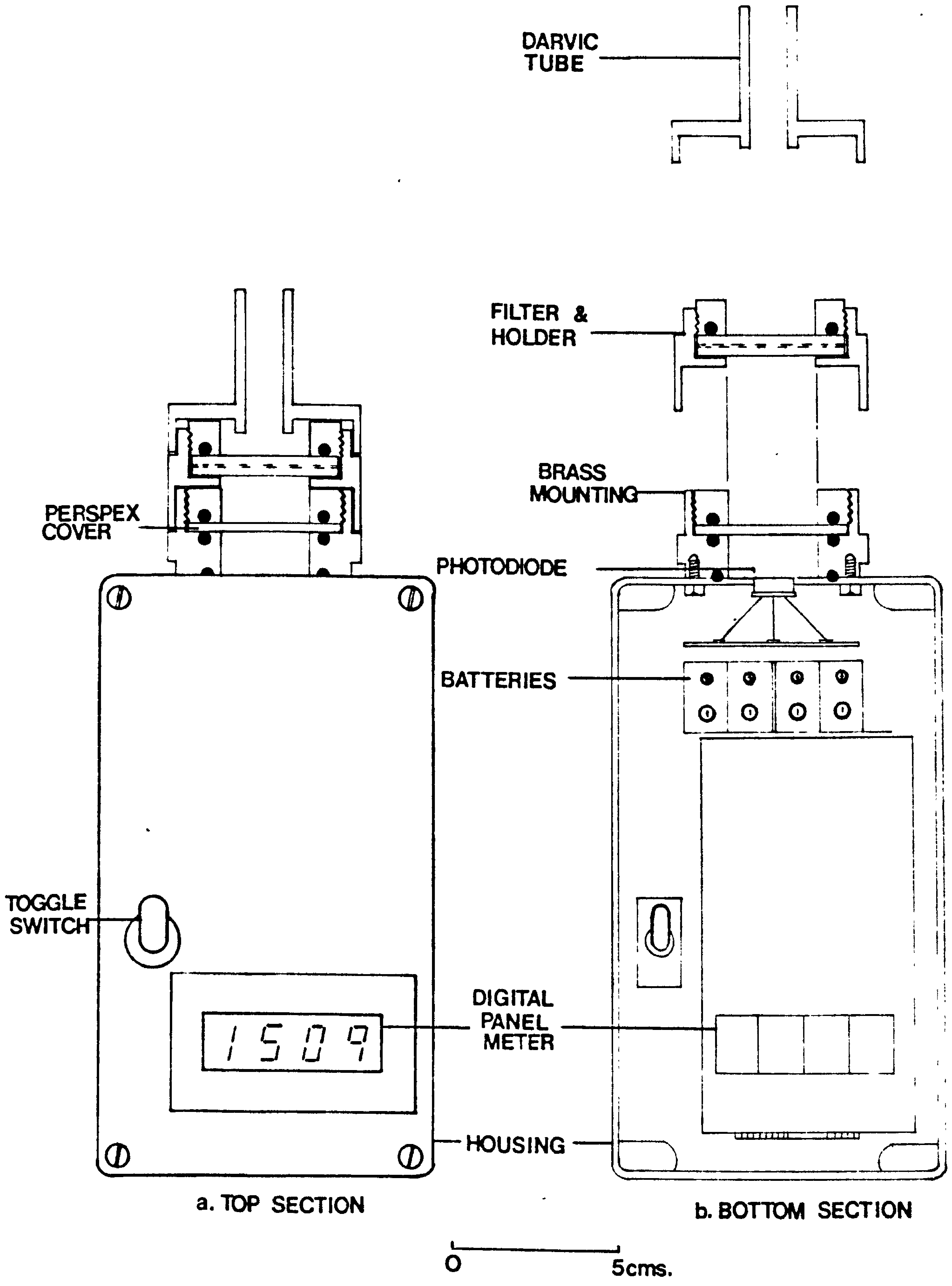
presented at various heights above the floor, to suit the underwater conditions. A short, rigid aluminium track, designed to accommodate a light meter (see over) extended in the plane normal to the centre of the front of the frame and facilitated the taking of light readings from a stable position. A surveyor's tape measure also extended in this plane from the centre of the frame to an aluminium stand of adjustable height. Two additional supports kept the tape measure horizontal. The entire system was readily portable, and could be assembled under water by two divers in about ten minutes.

Light readings were taken with an underwater photometer (Figure 3.5.), designed and built for the study. The housing was an aluminium diecast box (R.S. Components), modified for underwater use by replacement of the grommet inside the lid with a high quality 'O' ring seal. A brass mounting and a clear perspex cover sealed an aperture drilled into one end of the housing, into which was inserted a silicon photovoltaic photodiode (Rofin Ltd. type S.D. 290-12-12-041). A detachable wideband spectral filter (Barr and Stroud Ltd., type DB7) fitted onto the mounting. The acceptance angle of the meter (7.97° in air, 5.98° in water) was limited by a narrow Darvic tube, painted black on the inside, which attached to the filter.

The signals from the photodiode operating in logarithmic mode with its amplifier were displayed on a digital panel meter (Integrated Photomatrix Ltd) which was set into an aperture on the upper surface of the housing. The aperture was sealed with a perspex cover. The circuit diagram for the

Fig. 3.5. Diver operated underwater photometer.

Light passing through the Darvic tube fell on the photodiode. The resulting signals were amplified and displayed on the DPM.



a. TOP SECTION

b. BOTTOM SECTION

meter is given in Appendix E. The circuit was powered from four 1.25 V. batteries and operated via a waterproof toggle-switch (Sousmarine Diving and Engineering Ltd). A brass chain attached to the mounting allowed the meter to be fastened to a diving weight belt when not in use. The meter has been successfully tested to a pressure of four Bars (absolute).

Calibration was undertaken in the following manner: a tungsten bulb run from a stabilised power supply at a colour temperature of 2590° K provided illumination at 45° to a series of grey tiles of various reflectances. The luminance of each tile was measured in turn with a recently calibrated commercial photometer (a 40X Optometer) and by the underwater photometer. These values are plotted in the calibration curve (Appendix F), which confirms the log-linearity of the underwater meter. Repeat calibrations confirmed that the meter readings were stable (± one percent of the initial calibration). An external range switch was not fitted to the meter, because similar luminance levels were sought at each experimental site. Instead, resistors were added to or subtracted from the circuit. Clearly, if a wider range of readings was anticipated an external range switch would be preferable. The spectral response of the instrument was determined by integrating the spectral characteristics of the filter, photodiode and perspex, and is shown in Appendix G.

Due to the changes in reflectance at the various interfaces when the meter is immersed, compared with the situation in air, it was necessary to calculate a correction factor for the underwater readings. Theoretically, reflection is described by Fresnel's equation (Appendix A, equation A.1). Due to the angular distribution of light under water, it would be tedious to compute the reflection losses for the photometer by this method. However, reflection is invariant for angles up to about 20° (Williams, 1970, p. 34), and given the limited angle of acceptance of the meter a simplified form can be used for the reflection loss at each interface $n_1$, $n_2$:

$$p = \left[\frac{n_2 - n_1}{n_2 + n_1}\right]^2 \qquad (3.2)$$

where p is the reflectance and n is the refractive index. The correction factor calculated in this way was 1.1035.

3.2.2.3. Procedure. The experiment was conducted at the three sites detailed in Table 3.1. Conditions at the various sites necessitated slightly different arrangements for the apparatus. At Loch Turret, because of the bottom depth and steeply sloping sides, the experiment was carried out in mid-water. The aluminium frame was suspended from four ropes, five meters below a firmly anchored dinghy, and weighted to keep it vertical. The post to which the measuring tape was attached and the light meter frame were bouyed with life-jackets. A diver was stationed at the post to keep it aligned with the main frame. The lack of water movement at the site facilitated this task.

In Loch Airthrey and the Atlantic Ocean the frame was positioned on the bottom, and the height of the perspex cross-sections adjusted so that the stimuli were seen against an unobstructed background. Some stirring up of the bottom sediments is inevitable in such a procedure. Consequently,

## TABLE 3.1. Field sites for visual range studies (Experiment 3b)

| LOCATION | WATER TYPE | DATE | TIME | DEPTH (metres) | BOTTOM | SKY[1] |
|---|---|---|---|---|---|---|
| A. Loch Turret, Tayside, Scotland. | Turbid, peat stained freshwater. Relatively particle-free. | 6-6-79 | 11.15-13.30 | 5 | flat with heavy silt. | 0/8 |
| B. Loch Airthrey, Central Region, Scotland. | Turbid freshwater, highly particulate. | (a) 5-5-79<br>(b) 6-5-79 | 12.30-13.30<br>13.00-14.00 | 3.5<br>3.5 | flat, with heavy silt | 8/8<br>6/8 |
| C. Atlantic Ocean, harbour at Shirkin Island, Co. Cork, Eire. | Turbid inshore coastal, highly particulate. | (a) 19-7-79<br>(b) 20-7-79 | 12.00-13.30<br>12.15-13.45 | 4.5<br>4.5 | flat, sandy. | 8/8<br>8/8 |

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[1] The range is from 0/8 (no cloud) to 8/8 (totally overcast)

the frame was set down on the day prior to each experiment. At all three sites, the frame was positioned so that the stimuli were viewed down sun.

Prior to each test session, the background luminance in the horizontal plane of the frame was measured with the photometer. The blackbody distance was also measured. One diver was stationed at one end of the tape measure, while a second diver moved slowly away from him along the tape until the first diver was no longer visible. He then moved back towards the first diver, noting the distance at which the diver reappeared. The eight stimuli were then suspended, in random order, on a perspex cross-section of the frame. Having achieved neutral bouyancy, each observer moved slowly away from a position directly in front of the stimuli until none were visible. Then, touching the tape measure and keeping it level with his or her faceplate, the observer moved slowly forward until one of the stimuli was detected. The position of the stimulus on the frame (numbered from one to eight from left to right) and the observer's distance from the frame were then recorded on a small formica slate. The observer then moved further towards the frame until the next stimulus was detected, following the same procedure, and so on until all of the stimuli were visible. If an overshoot was made, the observer was allowed to move backwards and forwards until they were satisfied that the correct detection distance had been established. The positions of the stimuli on the frame were changed for each observer. The entire procedure was rehearsed by all six observers in a trial run of the experiment at Loch Airthrey.

When the last observer had completed the task, the photometer was used to measure the luminance of the stimuli. Each stimulus was placed in turn between two locating marks on the perspex cross-section, and the meter was moved along its guide rails to each of four predetermined distances (40, 30, 20 and 10 cm.) marked on the rails. The background luminance was also recorded. Finally, the blackbody measure was repeated.

3.2.2.4. Results. In Experiment 3a the values of the total attenuation coefficient and adaptation luminance were artificially equated in the three conditions, thereby enabling statistical comparison to be made between the three conditions. In the field tests (Experiment 3b) it was possible through exploration with the photometer to find approximately equal levels of adaptation luminance. To simultaneously equate the values of the total attenuation coefficient is a much more difficult task. Nonetheless, partly due to the 'floor effect' of working in turbid water and mainly due to chance, the total attenuation coefficients at the three sites turned out to be almost identical (see Appendix H).

The visual ranges of the eight stimuli for each observer (allowing for the location of the stimuli on the frame), together with the standard deviations and the blackbody distances, are given in Appendix H, for each site. The mean visual ranges (in metres) of the eight stimuli for the observers are shown in Figure 3.6, as a function of stimulus reflectance in air, together with the visual ranges predicted from Duntley's model. Two sets of predicted values were calculated. The first was computed as Experiment 3a. Comparison

Fig. 3.6. Predicted and observed visual ranges with low and high levels of light scatter (Experiment 3b).

The mean (N=4) horizontal visual ranges (binocular viewing) of eight grey tiles ( ♦ ) obtained in two test sessions at each of three sites have been plotted with the values calculated from the Duntley visibility model (continuous line). The error bars indicate the probable lower and upper limits of the values calculated from the model. The ranges predicted from the inherent contrast measured with the underwater photometer are also shown ( ◊ ). Adaptation luminances (AL) are given in photometric units. The dates of the test sessions were :

Loch Turret 1 : 5-6-79
2 : 5-6-79

Loch Airthrey 1 : 5-5-79
2 : 6-5-79

Atlantic Ocean 1 : 19-7-79
2 : 20-7-79

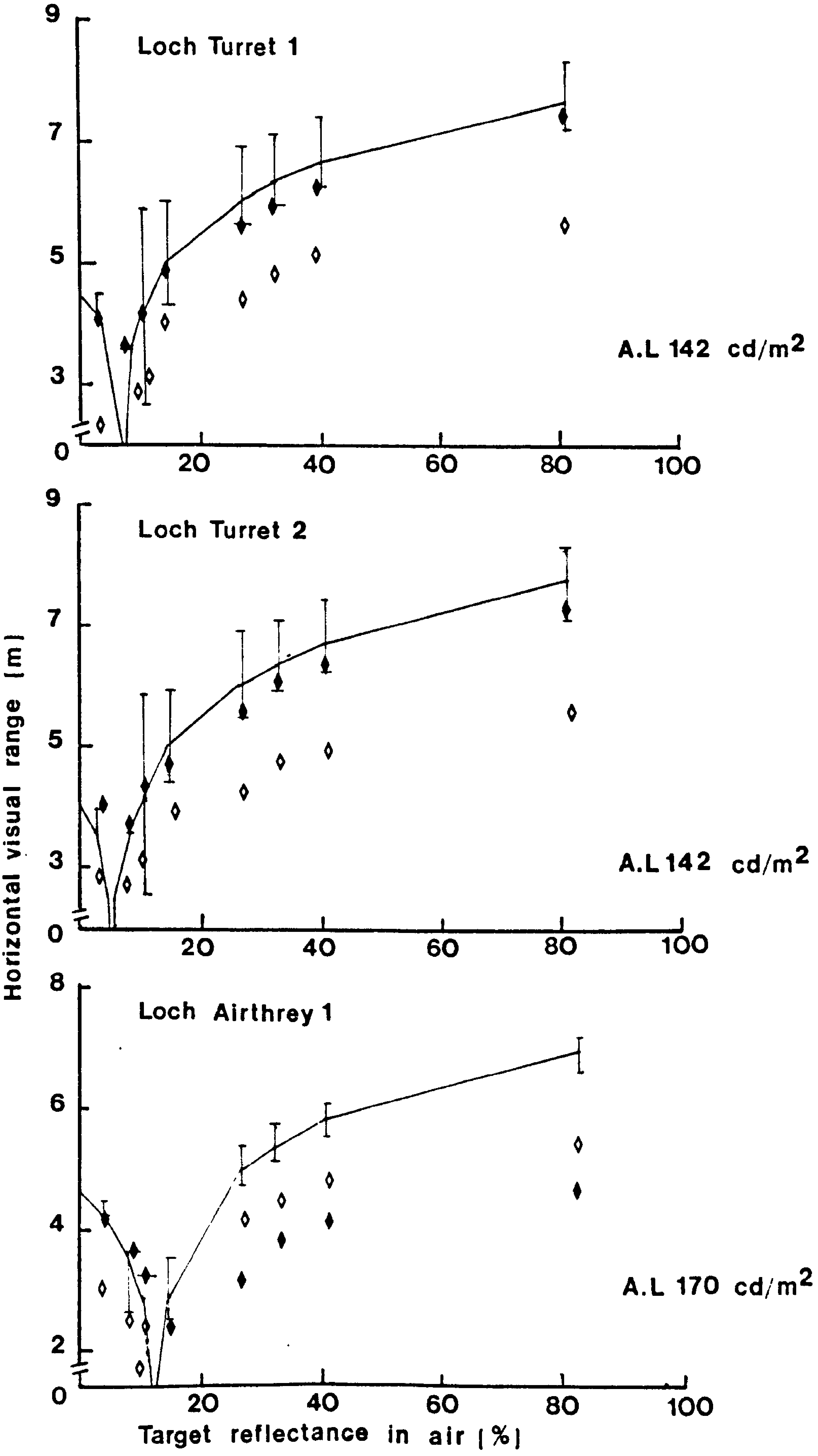
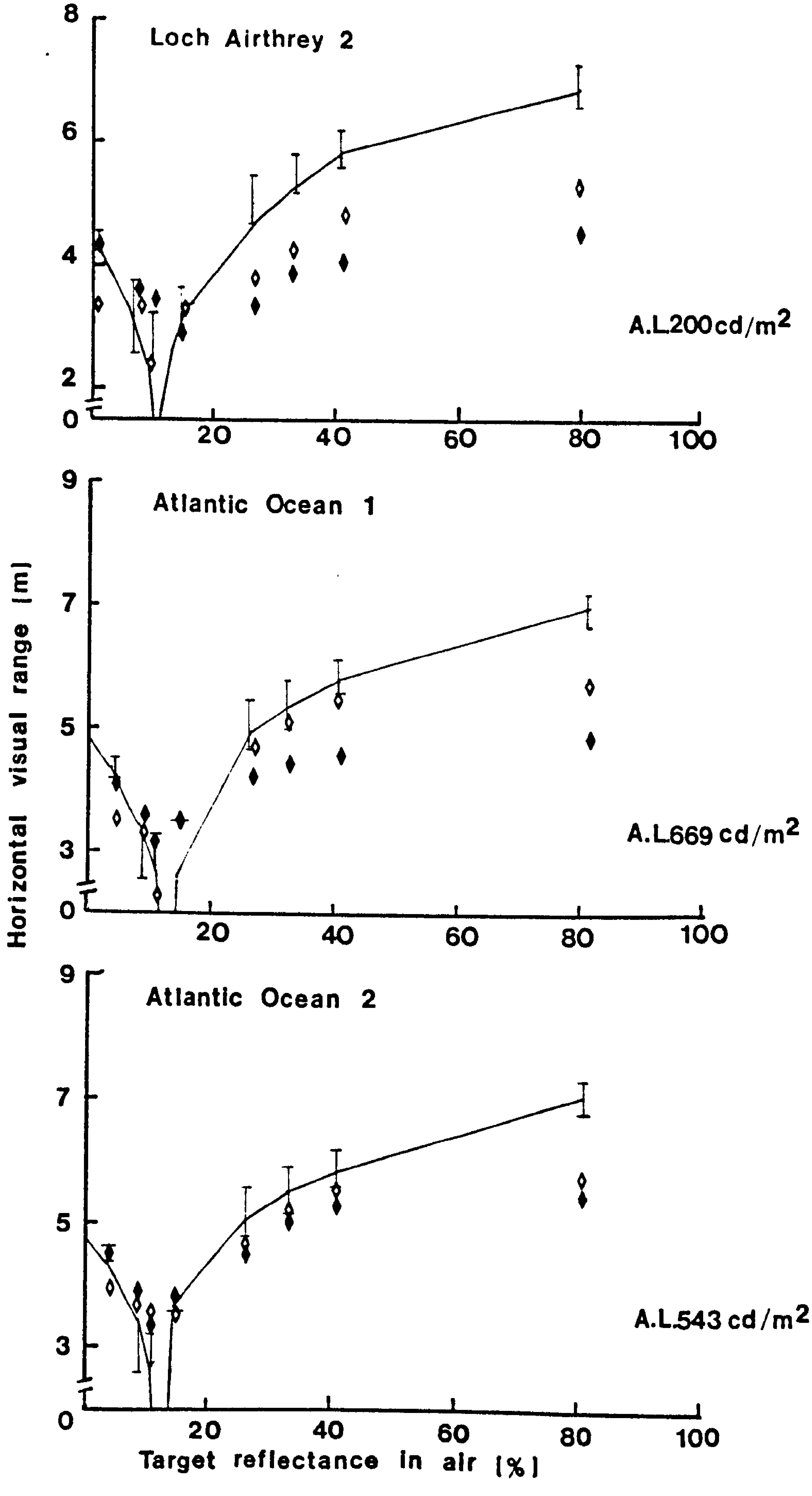

Loch Turret 1
A.L 142 cd/m2
Loch Turret 2
A.L 142 cd/m2
Loch Airthrey 1
A.L 170 cd/m2
Horizontal visual range (m)
Target reflectance in air (%)
0
3
5
7
9
2
4
6
8
20
40
60
80
100

Fig. 3.6. (continued).



with the observed visual ranges revealed that at Loch Turret there was quite close agreement with the predicted ranges in both test sessions. At the other sites, there was close agreement for the less reflective stimuli, but marked differences for the more reflective stimuli.

The second set of predicted values was calculated by substituting the inherent contrast measured by the photometer in the Duntley contrast reduction equation. The inherent photometric contrast of each stimulus was calculated by extrapolating from the photometric readings at the four measurement distances to 0cm. by linear regression. The raw data are given in Appendix I. In Table 3.2. is shown the inherent contrast for each stimulus at the sites, compared with that estimated from the observers' data. The visual contrast is generally greater than that measured by the photometer, and this difference is greater for stimuli of high reflectance. A sign test on the difference between the inherent photometric contrast and the visual contrast calculated on the assumption of a background reflectance midway between the extreme possible values revealed a significant difference ($\underline{L} = 6$, $\underline{T} = 40$, $\underline{p} < .01$). Comparison between the predicted and observed visual ranges (Figure 3.6) revealed that the predicted range in Loch Turret and the Atlantic Ocean was less than the obtained range, but greater than the obtained range in Loch Airthrey. The difference between predicted and obtained ranges at all three sites increased as the stimulus reflectance increased. A third comparison, between the predicted range calculated from the photometric

TABLE 3.2. Inherent photometric and visual contrasts of grey tiles in Experiment 3b. The inherent contrast with the water background in the horizontal plane at the depths given in Table 3.1 was calculated from photometric measurements and from the mean visual detection thresholds (N=4). For the latter, the range of possible values has been given.

| LOCATION | TYPE OF MEASUREMENT | INHERENT CONTRAST | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | TILE NO. | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Loch Turret 6-6-79 | Photometric | 2.28 | 1.56 | 1.14 | 0.83 | 0.59 | 0.25 | 0.11 | -0.12 |
| | Visual | 20.09/<br>7.93 | 9.50/<br>3.45 | 7.55/<br>2.62 | 6.14/<br>2.03 | 2.85/<br>0.63 | 1.79/<br>0.18 | 1.36/<br>0.00 | 0.00/<br>-0.58 |
| Loch Airthrey 5-5-79 | Photometric | 1.76 | 1.11 | 0.79 | 0.63 | 0.23 | -0.07 | -0.15 | -0.23 |
| | Visual | 6.57/<br>4.48 | 2.77/<br>1.73 | 2.07/<br>1.22 | 1.56/<br>0.85 | 0.38/<br>0.00 | 0.00/<br>-0.28 | -0.15/<br>-0.39 | -0.64/<br>-0.74 |
| Loch Airthrey 6-5-79 | Photometric | 1.52 | 0.96 | 0.64 | 0.43 | 0.29 | -0.14 | -0.30 | -0.31 |
| | Visual | 6.57/<br>4.48 | 2.77/<br>1.73 | 2.07/<br>1.22 | 1.56/<br>0.85 | 0.38/<br>0.00 | 0.00/<br>-0.28 | -0.15/<br>-0.39 | -0.64/<br>-0.74 |
| Atlantic Ocean 19-7-79 | Photometric | 2.14 | 1.67 | 1.26 | 0.88 | 0.38 | -0.14 | -0.32 | -0.35 |
| | Visual | 6.57/<br>4.48 | 2.77/<br>1.73 | 2.07/<br>1.22 | 1.56/<br>0.85 | 0.38/<br>0.00 | 0.00/<br>-0.28 | -0.15/<br>-0.39 | -0.64/<br>-0.74 |
| Atlantic Ocean 20-7-79 | Photometric | 1.88 | 1.65 | 1.29 | 0.84 | 0.35 | -0.36 | -0.38 | -0.46 |
| | Visual | 6.57/<br>4.48 | 2.77/<br>1.73 | 2.07/<br>1.22 | 1.56/<br>0.85 | 0.38/<br>0.00 | 0.00/<br>-0.28 | -0.15/<br>-0.39 | -0.64/<br>-0.74 |

data and from the experimentally obtained data, revealed (Figure 3.6) that the former was less in Loch Turret, but greater in Loch Airthrey. In the Atlantic Ocean the two sets of data were approximately equal on 20-7-79, but on 19-7-79 the photometric data predicted the greater visual range.

An Analysis of Variance, summarised in Appendix D, revealed a significant difference between the experimentally obtained visual ranges at the three sites ($F = 50.80$, $df = 2/2$. $p < .05$) and between stimuli ($F = 138.82$, $df = 7/7$, $p < .001$). The interaction between stimulus and site was also significant ($F = 9.74$, $df = 14/14$, $p < .001$). In performing this analysis, account was taken of the fact that not all of the observers took part in all of the trials by including missing values, using the BMDP2V Analysis of Variance computer program, and treating the experiment as a repeated measures design.

## 3.3 DISCUSSION

Taken together, the laboratory and field data confirm that modification of Duntley's contrast reduction equation is necessary if it is to successfully predict the visual range in different water types. The absence of a significant scattering component appeared to produce data that were in reasonable agreement with the predictions from the equation for all levels of stimulus reflectance, provided that the prediction was based on apparent visual contrast data. Where a strong scattering effect was present, on the other hand, the visual ranges of the more reflective stimuli were less than predicted from the visual contrast data. The photometric data led to the overestimation of visual range in high scatter conditions, and underestimation in low scatter conditions. In the present discussion, following comments about the form of the data, several factors related to the measurement of luminance that might have contributed to the differences between data and theory will be distinguished. Finally, some potential solutions to this problem will be suggested.

In Figures 3.3 and 3.6 the data from water types containing a high scattering component (Conditions II and III in Figure 3.3, and Sites B and C in Figure 3.6) are qualitatively similar to those of Lythgoe and Hemmings (1967), although the higher degree of water turbidity in the present experiments has resulted in a greater overall deviation from theory for the more reflective stimuli. In the Lythgoe and Hemmings experiment, for example, there was a ten percent error in the prediction of visual range from Duntley's equation for the most reflective stimulus, whereas in the present experiment, for a stimulus of similar reflectance, there was an average error of 35 percent at Site B (Loch Airthrey) and 25 percent at Site C (Atlantic Ocean). Similarly in the laboratory experiment, errors of 30 and 16 percent were obtained in Conditions II and III respectively.

An unexpected effect that occurred in the laboratory experiment merits attention. It would appear from Figure 3.2. that the background brightness was higher in the high scatter conditions (II and III) than in the low scatter condition. The subjective comments of several observers to this effect were not confirmed by photometric measurement. Instead, it was found that although the background luminance was equal in all three conditions, the illuminance was lower in Condition I than in Conditions II and III (Condition I = 0.032 lm/m$^2$, Condition II = 0.337 $lm/m^2$, Condition III = 0.183 $lm/m^2$). These data suggest a more complex distribution of light within the aquarium in the presence of a high scattering component. In the absence of detailed angular measures of the scattering function, attempts to explain the effect can only be speculative. Nonetheless, one might propose that light scattered at large angles close to the faceplate could have been accepted by the cosine collector but not by the six degree field of the luminance detector. It was unfortunate that illuminance data were not available for the field experiment, because they might have ruled out the possibility that the effect was specific to the laboratory viewing conditions. If correct, this explanation would suggest that in the presence of a sufficiently high degree of scattering, illuminance measurements would also need to be incorporated into the Duntley visibility model, and could perhaps be used as a basis for calculating the observers' adaptation level instead of luminance.

In attempting to explain the general finding, that the model does not appear to be fully accurate in the prediction of visibility in water with a high scattering component, the fact that there is close agreement between theory and data for the less reflective stimuli implies that it is unlikely that significant errors were made in the measurement of the total attenuation coefficient and inherent contrast, or in the estimation of the detection threshold. Furthermore, because environmental conditions were fairly stable during the experiments, the data were probably not significantly affected by changes in light intensity. In the laboratory the light level was carefully monitored, and in the field experiments the effects of light changes were minimised by conducting the experiment only when the sky was almost totally cloudless or totally overcast. Measurement of the background luminance before and after the visual range estimates confirmed that no significant changes occurred. It is also unlikely that the total attunuation coefficient changed markedly during the experimental period.

Because the blur was not measured directly the present data clearly cannot confirm that it was present in the high scatter conditions. Nonetheless, given that the scattering-absorption distinction is the only major difference between the experimental conditions, the most obvious hypothesis to account for the present data is that in the high scattering conditions an edge degradation effect existed, and that it led to a reduction in visual contrast and visual range, with the more reflective stimuli being most affected. The following discussion assumes that this hypothesis is indeed valid.

It is tempting to consider underlying physiological mechanisms that might be responsible for the raised detection threshold. Kulikowski and King-Smith (1973), for example, proposed separate detectors for lines, edges and gratings. For rectangular bars bigger that one degree of visual angle, the detection threshold was found to be determined by the response of the edge detection system,and blurring the target edge raised the detection threshold of such bars relative to bars with sharp edges. A similar finding was obtained by Fry (1948) and Rentschler and

Arden (1974). The relationship between psychophysical detectors and visual neurones is yet to be determined, but there are similarities (at least at threshold) between the sensitivities of line and edge detectors and the receptive fields of the 'simple' cortical cells responding to slits and edges found by Hubel and Wiesel (1962).

Alternatively, a less ambitious framework might usefully consider the present data for blurred stimuli as being determined by a reduction in the effects of an unspecified contrast detection system. Whereas this would imply the effect of lateral inhibition at the retinal level, it should also be noted that some luminance gradient effects have been considered to be partly the result of central processes at the level of attention (Van den Brink and Keemink, 1976). On this view, although retinal cells detect inhomogeneity of illumination, the decision as to whether or not brightnesses are equal takes place at the cortical level. Similar to the previous framework, the crucial factor is the brightness gradient across the target edge. As suggested by Rentschler and Arden (1974), also, it is likely that different detector mechanisms are involved in luminance discrimination above and below a specific degree of blur (0.7° for achromatic stimuli) - spatial summation being important above the blur threshold and edge detection below it. They proposed that if the gradient width covers more than the periphery of one receptive field, its detection will involve larger groups of neurones, which would complicate the discrimination task. Furthermore, they considered that a blurred border corresponds to a low-pass filtered luminance step function, and that the decreased contrast sensitivity could be predicted from the modulation transfer function of the human visual system, which suggests a drop in contrast sensitivity when the cut-off frequency is in the low frequency range of attenuation. Although the degree of blur in the present data was not determined, a gradient width of 0.7° does not seem unrealistic for highly turbid water. In addition, when chromatic effects are also involved, the threshold gradient width is essentially zero (Rentschler, 1973).

The suggestion of the presence of significant target edge blur differs from the situation in air, and casts doubt on the use of photometric and photographic techniques in predicting visibility for divers. In particular, it calls into question the suggestion by Duntley (1974) that in normal underwater conditions an edge degradation effect is not to be expected - the present data were collected in the types of turbid water that for some divers are quite normal. Furthermore, in Duntley's photographic studies (Duntley, 1974), target size was not considered, although Ross (1970) has pointed out that targets which subtend large visual angles should have blurred adges in any type of water. This effect was omitted from the Duntley nomograms (Duntley, 1960).

The visual ranges obtained in the present experiments imply that the presence of edge blur reduces vusual contrast relative to luminance contrast, partly because luminance is typically measured from the centre of a target, rather than at its edge. The photometric data further imply that even without edge blur, luminance contrast might be an inappropriate term to introduce into visibility calculations. Although Figure 3.6 confirms that in the high scatter conditions the experimentally obtained visual ranges were less than predicted for the more reflective stimuli, as would be expected if an edge degradation effect was present, the obtained ranges were greater than predicted for the stimuli of low reflectance (less than 20 percent). If this was due to the differences between the inherent visual and photometric contrast (Table 3.2), it would not be possible to ascribe the effect to target edge degradation. The same result can be deduced from the data for the low scatter condition, which show that the experimentally obtained visual ranges were greater than predicted.

Two classes of effects might be considered responsible for the observed differences between photmetric and apparent visual contrast. First, one might consider the potential effects of the induction factors noted in section 3.1.1. For example, a typically homogeneous adaptation field under water might be expected to affect the stimulus brightness (Diamond, 1953), as might the wide range of luminances that a diver is likely to experience at different depths. Similarly, perceived brightness might be influenced by attentional factors and the apparent spatial position of the target (Gilchrist, 1977). Again, Lythgoe (1971) has suggested that target imperfections might selectively reduce visual contrast. One possible explanation for this type of effect might be that the textural elements act like small contours, impairing the 'filling-in' process across the stimulus (Coren and Brussel, 1973). Finally, it is possible that contrasts of equal magnitude but opposite polarity are not of equal visual significance. Unfortunately, it is difficult to specify the precise significance of such effects without controlled experimentation.

The second class of effect is perhaps less ambiguous. In constructing the visibility model, Duntley specifically excluded the problem of colour contrast. For targets at or near threshold this would appear justified. By defining inherent contrast only in terms of luminance, however, erroneous values for apparent contrast at threshold can result if colour is not accounted for. This problem is highlighted by the reported breakdown of the correlation between luminance and brightness for stumuli of different chromaticities (Booker, 1981). In fact, it is difficult to imagine a naturally occurring water body that is spectrally neutral. Table 3.2 shows that the discrepancy between inherent photometric contrast and apparent visual contrast was greatest at the low scatter site (A), which also subjectively contained the most noticeable chromatic component (due to peat staining). Because the luminance data are extrapolated from a number of distances, the inherent photometric contrast values are not directly measured. However, the high correlations of the data points suggest that any errors of measurement are insignificantly small. The data therefore suggest that colour contrast is a relevant factor, although its exact role in the determination of visual contrast is likely to be made more complicated by the fact that at low luminance levels, the presence of a chromatic difference produces a border for which the visibility is greater than that for a luminance difference only (Frome, Buck and Boynton, 1981). Duntley (1960) was unable to recommend a method for the determination of inherent contrast of any target other than a black one. The present data suggest that the measurement of luminance contrast by itself is not a suitable starting point.

Although the major effects of edge blur and colour contrast present potential difficulties for the Duntley model, neither set of problems is insurmountable. If absorption and scatter could be measured separately (for example, using the technique of Bauer at al. (1971, cited in Jerlov, 1976), the problem of edge blur might be approached by replacing the single attenuation coefficient in the contrast reduction equation with separate terms for scattering and absorption, and relating the equation to empirically determined values of visual range by divers. This implies a fundamentally different approach to the visibility problem - namely starting from the visual data and working back to see how the optical properties of the water can be related to them. Such an approach would also be useful, through analysis of individual differences, in the determination of the limits of the variation in visual range in the sample population - the data from the single observer in the Duntley study (Duntley et al., 1959) being inadequate for this task. The standard deviations obtained for the observers in the present experiments are low enough to suggest that visual data could have predictive value, although further research is necessary to confirm this.

The problem of the determination of inherent contrast is also potentially soluble. One method was suggested by Williams (1970, p. 68). In brief, he recommended that the tristimulus values of both object and background could be treated in terms of separate contrast equations. In the case of a white target and a green background, for example, the maximum response from the target would be used with the response from the background through the same filter. This suggestion can be extended to include the comparison of such data with visual estimates of contrast. A similar approach has been recommended (for example, by Alman, 1977) for the improvement of the $V (\lambda)$ function. It was proposed that the luminance measurement be made from three filter-corrected photodetectors proportional to the CIE $\bar{x}$, $\bar{z}$, and updated $\bar{y}$ functions, using a single transformation equation for brightness. Even so, attention would need to be given to the analysis of the additional problems of simultaneous contrast and, where strong chromatic effects were present, of chromatic adaptation.

When considering visibility in a wider sense, some attention must be given to the question of the practical as well as the theoretical limits of a particular model. Unless an inherent contrast meter can be remotely operated from the surface, one can question the value of a system for predicting diver visibility that requires the diver to submerge to determine water parameters. One possibility would be to advance the design of the contrast meter reported by Patterson and Heemstra (1975) to incorporate spectral measurements from a range of targets, using a microprocessor system such as that described by Austin and Ensminger (1978) to control data collection and storage.

The fact that previous laboratory experiments have been criticised for failing to replicate natural viewing conditions (section 3.1.2.2.) required caution to be applied in the interpretation of the data from Experiment 3a - it was unlikely, for example, that in the laboratory there was adequate simulation of turbulence. That the visibility functions are similar in Experiments 3a and 3b encourages the view that, to the human eye at least, the edge degradation effect is robust. However, even under the most favourable conditions, laboratory data should not be regarded as a substitute for field data. In addition to the need to establish the optical differences between laboratory and field conditions, more data are required concerning the general effects of the underwater environment on human performance. If these differences can be clearly delineated, then the laboratory data might be regarded (at best) as complementary to the field data.

The present experiments relate to the somewhat idealised case of an experienced diver viewing stimuli in a known location. It has been suggested that under these conditions it might be possible to reduce the defects of the Duntley visibility model to the point where it can have predictive value. The logical extension of these experiments is to investigate how the visibility nomograms might be used in more realistic situations, such as when target location is unspecified or when highly chromatic stimuli are used. It will be the purpose of Chapters 4 and 6 to investigate these more realistic situations.

# CHAPTER FOUR - COLOUR RECOGNITION THRESHOLD AND THE ROLE OF BRIGHTNESS

## 4.1 INTRODUCTION

### 4.1.1. Preliminary remarks

The aim of the experiments to be reported in the present and following chapter was to attempt to clarify some of the ambiguity embedded within the literature on human underwater colour vision. The following sections (which relate to both chapters) describe the nature of the spectral distribution of light in water, and discuss the theoretical issues involved in the response of the human visual system to it. In the present chapter, the ambiguity attached to the concept of a colour recognition threshold will be investigated. Chapter 5 will be concerned with the detailed investigation of the physical and perceptual specification of supra-threshold colours. Strictly, colour is a sensation rather than a physical concept. Nevertheless, the distinction between perceived colour and colour measured physically is fairly common, and will be used throughout the present discussion.

A general review of the human colour vision literature is clearly beyond the scope of the present thesis. Consequently, attention will be focused on that part of the literature which relates to underwater viewing conditions. Because many aspects of colour vision theory can be related to the present work, a brief summary of the current status of the most relevant issues has been given in Appendix J.

### 4.1.2. The spectral distribution of light under water.

Although a complete theory was unavailable until 1923 (Shuleikin, 1923), an explanation for the spectral distribution of light under water had been the subject of speculation since at least 1847 (Bunsen, 1847, cited in Jerlov, 1976) and of physical measurement since 1912 (Tyler, 1964). In the absence of other agents, the observed blueness to the human eye (Hulbert, 1945; Tyler, 1965) is an intrinsic property of the water, caused by Rayleigh scattering of the water molecules and the spectral absorption of distilled water. In the presence of dissolved and suspended substances, the water can appear almost any colour of the spectrum. The chlorophyll content of phytoplankton, for example, coupled with the products of vegetable decay, act as an additional selective filter so that the maximum band of light transmission lies in the green-yellow region (Kalle, 1966). Water originating from acidic moorland or peat bogs, on the other hand, often appears reddish-brown.

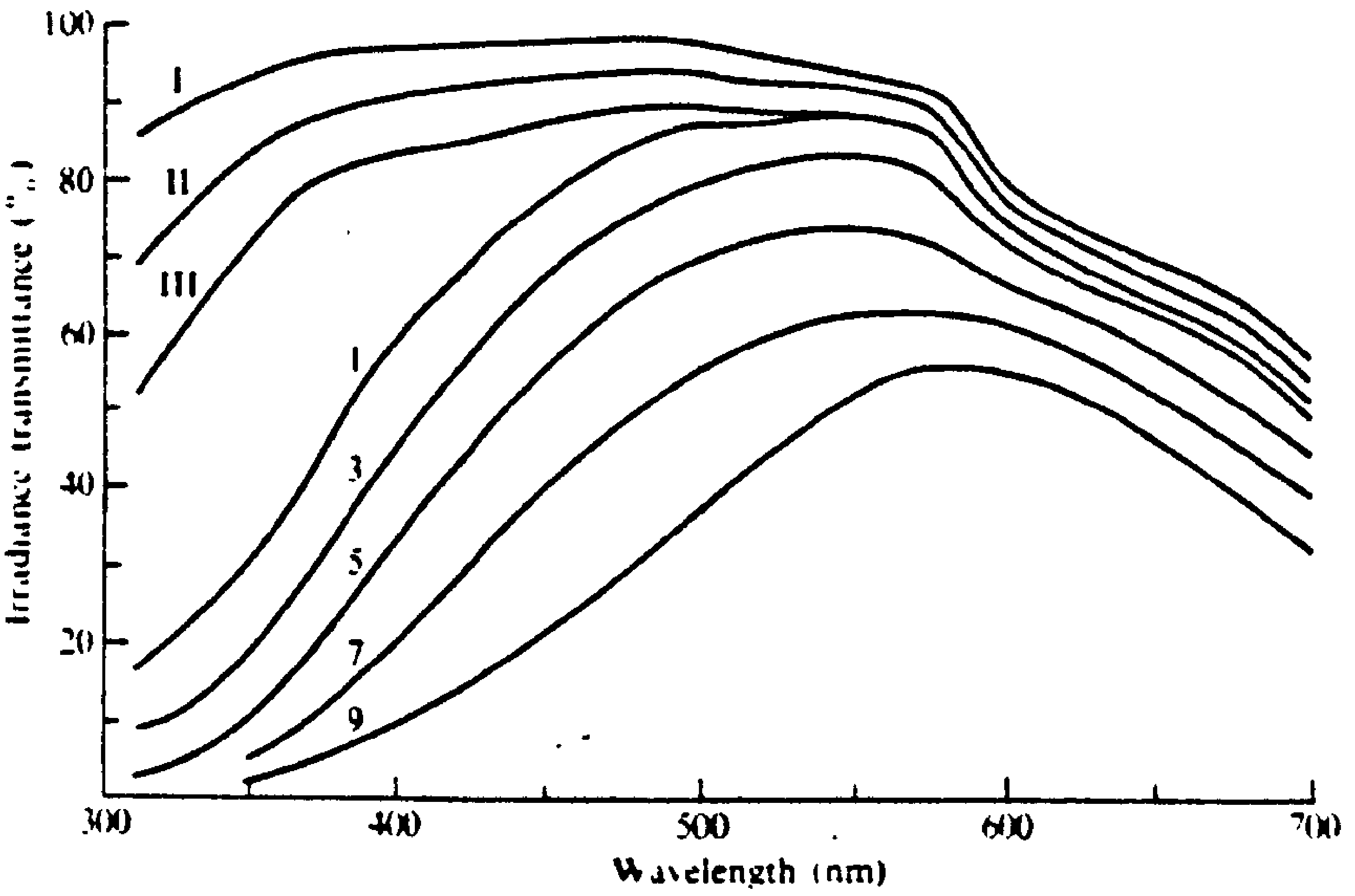
Through the accumulation of data from many sources it has become clear that geographical factors play a crucial role in the determination of water colour. In fresh water, the colour is strongly influenced by the ecology of the surrounding terrain. Spence (1972), for example, has indicated that the colour of adjacent rivers and lakes may differ considerably because their origins lie in different catchment areas. In the ocean, the importance of proximity to land is reflected in the map of the world-wide distribution of oceanic water types compiled by Jerlov (1976), on the basis of measurements of the spectral transmittance of downward irradiance at high solar altitudes.

The classification of water types used in the map is shown in Figure 4.1. Oceanic, coastal and brackish water are divided into five categories (of which only three of the oceanic types are shown). The figure clearly shows the attenuation of short wavelengths in coastal water (curves 1-9) compared with the oceanic water (I-III). This is due to the presence of the yellow substances, which are produced by the breakdown of plant chloroplasts. In fresh water subject to a similar effect, the attenuation is likely to be even more marked. The figure also shows the effects of nutrients on light transmission. Nutrient-poor regions of the oceans (curve 1, for example) transmit relatively more light at short wavelengths, whereas the increasing presence of nutrients shifts the transmission closer to that of chlorophyll (Morel and Smith, 1974), as shown in curve III. Nonetheless, caution should be applied in interpreting such curves in simple terms. As indicated above, the greenness that is characteristic of coastal water is often due to the joint effects of yellow substances and phytoplankton, and their relative contributions are sometimes difficult to evaluate.

Fewer data are available for the highly turbid conditions sometimes experienced in fresh water. Although very little light is transmitted anywhere in the spectrum, the shape of the transmission curves indicates that the background is not spectrally neutral, the greatest transmission often being at long wavelengths (for instance, Muntz, 1982).

Fig. 4.1. Jerlov's classification of water types.

The curves represent the irradiance transmittance for coastal (1-9) and Oceanic (I-III) water on a wavelength basis.



(after Jerlov, 1976)

Within a given water body at any specific time, noticeable differences in background also occur as a function of depth, orientation, and solar altitude. Lythgoe (1979, pp. 20-21) further mentions the role of such factors as temperature, time of year and tidal state. With increasing depth, there is a narrowing of the bandwidth of light until (in clear water, at least) the water behaves as a monochromator (Tyler, 1959; Tyler and Smith, 1967; Smith and Tyler, 1967). The specification of these changes, as well as those implied by the factors mentioned above, can be treated quantitatively within the radiance model outlined previously, by analysing radiance as a function of discrete wavebands. Alternatively, Jerlov (1974) has recommended the use of a colour index, a ratio between the radiances of two selected wavelengths, as a simple method of obtaining an objective measure of water colour.

### 4.1.3. Colour vision under water.

<u>4.1.3.1. The nature of underwater colour vision research - a methodological note</u>. Although the treatment of underwater visibility solely in terms of brightness contrast helps to answer a number of important questions, it is clear from the fact that few natural water bodies are spectrally neutral that colour vision must also be considered. From a theoretical viewpoint, at least, the physical specification of a chromatic stimulus under water is not significantly more difficult than that of an achromatic one - an object and the background against which it is viewed can be described in terms of the wavelength distribution of photons impinging

on the eye. Similarly, it is possible to obtain perceptual reports of one form or another from observers viewing the stimuli. However, in practice it is a difficult task to assess the relationship between the physical and perceptual specification of a colour, because of the limitations of current understanding of colour vision, and of the shortcomings of colour specification systems.

The ambiguity between the physical and perceptual aspects of colour has not seriously restricted advances in laboratory colour vision research. In the underwater environment, on the other hand, there is the additional problem of the physical specification of the target and its water background. To those well versed in colourimetry the literature on human underwater colour vision might appear to exhibit an unacceptable level of methodological crudeness. A closer examination of the conditions under which data must be obtained, however, might convince most sceptics that the operating environment has a crucial role in determining methodology. Nonetheless, there have been several successful modifications of laboratory techniques, some of which are described by Lythgoe (1971).

4.1.3.2. Empirical studies. The problem of specifying the spectral characteristics of a target and the water background against which it is viewed is indicated by Lythgoe's comment that "the theory of radiance transfer through the water and our knowledge of the visual functions outstrip the available data on light transmission through the sea." (1979, p. 129). Consequently, it has sometimes been difficult to obtain field data that could be quantitatively assessed within the sophisticated theoretical models of colour vision now available (Appendix J). For example, it has been known for some time that chromatic adaptation takes place rapidly on immersion, but a quantitative field study has not been attempted, and the most important findings have been discussed in qualitative terms. Thus in reporting on the relationship between target brightness and horizontal visual range, Lythgoe and Hemmings (1967) noted that the grey targets appeared slightly pinkish aginst the blue background, indicating the presence of simultaneous colour contrast. A similar effect was noted, almost anecdotally, in the Sealab II experiment (Kinney and Cooper, 1967).

Several methods have been employed in the attempt to overcome the limitations imposed on underwater colour vision research by the shortage of data on light transmission through water. One method, adopted by Kinney and Cooper (1967), is to conduct simulation studies in the laboratory. Clearly, the value of such experiments is mainly determined by how closely the experimental conditions resemble those in the field. In their study, Kinney and Cooper investigated adaptation to diffuse chromatic fields. They found sizeable shifts in colour appearance, to the extent that in a blue-green field yellow-reds could be seen for which no physical stimulus was present. They also noted that such adaptation was rapid - requiring in the order of five minutes to complete.

A second method is to use empirically obtained data for the optical characteristics of the water in conjunction with mathematical models of colour vision. This method lends itself to the investigation of sophisticated hypotheses which might be otherwise difficult to test. It also has the advantage of allowing detailed analysis within a pre-existing theoretical framework. Given these advantages, it is perhaps surprising that only one study has been reported that employs this technique. Lythgoe and Northmore (1973) used the Stiles-Helmholtz line element equation to investigate whether any of the known visual pigments might render red more visible than yellow in blue water and yellow more visible than red in yellow-green water (it was assumed, therefore, that the three receptor mechanisms acted independently). The lack of optical data for natural water limited the analysis to the case of a grey target containing a coloured area of variable brightness. The authors confirmed that for this condition, no combination of the pigments could reverse the visibility of red and yellow in the blue and yellow-green waters, thereby suggesting that water colour, rather than the physiology of the eye, determined relative visibility.

In situ experiments have produced stimulus specifications of varying degrees of sophistication. One approach has been to limit the physical specification of the stimulus to normal (air) viewing conditions and to record the colour name or distance at which it can be detected or recognised under water. Thus Lythgoe (1969) found that the conspicuity of red and yellow could be reversed when viewing took place in green fresh water, compared with the blue water of the Mediterranean. Kinney and Miller (1974) reported the conspicuity of various colours judged from an underwater habitat at a depth of 30 metres in the Carribean. Finally, Luria and Kinney (1974) recorded the percentage of each colour of disc recovered from the bottom of a turbid lake during free-swimming search.

In a second class of in situ experiments, photographic techniques have been used in the attempt to specify the physical characteristics of the stimulus colour. Lingrey (1968) had observers view and photograph various commercial photographic colour charts in shallow seawater. Colour saturation was found to be less in the photographs than reported subjectively by the observers. Lythgoe (1971) published the photographs of a series of coloured targets taken in the Mediterranean and an English lake. As expected, the photographs showed that the red (in air) targets appeared black (on the film) in the Mediterranean, while yellow retained its colour. In the lake, the red retained its colour much better than the yellow. Behan, Behan and Wendhausen (1972) found that photographic film did not record all of the colours seen by the photographer viewing Pseudoisochromatic Plates in 15 metres of coastal water. Highly saturated colours were still correctly identified at a depth of 30 metres in clear water. As qualitative assessments, such studies are valuable. At the same time, care must be taken if the results are to be assessed quantitatively, because they relate to films which probably differed in spectral sensitivity, exposure time and development time.

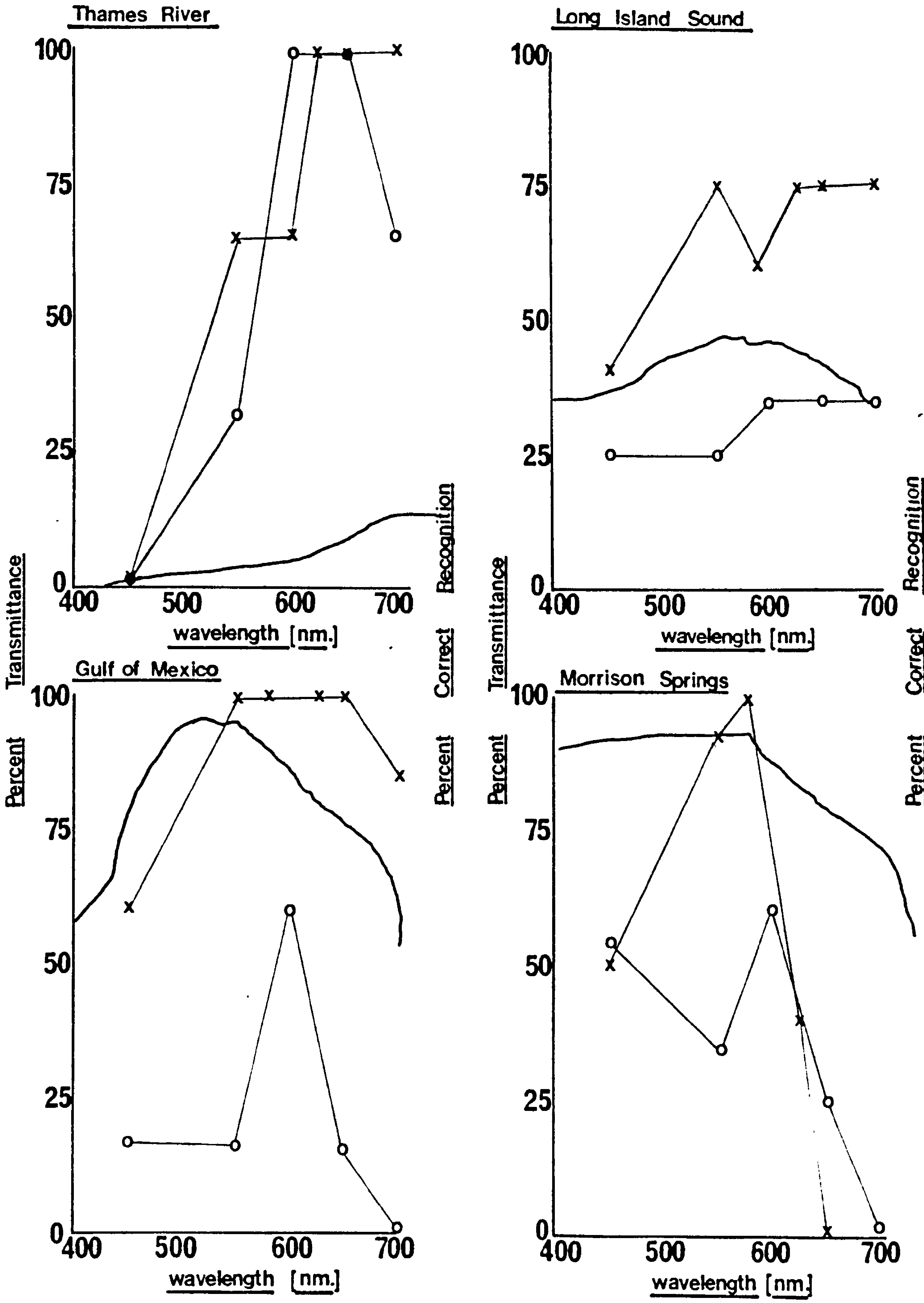
A further approach to the problem of assessing underwater colour vision is based on the comparison between observers' perceptual reports and physical specifications extrapolated from the assumed optical properties of the experimental site. Several researchers at the United States Naval Submarine Medical Centre, Groton, have explored aspects of underwater visibility that broadly follow this method. Kinney, Luria, Weissman and Matteson (1965) and Kinney, Luria and Weitzman (1967) had divers give colour names to a number of spheres coated with fluorescent or non-fluorescent paint of various colours, viewed in the horizontal or vertical plane.

To specify the visible radiant energy reaching the observers, water samples taken at the experimental sites were then measured in a spectrophotometer, and the spectral transmittance curves extrapolated to the appropriate viewing distances. Both teams of investigators found that fluorescent paints were generally more easily recognised than non-fluorescent paints of similar hue. With increasing water clarity, also, the colours most easily recognised changed towards the blue region of the spectrum. The data for viewing under artificial light (Kinney et al., 1965) were predictable in a general sense from those obtained under natural light, when allowance was made for the effects of the spectral distributions of the artificial sources.

The data for the natural light study have been summarised in Figure 4.2, where the transmission of the water background has been plotted with the relative

Fig. 4.2. Relative visibility of fluorescent and non-fluorescent colours at four sites.

The data are those of Kinney, Luria and Weitzman (1967). The frequency of recognition of fluorescent (x—x) and non-fluorescent (o—o) colours is shown, together with the spectral transmission of 1 m of the water background.


Thames River
Long Island Sound
Gulf of Mexico
Morrison Springs
Percent Transmittance
Percent Correct Recognition
100
75
50
25
0
400
500
600
700
wavelength [nm.]

visibility of the colours to the observers at various sites. The data are the most comprehensive to have been obtained in a study of human underwater colour vision in natural viewing conditions, and have been widely cited. To a first approximation, they confirm the relationship between the wavelengths assumed to be present in the water and the relative recognition thresholds of different colours. Thus, in clear blue water of Morrison Springs the relative thresholds of the targets were markedly different from those in the clear green water of the Gulf of Mexico and the turbid water of the Thames river. The general effects have been well illustrated by Lythgoe (1971), in the form of a chart showing the colours that remain when various parts of the spectrum are absorbed or transmitted. When the spectral reflectance of the target changes rapidly with wavelength in a region of the spectrum where the water has a relatively high transmission, there will be the most noticeable difference in hue between the object and its water background (Lythgoe and Northmore, 1973). Thus colours with a sharp cutoff in their spectral reflectance curves can be particularly conspicuous under water. On the other hand, in the case of a long wavelength target, if there is light only in the short wavelength region of the spectrum, it will appear black; if the only light present is at very long wavelengths, it will appear white or light grey (Lythgoe, 1979, p.184).

Several researchers have attempted to obtain <u>in situ</u> light measurements simultaneously with the visual data. Hemmings (1966) measured the horizontal distance at which fishing nets of various colours could be seen. At the same time, the beam and diffuse attenuation coefficients were determined using a twin-cell light meter. Although Hemmings was measuring detection rather than recognition thresholds, the visual observations were in broad agreement with those obtained by Kinney et al. (1967). Radloff and Helmreich (1968) recorded the observations of members of the Sealab II Man-in-the-Ocean project simultaneously with scalar irradiance and beam attenuation measurements. The visual data were subsequently published, but unfortunately no attempt was made to compare them with the (unpublished) data on the spectral characteristics of the water.

In addition to the efforts of researchers interested in human performance under water, considerable impetus to the field of colour vision under water has been given by experiments on fish vision (reviewed in Lythgoe and Northmore, 1973; Munz and McFarland, 1977; Ali, 1975; Lythgoe, 1979). As a result of investigations into the influence of different visual pigments on spectral sensitivity (for example Lythgoe, 1966, 1968, 1969, 1972; Loew and Lythgoe, 1978) it has been possible to examine the theory of contrast reduction under water on a spectral basis. A further important feature of this work is that it has emphasised the importance of _in situ_ light measurements. For example, using a diver operated instrument, Lythgoe (1968) found it possible to quantify the relationship between spectral contrast and horizontal visual range. Such studies confirm that the measurement of light under water and of observers' visual responses to the light are not mutually exclusive activities. Nonetheless, the researcher is constantly aware that sometimes practical considerations pre-empt detailed theoretical analysis. Thus, Munz and McFarland (1977) have cautioned that the equation used by Lythgoe (1968) to calculate visual contrast represents only the potential visual capability of an animal on the basis of absorbed photons, and excludes such neural processing as lateral inhibition.

Despite the lead given by some biologists, there has been a decrease in the number of experiments into human underwater colour vision in recent years. Fay (1976) examined colour adaptation at various depths in clear coastal water. Divers viewed small coloured plaques and then tried to recall their apparent colours above the surface by selecting from a large range of colours. Red targets were tested by having the divers write a description of the apparent colour on a slate. The spectral distribution of irradiance incident from above was recorded at six wavebands with a portable spectroradiometer that a diver carried round his neck like a camera. No measurements were taken from the targets, however. The main conclusion of the study, that human colour vision under water represents a compromise between the effects of selective absorption of the water and the selective chromatic adaptation of the eye, was in agreement with the conclusions drawn by Kinney et al. (1967).

#### 4.1.3.3. The potential importance of brightness in colour visibility studies.

Partly due, perhaps, to the diversity of experimental methods outlined above, the literature on underwater colour vision has to some extent been burdened with a degree of ambiguity over operational definitions. Thus Kinney et al. (1967) defined the 'visibility' of a coloured target in the vertical plane as the depth of the target when it was first seen. It remains unclear whether this refers to the detection threshold of the target or the recognition threshold of its colour. In the horizontal plane, on the other hand, the divers were instructed to give colour names to the targets which were all placed at the mean of the distances at which the most and least visible of them were detected (no definition of 'detection' was given). Close attention must also be given to the details of the viewing conditions. Lythgoe (1971) has suggested that the discrepancy between Kinney et al. (1967), who reported that their black target was inconspicuous, and Hemmings and Lythgoe (1965), who found theirs to be conspicuous, was partly because the sightings were made in different directions relative to the surface.

The starting point for the present experiments was the ambiguity attached to the specification of thresholds by colour naming. Because colour is a three dimensional concept, caution is required in interpreting the recognition thresholds of colours that are classified only by hue name. Indirect evidence to this effect was given by Hemmings (1966), who determined the detection thresholds of various coloured targets (he measured the detection distance of the target rather than the recognition distance of the colour). He noted that when a considerable colour contrast existed between an object and its background, it was still the least visible of a series of colours, because its brightness was similar to that of the background. It was concluded that "the result is of very great significance because it confirms that brightness contrast is very much more important than colour contrast, even in conditions of illumination and in water sufficiently shallow for colour vision to be significant" (Hemmings, 1966, p. 367). A similar conclusion can be deduced from the colour recognition data of Kinney et al. (1967). If hue had been the only determinant of the threshold, the finding that yellow was the most recognisable non-fluorescent colour in all types of water tested would be quite surprising. Reference to the target specification, however, reveals that the non-fluorescent yellow had a luminance factor almost three times higher than any other non-fluorescent target (excluding white). As one might expect, examples can also be taken from the data which confirm the superiority of hue over brightness. However, this still leaves saturation unaccounted for.[1] The finding that the fluorescent targets were almost always more recognisable than non-fluorescent targets of the same hue name could have resulted from the fact that fluorescence typically produces colours of both high brightness and saturation.

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[1] Considerable effort has been devoted to the clarification of colour terminology. Despite recent proposals for the introduction of new terms for describing colour (Hunt, 1977, 1978), in the present discussion the terms hue, brightness and saturation will be retained. Their intended meanings are those specified in any introductory text on colour science (for example Wright, 1964).

It was decided that two experiments should be undertaken. First, it was hoped to examine the effects of target reflectance on colour recognition thresholds under controlled conditions. Second, it was hoped to investigate the same effects under less rigorously controlled conditions that allowed comparison with the data of Kinney et al. (1967), whose discussion of thresholds largely ignored brightness and saturation.

## 4.2. EXPERIMENT 4a - LABORATORY STUDY

### 4.2.1. Method

4.2.1.1. Observers. A total of 16 unpaid volunteers, seven males and nine females, participated Their age range was 18-26 years, with a mean of 20 years. All had normal uncorrected visual acuity (on the Snellen Chart) and normal colour vision (on the Ishihara Colour Test). All had previously participated in psychophysical experiments.

4.2.1.2. Apparatus. The basic apparatus was that shown in Figure 3.1. The test stimuli were four Munsell Colour chips, each 16 x 21 mm., chosen from the Munsell Matte Finish Collection (1976 Edition). Their notations were 5GY 8/6; 5GY 5/6; 2.5Y 8/6; and 2.5Y 5/6.[1] Each chip was waterproofed with a covering of clear adhesive plastic (Transpaseal). A small metal clip was cemented to the reverse side of the chip to allow it to hang on

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[1] In the Munsell notation, a colour is specified in terms of threee variables. These are:- (a) Hue (given by a letter and a number); (b) Value, on a scale from 0 to 10, defined on the basis of the luminous reflectance of the sample as calculated, as based on the CIE Standard Observer and illuminant C; (c) Chroma, on a scale from 0 upwards, defined as the difference from a grey of the same lightness.

the perspex frame of Figure 3.1. Three additional stimuli were prepared in the same manner from coloured card (either red, orange or blue).

4.2.1.3. Procedure. Each observer was assigned to one of the two parts of the experiment, the first part of which was concerned with stimulus recognition, the second with stimulus detection. In the first part, the aquarium was filled with a solution of Aluminium Hydroxide Gel and tap water. The concentration was adjusted until all of the stimuli could be correctly identified at a distance less than the full length of the aquarium by a preadapted observer (E) viewing through the facemask. The background luminance inside the aquarium was then measured, as in Experiment 3a. After an adaptation period of five minutes, a modified method of limits was used to establish the recognition threshold distances of the stimuli for each of ten observers viewing through the facemask (as previously, the ascending series was omitted). Following ten practice trials, each observer was given eight test trials with each of the four Munsell chips, presented singly, in random order in a fixed position on the centre of the perspex frame. On each trial, the frame was moved manually by E (in one centimetre increments) along the aquarium towards the observer. The observer was instructed to indicate verbally when the stimulus could be identified as either violet, blue, green, yellow, orange, or red. To help prevent the observers making guesses (because of the limited number of test stimuli), five trials of each of the three dummy stimuli were also given.

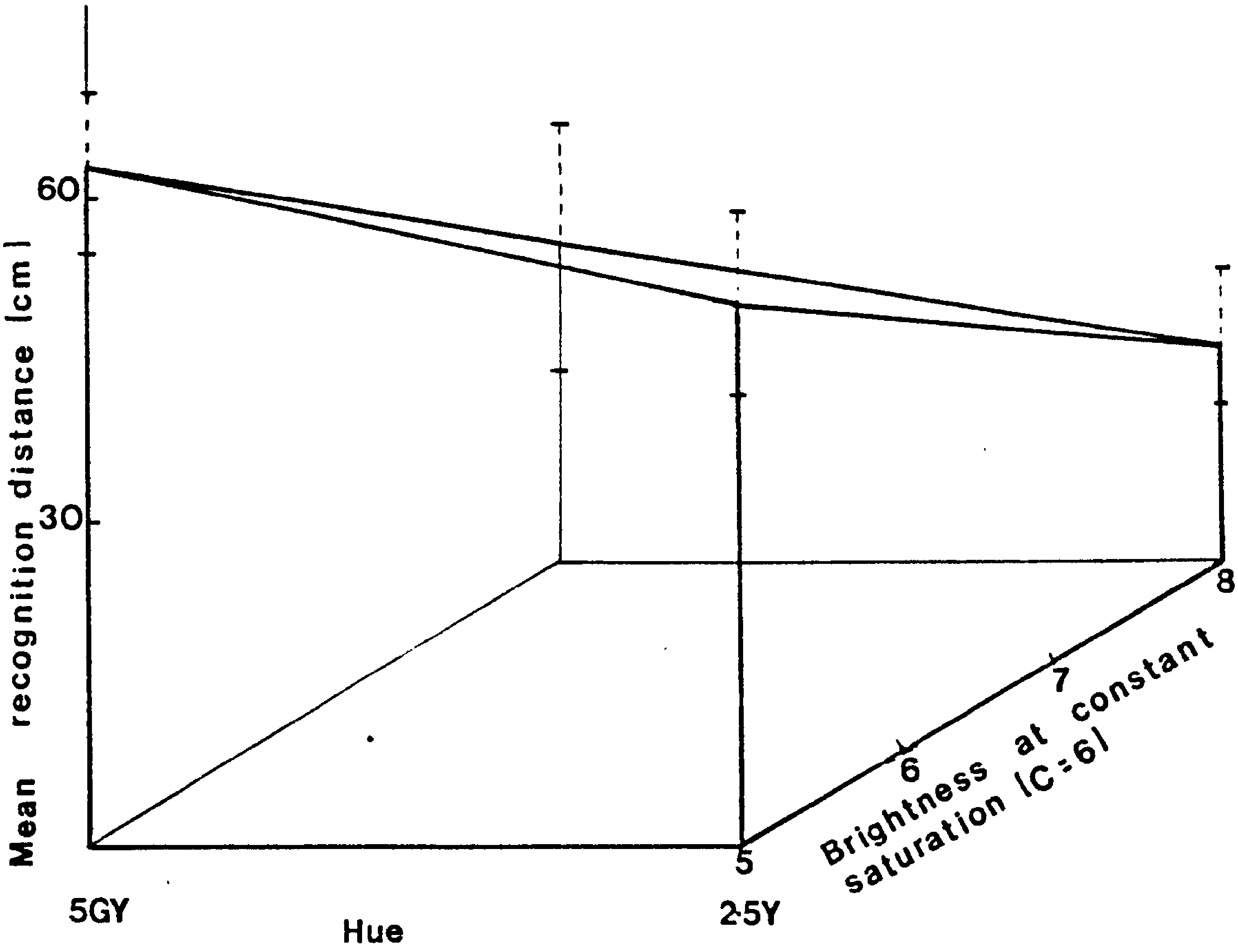
Although observers' adaptation levels were maintained as far as possible, rest periods were allowed at any time on request. These were followed by a further period of adaptation Before each test session, which lasted about one hour, the luminance level was checked and a blackbody estimate made by E. No changes were noted during the experimental period.

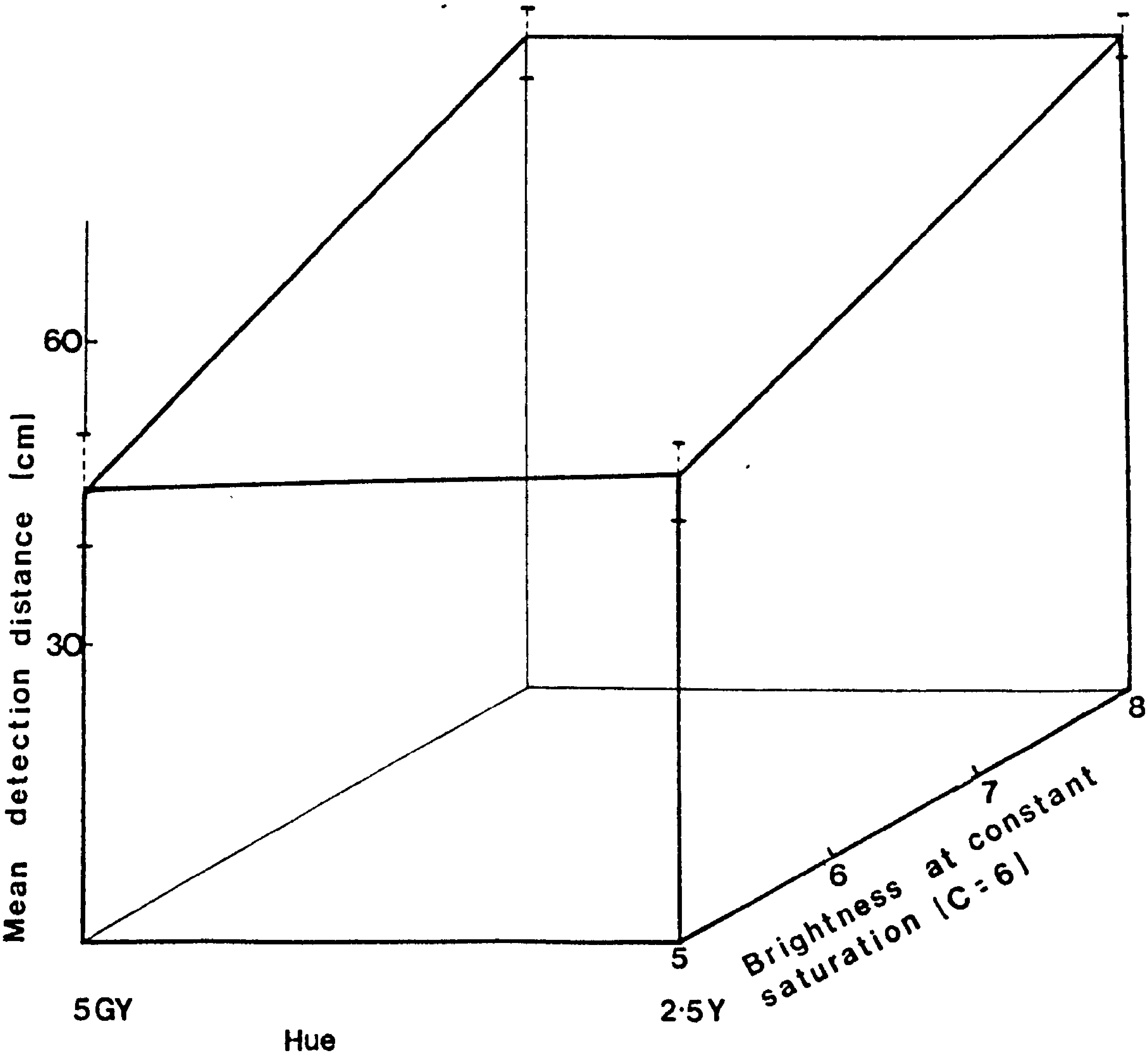
For the second part of the experiment, the visual range in the aquarium was reduced, through the addition of Aluminium Hydroxide Gel, until none of the Munsell chips could be detected by an observer (E) at the furthest distance from the facemask and the background luminance matched that obtained in the first part of the experiment. The procedure then followed that in the first part of the experiment, except that the detection threshold was established for the six observers over ten test trials for each stimulus. No dummy trials were given. Each test session lasted approximately one hour.

4.2.2. Results and discussion. The mean recognition threshold distances of the four Munsell chips (in centimetres) for each observer are shown in Figure 4.3, together with the standard deviations. It is evident that for a stimuli of a given hue and saturation, different levels of brightness resulted in markedly different recognition thresholds. In addition, increasing the target brightness decreased the recognition distance. Repeated measures analyses of variance, summarised in Appendix K, confirmed that there was a significant difference between the recognition thresholds of the four targets ($F$ = 5.40, $df$ = 3/27, $p$<.005). Orthogonal comparisons following the analysis of variance

Fig. 4.3. Recognition and detection threshold distances of Munsell chips against an achromatic water background (Experiment 4a).

The mean (N=10) recognition and detection (N=6) thresholds (binocular viewing) for the four Munsell chips are plotted in two dimensional colour space (hue and brightness at constant saturation). The error bars indicate the standard deviations from the mean. The background luminance was 8 cd/m$^2$ for both parts of the experiment.


Mean recognition distance (cm)
60
30
5GY
2·5Y
Hue
5
6
7
8
Brightness at constant saturation (C=6)


Mean detection distance (cm)
60
30
5GY
2·5Y
Hue
5
6
7
8
Brightness at constant saturation (C=6)

are summarised in Table 4.1. The results confirmed that the differences between the recognition threshold distances of the bright and dark green and dark and bright yellow targets were both statistically significant. Initially, the brighter of the green targets was more visible than the yellow of identical brightness. Similarly the darker green was more visible than the darker yellow. However, when the darker yellow was compared with the brighter green, the green was significantly less visible. Finally the brighter yellow was less visible that the darker green.

The mean detection thresholdsof the four Munsell chips (in centimetres) for each observer are also shown in Figure 4.3 together with the standard deviations. It is clear that for a stimulus of given hue and saturation, different levels of brightness resulted in markedly different detection thresholds. Increasing the target brightness resulted in an increased detection distance. Repeated measures analysis of variance, summarised in Appendix K, confirmed that there was a significant difference between the detection thresholds of the four targets ($F$ = 47.1, df = 3/15, $p<.005$). Orthogonal comparisons following the analysis of variance are summarised in Table 4.1. The results confirmed that the differences between the bright and dark green and bright and dark yellow targets were both statistically significant. Initially, there was no difference between the detection threshold distances of the green and yellow targets of comparable brightnesses. However, the differences between the brighter green and darker yellow and the brighter yellow and darker green were both significant.

The results of the two parts of the experiment suggest the presence of several interesting effects. First, the

TABLE 4.1. Summary table of orthogonal comparisons for Experiment 4a (detection and recognition threshold study).

| | TARGET COMPARISON | *df* | *F* | *p* |
|---|---|---|---|---|
| RECOGNITION THRESHOLD | Bright green/dark green | 1/9 | 54.2 | <.005 |
| | Bright yellow/dark yellow | 1/9 | 212.6 | <.005 |
| | Bright green/bright yellow | 1/9 | 10.6 | <.025 |
| | Dark yellow/bright green | 1/9 | 26.9 | <.005 |
| | Dark green/dark yellow | 1/9 | 10.0 | <.025 |
| | Bright yellow/dark green | 1/9 | 105.1 | <.005 |
| DETECTION THRESHOLD | Bright green/dark green | 1/5 | 112.0 | <.005 |
| | Bright yellow/dark yellow | 1/5 | 67.2 | <.005 |
| | Bright green/bright yellow | 1/5 | 0.0 | >.05 |
| | Dark yellow/bright green | 1/5 | 62.1 | <.005 |
| | Dark green/dark yellow | 1/5 | 0.3 | >.05 |
| | Bright yellow/dark green | 1/5 | 52.4 | <.005 |

data confirm that both the detection and recognition threshold of a coloured stimulus can be influenced by its brightness. Furthermore, they show that the size of this effect can be large enough to reverse the recognition and detection thresholds of stimuli having different hue names. Consequently, it seems likely that the omission of a control for brightness in studies of colour 'visibility' might result in equivocal data. In the present experiment the interpretation of the data is simplified by the fact that the background was spectrally neutral. In most natural water bodies, on the other hand, the interaction between the spectral characteristics of the target and background must be considered. In the study of Kinney et al. (1967), for example, the recognition thresholds of targets in the turbid waters of Long Island Sound and the Thames river (which had relatively flat transmission curves) closely matched their luminance factors. In the clear water conditions, this was not the case. In Morrison Springs, for instance, the blue target, which had previously been the least visible colour, became one of the most visible, despite having a low luminance factor and being similar in hue to the background.

A second interesting feature of the data is that the detection thresholds of targets differing in hue but having identical brightness and saturation are very similar (Figure, 4.3). This is compatible with the suggestion of Middleton (1952) and Hemmings (1966) that target detection is influenced more by brightness contrast than colour contrast. On the other hand, the finding that colours of the same brightness and saturation but different hue have different recognition thresholds (Figure 4.3) does not necessarily imply that hue is more important than brightness for colour recognition. This can be deduced from the fact that the proportionate changes in the mean thresholds of the ten observers due to a change in brightness alone (49 percent for green, 52 percent for yellow) are greater than those due to hue alone (26 percent for the brighter green to the brighter yellow, 21 percent for the darker green to the darker yellow).

Finally, Figure 4.3 shows that as the target brightnesses increased the detection distances increased but the recognition distances decreased. Because the changes in absolute viewing distances were not accompanied by a change in the background luminance (12 cd/m$^2$ for both parts of the experiment, measured with the UDT 40 Optometer), these results are unlikely to have been due to differences in relative brightness contrast. One explanation, therefore, might be that the recognition of a colour is made more difficult as any of the primary variables (hue, saturation or brightness) departs significantly from some optimal value. For example, one might also anticipate the situation where decreasing the target brightness in the recognition study past a critical value could reduce the threshold.

## 4.3. EXPERIMENT 4b-FIELD STUDY

### 4.3.1. Introduction

4.3.1.1. Colour specification. The methods and tools of contemporary colourimetry are based on fundamental laws of colour matching and internationally agreed standards of illumination and viewing conditions. The aim of the recommendations of the CIE Colourimetry Committee is to facilitate colour specification in terms of the amounts of three primary stimuli required for an ideal observer with normal colour vision. Many summaries are available, of which some are excellent (see, for example, Wright, 1969; Wyszecki and Stiles, 1967; Judd and Wyszecki, 1975).

The measurement of the chromaticity coordinates of a colour without the direct use of the human eye commonly involves one of three classes of instrument - a spectrophotometer, a photoelectric colourimeter, or a spectroradiometer. For determining the colour of both background and target colour under water, the spectrophotometer is probably the least suitable instrument. Photoelectric colourimeters can employ either a triple monochromator and three templates, or coloured filters duplicating the standard tristimulus value ($\bar{x}$ ($\lambda$), $\bar{y}$ ($\lambda$), and $\bar{z}$ ($\lambda$) ). The former is an elaborate and expensive instrument, and the latter lacks accuracy, even with computer aided filter selection. Furthermore, because they illuminate reflecting samples under specific geometric conditions, it would be difficult to use them to measure the water background. A spectroradiometer is designed to measure the spectral irradiance distribution (or any other radiometric quantity) of a source. It has been frequently used for underwater measurements (for example, Duntley et al., 1955; Sasaki et al., 1962; Tyler and Smith, 1970; Austin and Ensminger, 1978). However, the data are rarely transformed into the CIE system (Jerlov, 1976, Ch. 13).

Although a spectroradiometer of conventional design could provide the data required to specify colour under water, several factors weighed against the possibility of using such an instrument in the present study. Most important, perhaps, was the practical consideration that the financial cost of buying the meter, and, alternatively, the technical problems involved in building an instrument were prohibitive. The loan of an existing meter was also not a realistic option, because typically such meters measure irradiance via an underwater cable from the surface, making it difficult to measure radiance (with a modified receiver to restrict the angle of acceptance) from static targets, particularly at sites where boat access is restricted. Furthermore, even if the whole unit was waterproofed, with a large number of spectral filters and targets the amount of data to be recorded under water would be considerable.

Because of these difficulties, an alternative solution was sought. It was based on the theory that by coupling three primary colour filters with a photocell, it is possible to establish a colour triangle within the CIE chromaticity diagram whose corners are specified by the spectral transmission curves of the filters, photocell and the eye of a standard observer. For such a case, CIE chromaticity coordinates can be specified in terms of the proportions of the three primaries measured by the meter, and plotted within the chromaticity diagram by simple geometry.

### 4.3.2. Method.

4.3.2.1. Observers. Eight trained and experienced divers, seven males and one female, participated in the study. Their age range was 24 to 46 years, with a neam of 27.5 years. All of the observers had normal colour vision (on the Ishihara Colour Test) and seven had normal uncorrected visual acuity (on the Snellen Chart). Observer H. H. wore corrective lenses inside his facemask.

4.3.2.2. Apparatus. The stimuli were 10 Aluminium tiles, each 300 sq. cm., coloured blue (2), green (2), yellow (2), red (1), fluorescent red (1), fluorescent yellow (1) and fluorescent green (1). Their spectral reflectances are given in Appendix B. The tiles labelled 'dark' were prepared by covering copies of the standard blue, green and yellow tiles with sheets of Kodak Wratten Neutral Density Filters (density 0.3) which were then sealed with clear plastic (Transapeal). The tiles were displayed on the aluminium frame shown in Figure 3.4.

Light readings were taken with the underwater photometer described on page 38 and a modified type of spectroradiometer designed and built for the study (Figure 4.4). The housings were aluminium diecast boxes (RS Components), modified (as described on page 38) for underwater use. A silicon photovoltaic photodiode (Rofin - type S.D. 290-12-12-041) fitted into an aperture in one side of the housing. A waterproof seal was formed by a bi- convex lens (Bolco Ltd.), 50 mm. in diameter, fixed at its focal length (in air) into one end of a brass mounting covering the aperture. A small baffle, made from Darvic, fitted over the lens to restrict the meter's acceptance angle to 2° (in air). Three detachable filters, 50 mm. in diameter, were

Fig. 4.4. (a and b). Underwater spectroradiometer.

(a) Side view - Light entering through the lens was detected by the photodiode, amplified and displayed on the DPM.

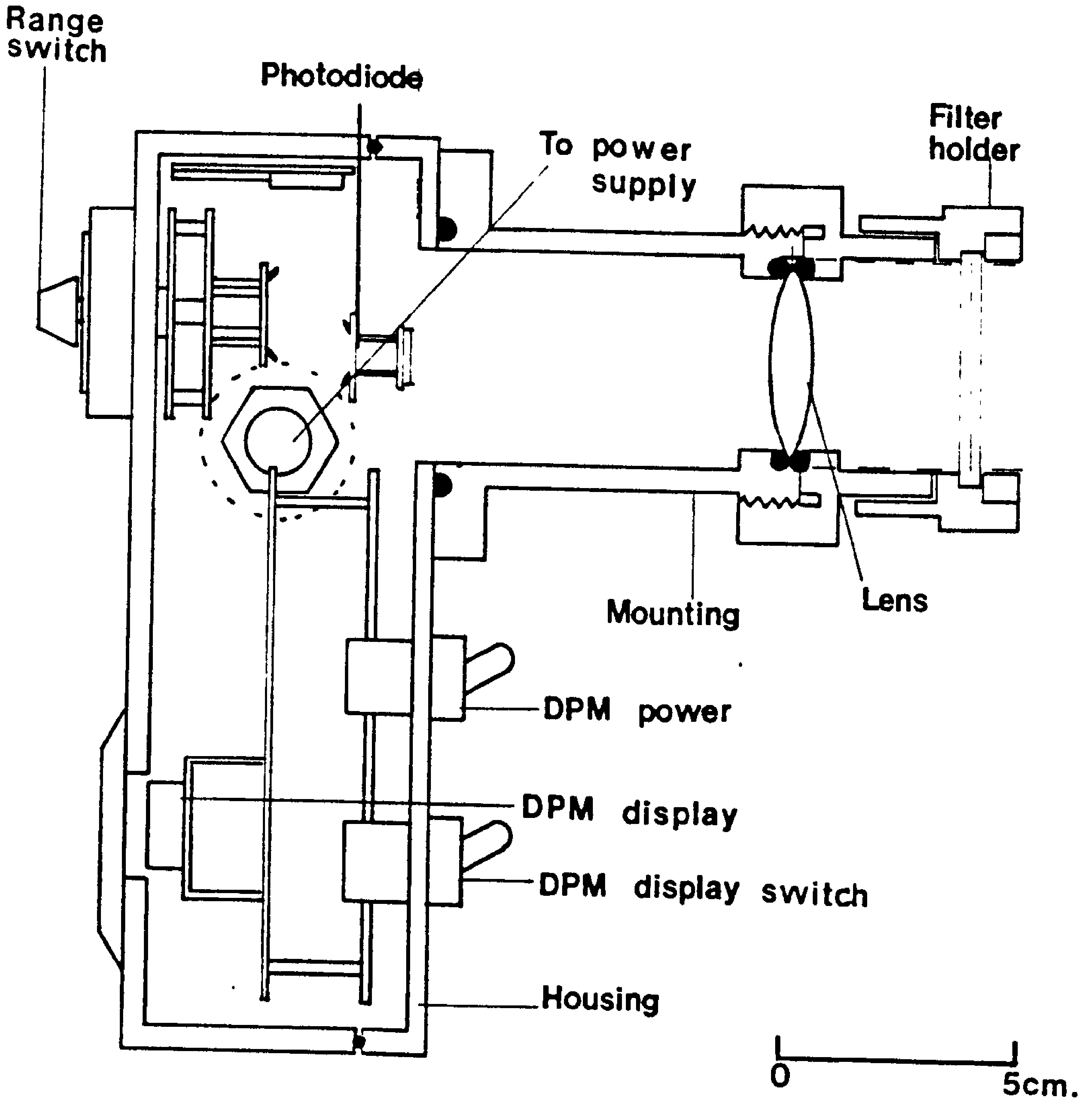
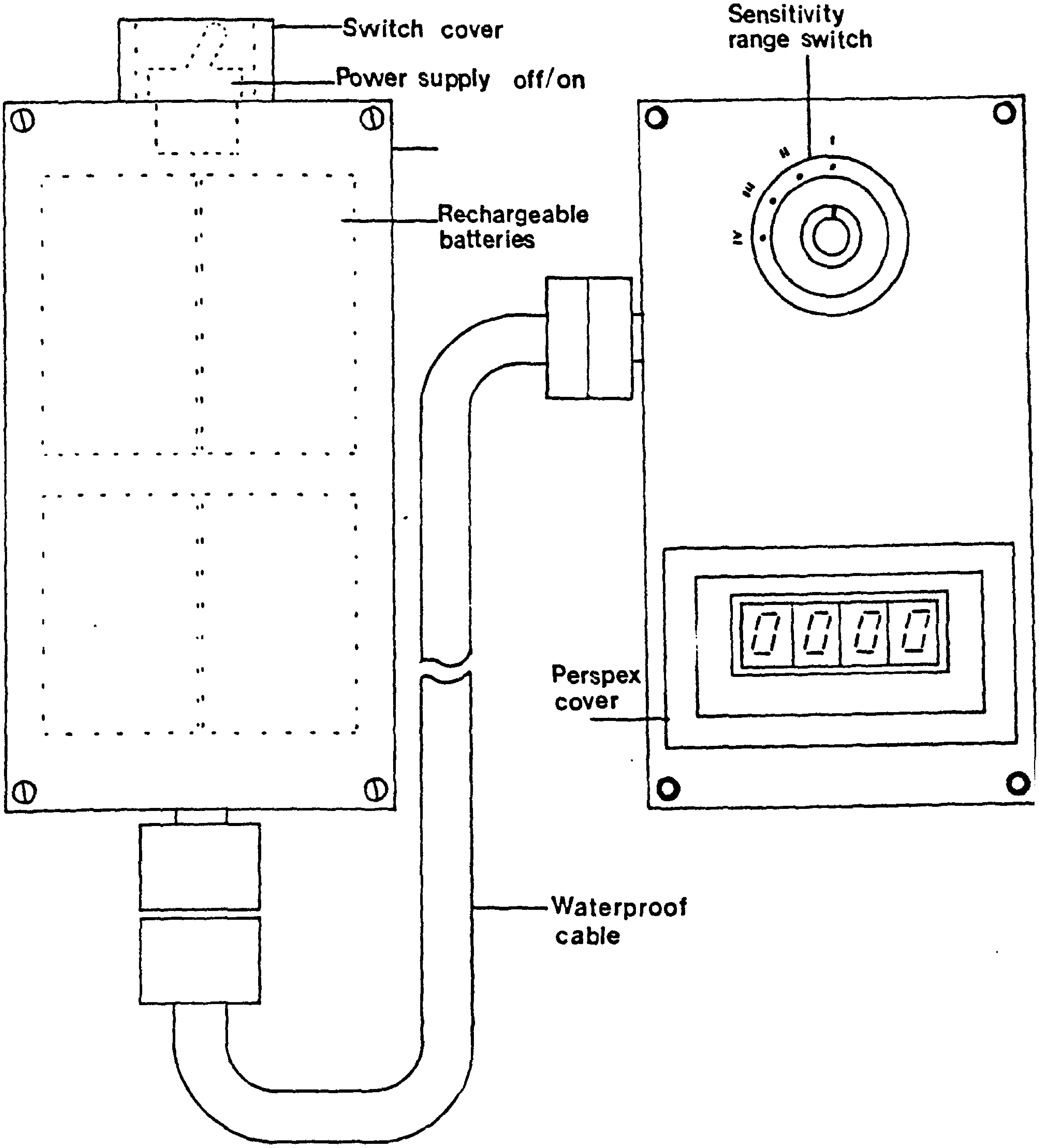


Fig. 4.4. (b) - Top view.



mounted in brass holders and could be fitted onto the mounting. The filters were Kodak Wratten gelatin (numbers 61, 26 and 48), individually waterproofed by being cemented between two thin perspex covers (each 2.5 mm. thick). In case of accidental damage, they were secured in the holders with a screw-down bezel to facilitate replacement. The three brass holders were chained together and could be attached to the operator by an aluminium karabiner.
The signals from the photodiode were amplified and displayed on a digital panel meter (Integrated Photomatrix Ltd), which was set into an aperture on the rear surface of the housing. The aperture was sealed with a perspex cover. The circuit diagram for the meter is given in Appendix L. The circuit was powered from four 1.25 V Nickel-Cadmium rechargeable batteries contained in the second housing, which was linked to the first by a waterproof cable. The cable contained a waterproof plug and socket (Swift Sub Aqua Supplies) to enable the batteries to be recharged without breaking the housing seal. A waterproof toggle switch (Sousmarine Diving and Engineering Ltd) controlled the power supply from the batteries. A switch cover prevented the batteries from being accidentally turned on. Three switches were provided on the first housing. One governed the range sensitivity over four decades of light input to the photodiode. The other two controlled the power to the digital panel meter and its display. An external attachment to the battery housing (not shown in the figure) enabled it to be attached to the operator's weight belt. Beneath the first housing

(also omitted from the figure) an external attachment allowed it to be fixed to the extension of the aluminium frame so that the meter was stable when measurements were being made. The meter has been successfully tested to a pressure of four Bars (absolute).

Calibration of the meter was undertaken as follows: first, the linearity of the signal amplication was confirmed by measuring the radiance from a white screen with various neutral density filters covering the lens. Because of the sensitivity of the photodiode and filters to infrared energy, a cutoff filter was required to exclude this region of the spectrum from the calibration. Such a filter is unnecessary when the meter is used in water, because water itself acts as an infrared cutoff filter. Consequently, it was decided to calibrate the instrument as if the filters were fronted by a 1 meter pathlength of pure water. The transmission curve of pure water (380 to 750 nm.), taken from the data of James and Birge (1938), was integrated with the transmission curve of each filter-photodiode combination. The filter plus perspex cover transmission curves were obtained on a Perkin-Elmer spectrophotometer, and the photodiode sensitivity curve was that supplied by the manufacturer, normalised at 750 nm. The location of each water-filter-photodiode combination in CIE space was calculated for the 1931 Standard Colourimetric Observer, following the method outlined in Judd and Wyszecki (1975). By equating (mathematically) the relative transmissions of the three water-filter-photodiode combinations, it was then possible to measure the chromaticity coordinates of any colour within the triangle in CIE space formed by the combinations. These coordinates were: blue filter, x = 0.1442, y = 0.0415; green, x = 0.2191, y = o.7039; red, x = 0.691, y = 0.309.

As a cross-check on this calibration, it would have been desirable to compare measurements from the meter through 1 metre of pure water with those from a pre-calibrated meter of known accuracy. Because pure water is notoriously difficult to prepare (Jerlov, 1976, p. 32), sample colours were measured (under illuminant $D_{65}$) through a 21 mm. thick solution of 2.5 percent Cupric Chloride, which acts like an infrared cutoff filter (Moon, 1961, p. 169). The transmission of the solution was measured on a Cecil CE 505 double beam spectrophotometer, and the calibration calculation outlined above repeated, substituting the transmission of Cupric Chloride for that of pure water and assuming illuminant $D_{65}$. The chromaticity coordinates of the samples as measured through the solution are given in Table 4.2., together with the values calculated from the spectral reflectance data. The table confirms the close agreement between the two sets of data.

As with the underwater photometer, it was necessary to calculate a correction factor for the immersion effect on the absolute response level of the meter. This was found to be 1.082.

Normally, the complete colourimetric specification of a colour includes reference to its luminance or luminance factor. The latter is defined as the luminance of the colour relative to the luminance of the perfect reflecting diffuser illuminated and viewed in the same way as the colour. This is represented as the tristimulus value Y, normalised at

TABLE 4.2. Calibration of the underwater spectroradiometer.

The table shows the chromaticity coordinates of light samples under illuminant $D_{65}$, as measured by the spectroradiometer through a 21mm. thick 2.5 per cent solution of Cupric Chloride, and calculated from the sample reflectance data obtained from a calibrated spectrophotometer.

| CHROMATICITY COORDINATES | | | |
|---|---|---|---|
| x | | y | |
| Spectroradiometer value | Calibrated value | Spectroradiometer value | Calibrated value |
| .169 | .176 | .240 | .245 |
| .260 | .262 | .512 | .516 |
| .409 | .413 | .357 | .354 |
| .393 | .396 | .444 | .449 |
| .252 | .258 | .312 | .318 |
| .267 | .270 | .510 | .500 |
| .222 | .216 | .387 | .396 |
| .365 | .371 | .323 | .318 |

100 for the perfect reflecting diffuser. Because the present meter relates to chromaticity coordinates rather that tristimulus values, an alternative method was required for the luminance measurements. Consequently the target colours were also measured with the underwater photometer described previously (Chapter 3). At the same time, a number of grey tiles were also measured with the photometer, to allow the prediction of the luminance of a target of 100 percent reflectance.

4.3.2.3. Procedure. The study was conducted at the three sites detailed in Table 4.3. The aluminium frame was positioned on the bottom, and the height of the perspex cross-sections adjusted so that the targets were seen against an unobstructed water background. At the Shirkin Island and Loch Airthry sites the frame was set down the day prior to the experiment. At Rainbow Springs this was unnecessary because of the rate of water movement and lack of fine sediment. At all three sites the frame was positioned so that the targets were viewed down-sun. As previously, a tape measure extended perpendicularly from the centre of the frame.

Prior to the experiment, the background luminance was measured with the underwater photmeter. The coloured tiles were then presented singly on each trial in a central position on the frame. Having achieved neutral bouyancy, each observer moved slowly along the tape, keeping it level with his or her faceplate, from a position at which the tile was not visible to that at which the tile was at approximately arm's length. The observers viewed

## TABLE 4.3. Field sites for colour recognition studies (Experiment 4b).

| LOCATION | WATER TYPE | DATE | TIME | DEPTH (metres) | BOTTOM | SKY[1] |
|---|---|---|---|---|---|---|
| A. Loch Airthrey,<br>Central Region,<br>Scotland. | Turbid freshwater,<br>highly particulate. | (a) 7-5-79<br>(b) 8-5-79 | 12.00-13.30<br>11.45-13.15 | 3.5<br>3.5 | flat with heavy silt. | 7/8<br>7/8 |
| B. Atlantic Ocean,<br>harbour at<br>Shirkin Island,<br>Co.Cork,<br>Eire. | Turbid inshore<br>coastal,<br>highly particulate. | (a) 17-7-79<br>(b) 24-7-79 | 11.00-12.30<br>11.15-12.45 | 4.5<br>4.5 | flat,<br>sandy | 7/8<br>1/8 |
| C. Rainbow Springs,<br>headpool,<br>Florida,<br>U.S.A. | Extremely clear<br>freshwater spring. | 12-5-80 | 11.00-13.00 | 3 | flat,<br>sandy | 0/8<br>0/8 |

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[1] The range is from 0/8 (no cloud) to 8/8 (totally overcast)

binocularly. They were instructed to write the distance and hue name of any colour that could be identified during each trial on a small formica slate. The hue names allowed were blue, green, yellow, red and violet. If the tile appeared to be a mixture of two or more hues, the dominant hue was to be recorded. This procedure was repeated until all of the coloured tiles had been presented twice to each observer (four times at the Rainbow Springs site). A blackbody distance estimate was then made by each observer, following the method described on page 44.

When the last observer had completed the task, the spectroradiometer was used to measure the spectral characteristics of the tiles at a number of distances. Enlarged copies of the tiles, each 0.09 $m^2$, were placed between the two locating marks on the perspex cross section. The meter was then moved along the guiding rails to the mark at 25 cm., and a reading taken through one of the filters. This was repeated at 50,75 and 100 cm. When all of the tiles had been measured in this way, the procedure was repeated for the two remaining filters and the photometer. To optimise time spent under water, two experimenters were involved in this process. One changed the coloured tiles in a predetermined order, while the other operated the meter and recorded the data on a formica slate. With practice, the measurements could be completed in about 15 minutes.

4.3.3. Results. The mean recognition threshold distances of the tiles at the three experimental sites are shown, together with the standard deviations and blackbody estimate, in Figures 4.5 to 4.7. In Loch Airthrey (Figure 4.5), and the Atlantic Ocean (Figure 4.6), where the visual range was short, the differences between the colours were small but systematic. The fluorescent tiles were recognised at a greater distance than the non-fluorescent tiles of the same hue name. In Lock Airthrey, the long wavelength tiles were recognised at a greater distance than the shorter wavelength tiles, whereas in the Atlantic Ocean the medium wavelengths were more recognisable. In the clear water of Rainbow Springs (Figure 4.7), the order of magnitude of the differences between colours was similar to those at the other sites, although the superiority of the fluorescent tiles was less marked. Red was the least recognisable colour, and yellow the most easily recognised. At the Rainbow Springs site also, the effects of the neutral density filters were quite marked. Covering the yellow tile reduced its recognition threshold to that of the red tile. The reduced reflectance of the blue tile resulted in its threshold distance falling below that of the green tile. Finally, reducing the reflectance of the blue and green tiles resulted in the darker blue tile having a shorter threshold distance than the darker green tile.

Repeated measures analyses of variance, summarised in Appendix K and in Table 4.4 revealed that there were statistically significant differences between the recognition thresholds of the coloured tiles at each of the three sites. On the other hand, except for one occasion in Loch Airthrey, there was no significant variation between individual observers. For the data at Rainbow Springs, orthogonal comparisons

Fig. 4.5.(a and b). Recognition threshold distances of various colours in Loch Airthrey (Experiment 4b).

Horizontal viewing path, at a depth of 3.5 m. Each of the four observers made two sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown.

Fig. 4.5(a) Date : 7-5-79

Fig. 4.5(b) Date : 8-5-79


4·5a
Background colour : Grey
± 1S.D.
Mean recognition distance (metres)
0
1
2
3
4
Blue
Green
Fl. Green
Yellow
Fl. Yellow
Red
Fl. Red
Black
4·5b
0
1
2
3
4
Blue
Green
Fl. Green
Yellow
Fl. Yellow
Red
Fl. Red
Black
Target hue name

Fig. 4.6.(a and b). Recognition threshold distances of various colours in the Atlantic Ocean (Experiment 4b).

Horizontal viewing path, at a depth of 4.5 m. Each of the four observers made two sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown.

Fig. 4.6(a) Date : 17-7-79

Fig. 4.6(b) Date : 24-7-79

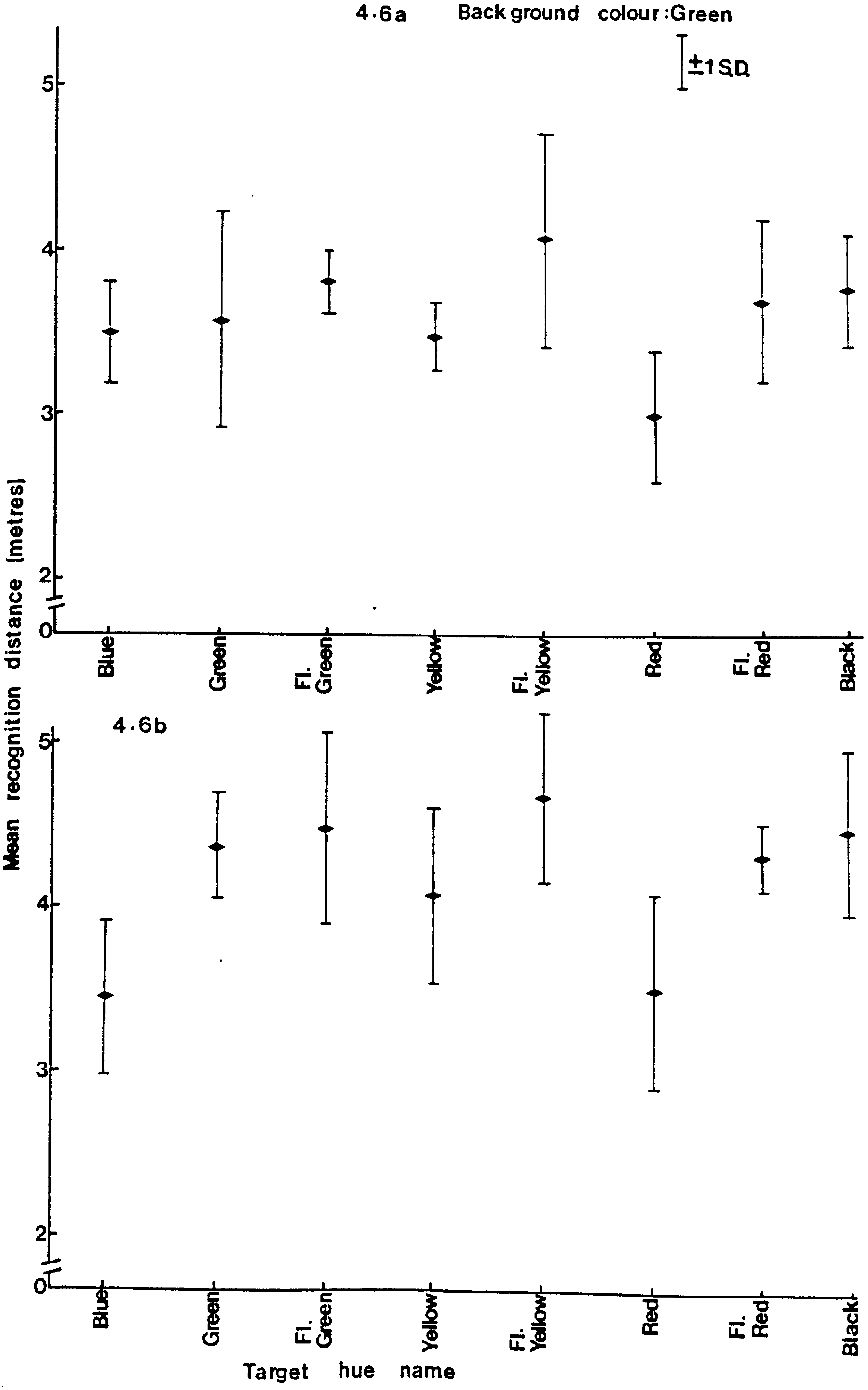
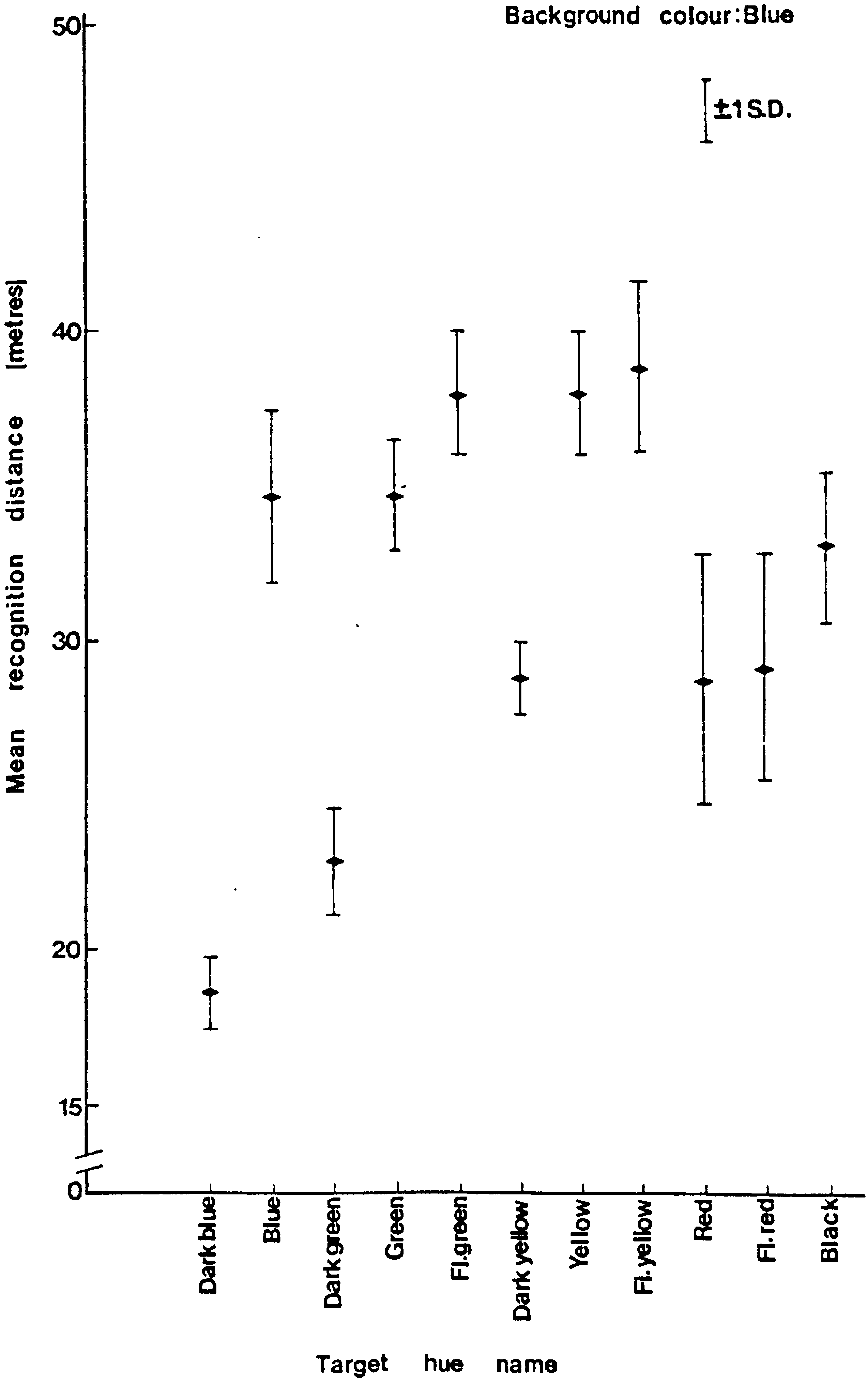

4·6a
Back ground colour:Green
±1 S.D.
5
4
3
2
0
Blue
Green
Fl. Green
Yellow
Fl. Yellow
Red
Fl. Red
Black
Mean recognition distance (metres)
4·6b
5
4
3
2
0
Blue
Green
Fl. Green
Yellow
Fl. Yellow
Red
Fl. Red
Black
Target hue name

Fig. 4.7. Recognition threshold distances of various colours in Rainbow Springs (Experiment 4b).

Horizontal viewing path, at a depth of 3m. Each of the four observers made two sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown. Date : 14-5-80.



## TABLE 4.4. Repeated measures ANOVA summary tables for Experiment 4b (recognition threshold study).

| LOCATION/DATE | SOURCE | *df* | *F* | *p* |
|---|---|---|---|---|
| Atlantic Ocean/ 17-7-79 | Tile colour | 6 | 2.75 | <.05 |
| | Subjects | 3 | 2.51 | >.05 |
| Atlantic Ocean/ 24-7-79 | Tile colour | 6 | 2.95 | <.05 |
| | Subjects | 3 | 0.59 | >.05 |
| Loch Airthrey/ 7-5-79 | Tile colour | 6 | 6.30 | <.005 |
| | Subjects | 3 | 2.66 | >.05 |
| Loch Airthrey/ 8-5-79 | Tile colour | 6 | 10.06 | <.005 |
| | Subjects | 3 | 3.97 | <.05 |
| Rainbow Springs/ 14-5-80 | Tile colour | 9 | 31.10 | <.005 |
| | Subjects | 3 | 2.90 | >.05 |

following the repeated measures analysis of variance confirmed that there was a significant difference between the red and yellow thresholds (*F* = 15.1, *df* = 1/3, *p*<.01), but not between the dark yellow and red (*F* = 0.01, *df* = 1/3, p>.05). Initially, there was no difference between the green and blue tiles (*F* = 0.05, *df* = 1/3, *p*>.05). However, when the reflectance of the blue tile was reduced, its recognition threshold distance became significantly shorter than that of the green tile (*F* = 528.9, *df* = 1/3, p<.005). The darker blue tile also had a significantly shorter threshold distance than the darker green (*F* = 37.9, df = 1/3, p<.025). Comparisons of the threshold between sites were not possible because of the differences in visual ranges at the sites, as shown by the blackbody estimates.

The data from the photometric and spectroradiometric readings at the three sites are plotted in Figures 4.8 to 4.11. A battery failure prevented readings being taken during the second test session at Loch Airthrey. The position of each target in the CIE 1931 x, y colour space has been plotted at zero viewing distance, and at the mean recognition threshold distance of the observers, by extrapolation from the measurements at the four distances, according to equation 2.6, through each of the three filters. The coordinates of the water background and of the target colours in air (under illuminant A) have also been plotted. The lines connecting the points in the figures are for visual clarity only, and bear no fixed relationship to the actual chromaticity changes with viewing distance. The figures show that the target chromaticities shifted towards that of the water background as

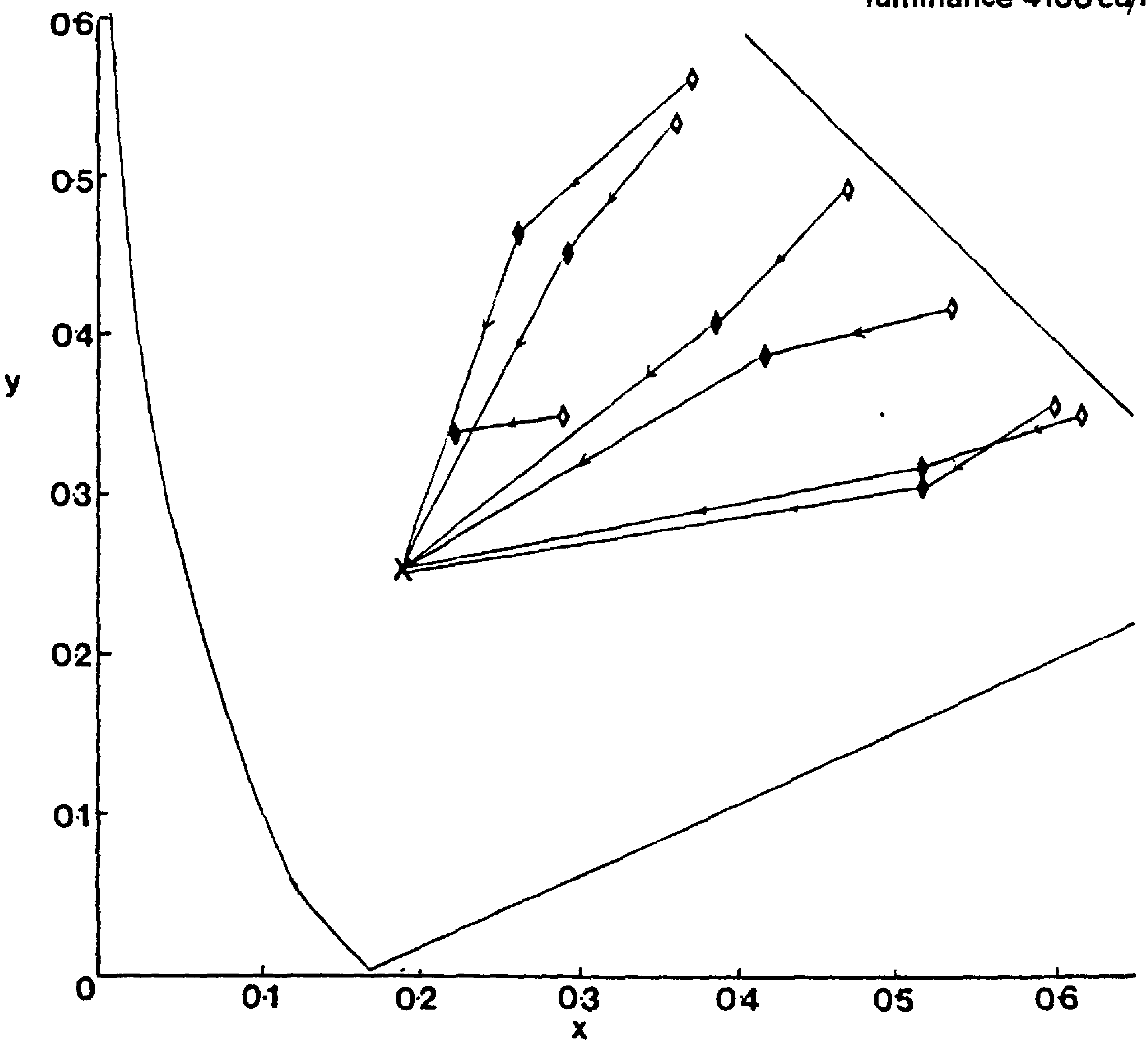
Fig. 4.8. The effect of viewing distance on the chromaticity coordinates of various targets in Rainbow Springs (Experiment 4b).

The coordinates x,y (1931 CIE colour space) of each of the standard tiles are shown in air under illuminant 'A' ( ◊ ), in Rainbow Springs at zero viewing distance ( ♦ ), and at the mean recognition threshold distance (binocular viewing) for the four observers (for visual clarity represented without symbols at the heads of the arrowed lines). The arrowed lines bear no fixed relationship to the actual change of chromaticity coordinates with increasing viewing distance between the data points. The chromaticity coordinates of the water background in the horizontal plane at the experimental depth are also given ( X ).

Fig. 4.9. The effect of viewing distance on the chromaticity coordinates of various targets in the Atlantic Ocean on 17-7-79 (Experiment 4b).

The coordinates x,y (1931 CIE colour space) of each of the standard tiles are shown in air under illuminant 'A' ( ◊ ), in the Atlantic Ocean at zero viewing distance ( ♦ ), and at the mean recognition threshold distance (binocular viewing) for the four observers ( x ). The arrowed lines bear no fixed relationship to the actual change of chromaticity coordinates with increasing viewing distance between the data points. The chromaticity coordinates of the water background in the horizontal plane at the experimental depth are also given ( X ).

4·8 Background luminance 4166 cd/m$^2$



4·9 Background luminance 86 cd/m$^2$

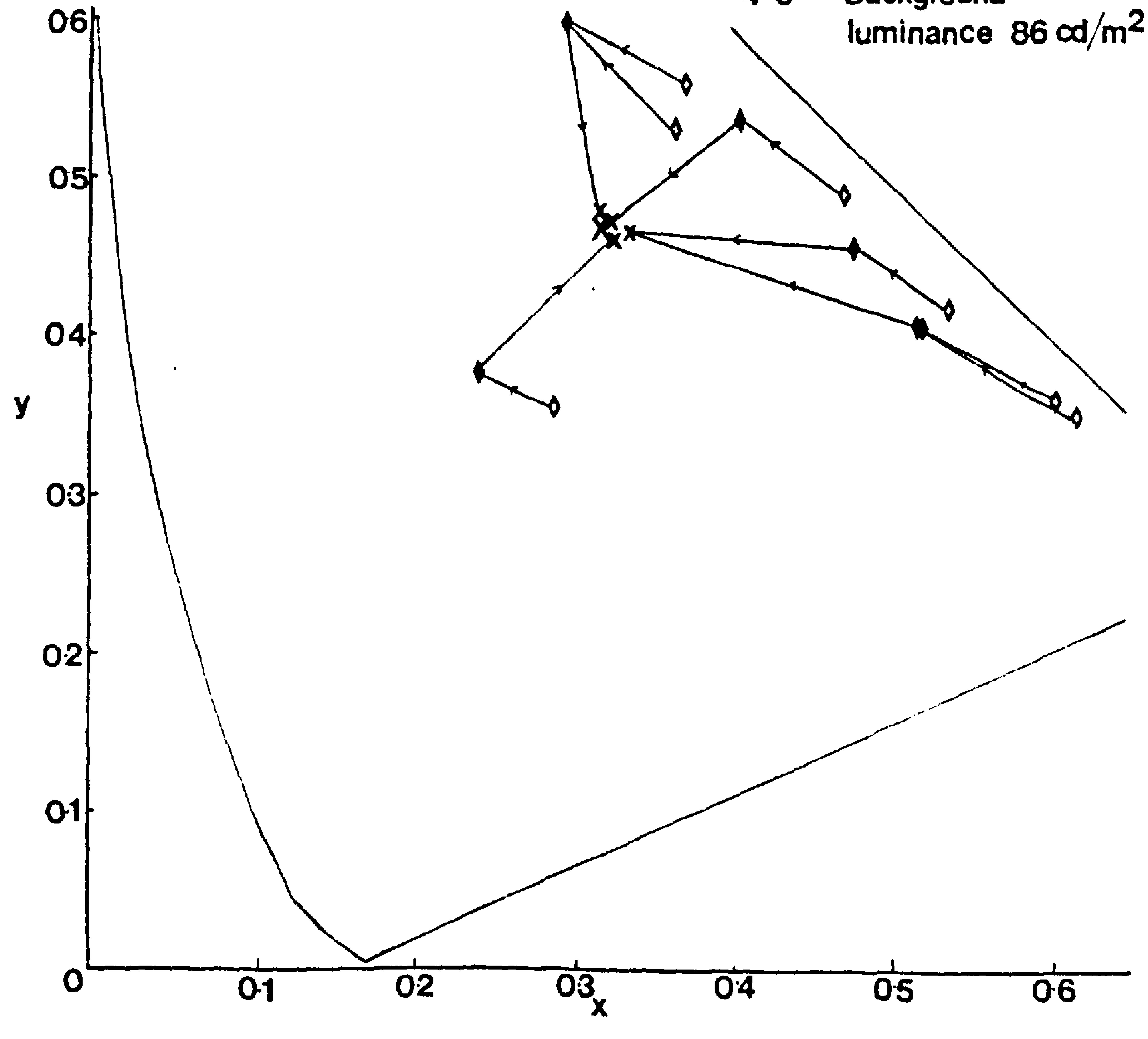
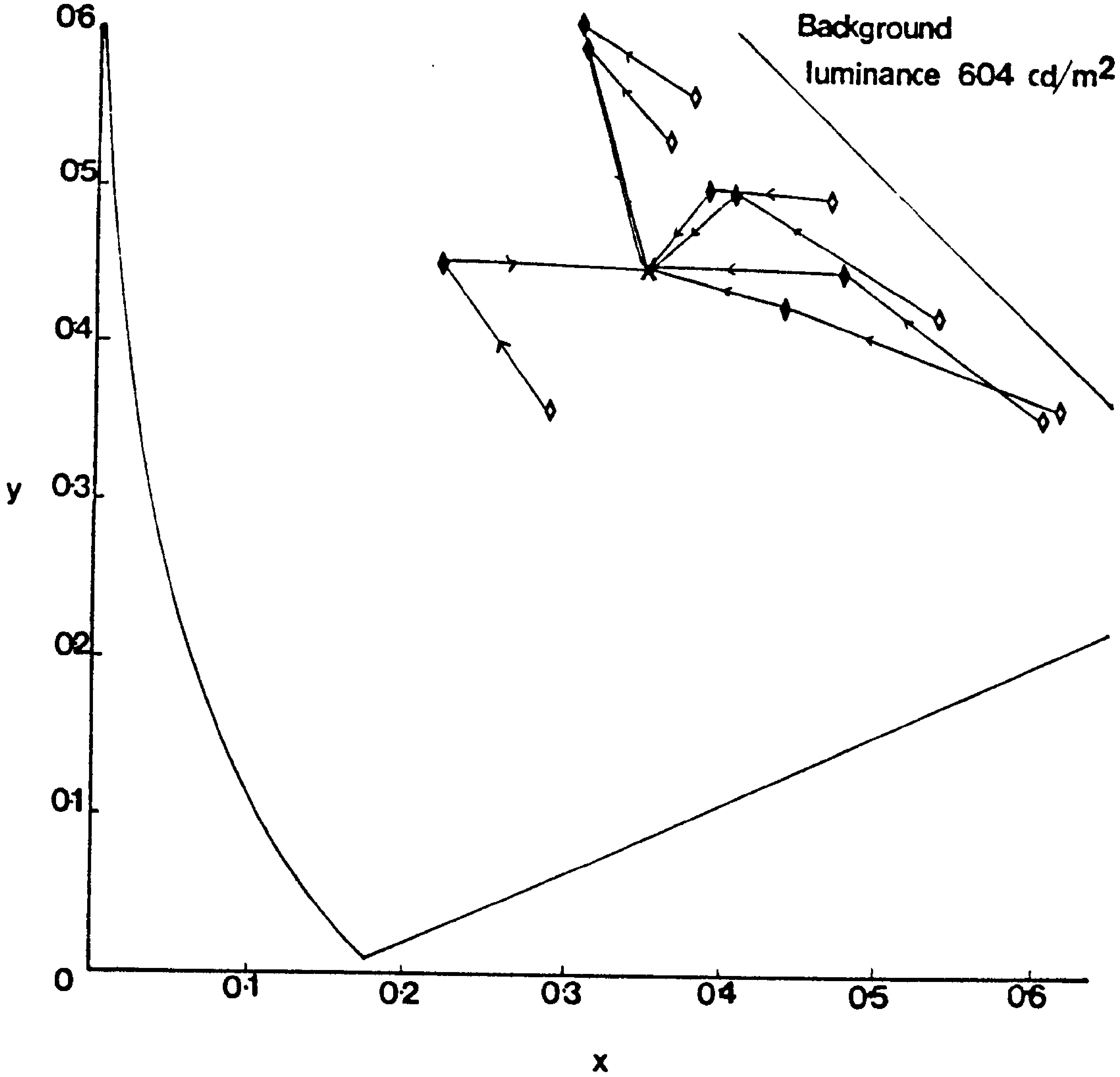


Fig. 4.10. The effect of viewing distance on the chromaticity coordinates of various targets in the Atlantic Ocean on 24-7-79 (Experiment 4b).

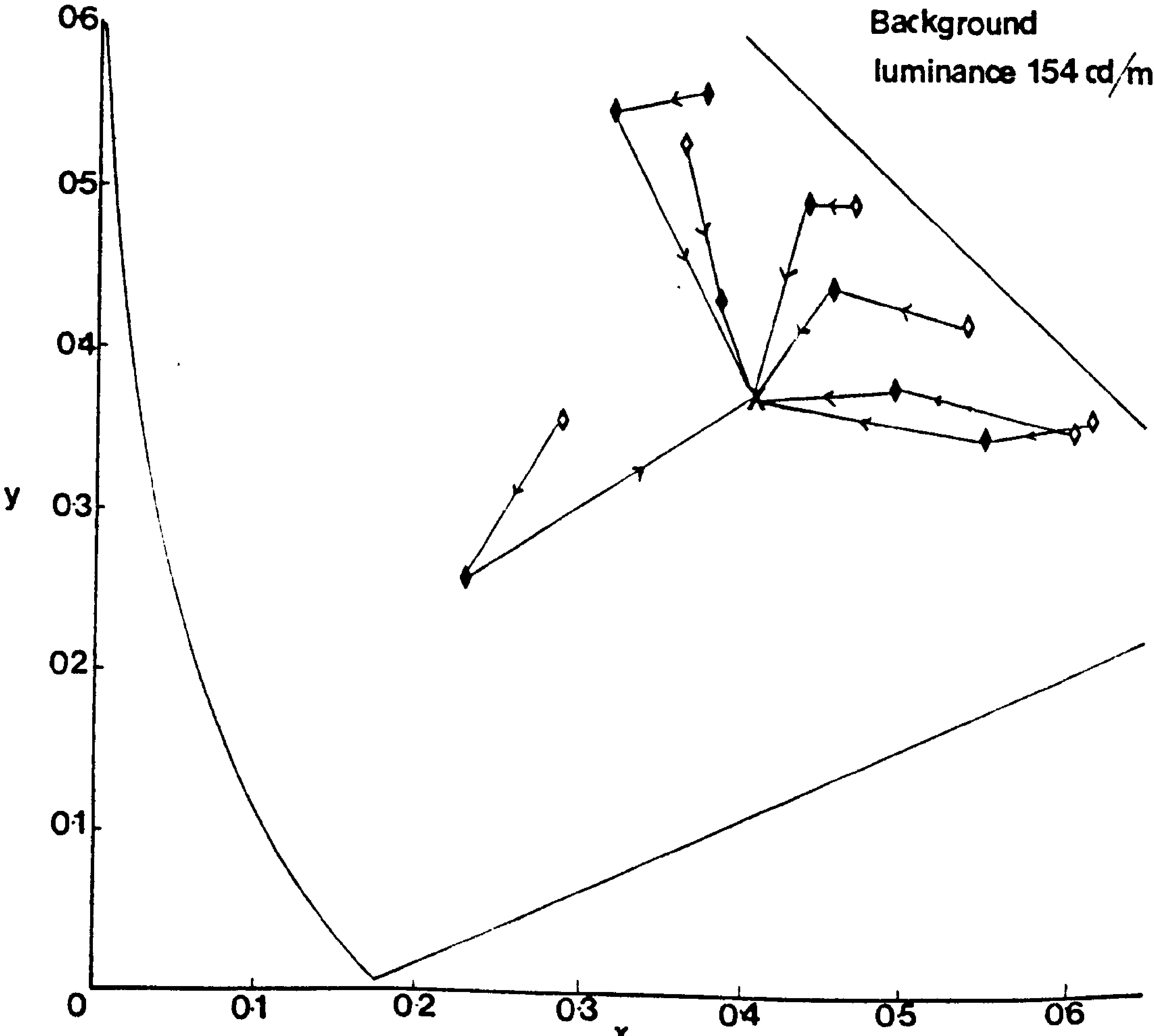
The coordiantes x,y (1931 CIE colour space) of each of the standard tiles are shown in air under illuminant 'A' ( ◊ ), in the Atlantic Ocean at zero viewing distance ( ⧫ ) and at the mean recognition threshold distance (binocular viewing) for the four observers (for visual clarity represented without symbols at the heads of the arrowed lines). The arrowed lines bear no fixed relationship to the actual change of chromaticity coordinates with increasing viewing distance between the data points. The chromaticity coordinates of the water background in the horizontal plane at the experimental depth are also given ( X ).

Fig. 4.11. The effect of viewing distance on the chromaticity coordinates of various targets in Loch Airthrey (Experiment 4b).

The coordinates x,y (1931 CIE colour space) of each of the standard tiles are shown in air under illuminant 'A' ( ◊ ), in Loch Airthrey at zero viewing distance ( ⧫ ) and at the mean recognition threshold distance (binocular viewing) for the four observers (for visual clarity represented without symbols at the heads of the arrowed lines). The arrowed lines bear no fixed relationship to the actual change of chromaticity coordinates with increasing viewing distance between the data points. The chromaticity coordinates of the water background in the horizontal plane at the experimental depth are also given ( X ).



**4·10**
Background
luminance 604 cd/m$^2$



**4·11**
Background
luminance 154 cd/m$^2$

the viewing distance increased, and were generally indistinguishable from it at the mean recognition thresholds.

## 4.4. EXPERIMENT 4c - LABORATORY STUDY

### 4.4.1. Method

4.4.1.1. Observers. Eight trained and experienced divers took part in the study. Their age range was 21 to 31 years, with a mean of 26.3 years. All had normal colour vision (on the Ishihara Colour Test) and normal or corrected visual acuity (on the Snellen Chart).

4.4.1.2. Apparatus. The stimuli were ten aluminium tiles, each 6.45 sq. cm., whose spectral reflectance curves were identical to those in the field study. They were displayed against an unobstructed water background with the experimental apparatus described in Fig 3.1, except that a larger aquarium (200 cm. long) was used. Light readings were taken with the photometer described on page 38 and the underwater spectroradiometer fronted by a 21 mm. thick filter of 2.5 percent solution of Cupric Chloride.

4.4.1.3. Procedure. The aquarium was filled with one of three solutions. One was a mixture of Aluminium Hydroxide Gel, tap water and Methylene Blue dye. The second was a mixture of the Hydroxide Gel, tap water and red writing ink (Quink). The third was a mixture of the Hydroxide Gel, tap water, Methylene Blue dye and Riboflavin. The concentration of each solution was adjusted until all of the tiles could be correctly identified within the aquarium by a preadapted observer (E), viewing binocularly through the facemask. The luminance and chromaticity coordinates of the water background in the horizontal plane at the facemask were then measured.

In a repeated measures design, each observer took part in three test sessions, within a period of one week. In each session, after an adaptation period of five minutes, the binocular recognition threshold distance of each tile was determined, using a modified method of limits. Following ten practice trials, each observer was given ten test trials with each of the stimuli, presented singly, in random order in a fixed position on the centre of the frame. On each trial, the frame was moved manually by the Experimenter (in increments of one centimetre) along the aquarium towards the observer. The observer was instructed to indicate verbally when the tile could be identified as either blue, green, yellow, red or violet. The viewing distance was also recorded. If the tile appeared to be a mixture of two or more hues, the dominant hue was recorded.

The frame was then brought closer to the observer until either a different hue name was reported or the frame reached the facemask. All subsequently reported hue names were recorded together with the viewing distances. Although the observers' adaptation levels were maintained as far as possible, rest periods were allowed at any time on request. These were followed by a further period of adaptation. Each test session lasted approximately ninety minutes.

4.4.2. Results. The chromaticity coordinates of the field and laboratory water backgrounds of Experiments 4b and 4c are compared in Figure 4.12. The figure shows that the laboratory coordinates are in reasonable agreement with those of the field sites, although the luminance levels were much lower in the laboratory. The coordinates of the backgrounds in the study of Kinney et al. (1967) have been included in the figure for comparison. No luminance values have been published for the latter data.

The mean recognition threshold distances (in centimetres) for the tiles in the three types of water in the laboratory study are shown, together with their standard deviations, in Figures 4.13 to 4.15. The figures show that the fluorescent tiles are generally recognised at a greater distance then the non-fluorescent tiles of the same hue name. Against the off-white background (Figure 4.14), the long wavelength tiles are recognised more easily than the short wavelength tiles. Against the green background (Figure 4.13), the medium wavelengths are more easily recognised, although the superiority of the fluorescent tiles is less marked. Reducing the reflectance of a tile with the neutral density filter had the general effect of increasing the recognition distance, by an amount that depended on the particular water target colour combination (see below). Repeated measures analyses of variance, summarised in Appendix K and in condensed form in Table 4.5, revealed that there were statistically significant differences between the recognition threshold distances of the coloured tiles within each water

Fig. 4.12. Comparison of the chromaticity coordinates of the water backgrounds in Experiments 4b and 4c with those in Kinney et al. (1967).

The coordinates x,y (1931 CIE colour space) were measured in the horizontal plane in the following conditions (luminance levels given in brackets) :

Field studies

1.♦ Atlantic Ocean (86 $cd/m^2$)
2.♦ Atlantic Ocean (604 $cd/m^2$)
3.♦ Loch Airthrey (154 $cd/m^2$)
4.♦ Rainbow Springs (4166 $cd/m^2$)

Laboratory studies

5.■ Green background (17 $cd/m^2$)
6.■ Off-white background (18 $cd/m^2$)
7.■ Blue background (17 $cd/m^2$)

Results from Kinney et al. (1967)

8.◊ Gulf of Mexico (-)
9.◊ Long Island Sound (-)
10.◊ Morrison Springs (-)

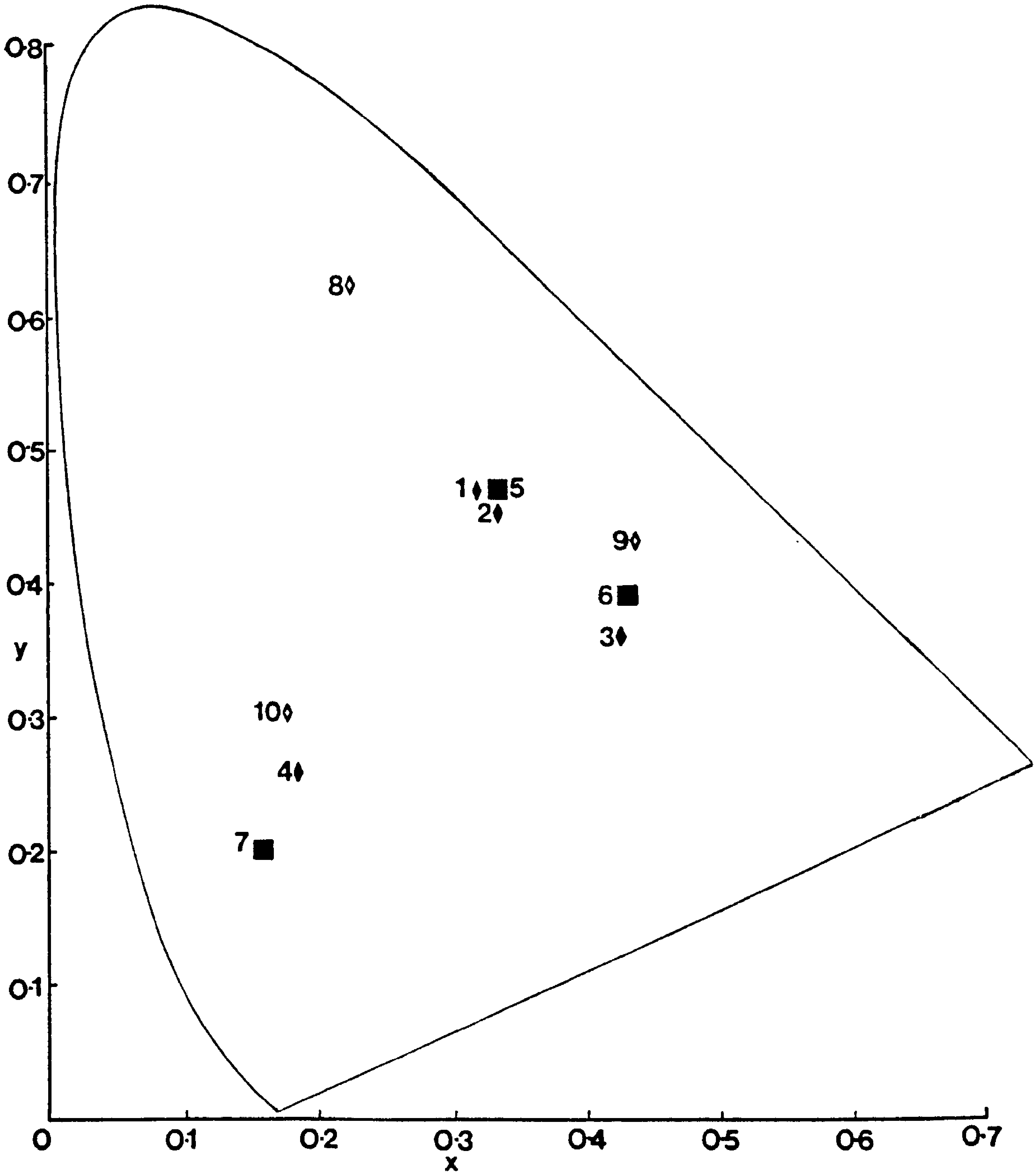

0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
y
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
x
8
1
5
2
9
6
3
10
4
7

Fig. 4.13. Recognition threshold distances of various colours against a green water background (Experiment 4c).

Horizontal viewing path. Each of the eight observers made ten sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown.

Fig. 4.14. Recognition threshold distances of various colours against an off-white water background (Experiment 4c).

Horizontal viewing path. Each of the eight observers made ten sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown.


4·13 Background colour :Green
± 1 S.D.
36
32
28
24
20
16
0
Dark blue
Blue
Dark green
Green
Fl. green
Dark yellow
Yellow
Fl. yellow
Red
Fl. red
Black
4·14 Background colour :Off- white
± 1 S.D.
70
60
50
40
30
20
0
Dark blue
Blue
Dark green
Green
Fl. green
Dark yellow
Yellow
Fl. yellow
Red
Fl. red
Black
Mean recognition distance [cms.]
Target hue name

Fig.4.15. Recognition threshold distances of various colours against a blue water background (Experiment 4c).

Horizontal viewing path. Each of the eight observers made ten sightings of each colour (binocular viewing). The mean detection threshold distance of the black target is also shown.


Background colour: Blue
± 1 S.D.
Mean recognition distance (cms.)
150
140
130
120
110
100
90
80
70
60
50
40
0
Dark blue
Blue
Dark green
Green
Fl. green
Dark yellow
Yellow
Fl. yellow
Red
Fl. red
Black
Target hue name

TABLE 4.5. Repeated measures ANOVA summary tables for Experiment 4c (recognition threshold study)

| WATER COLOUR | SOURCE | df | F | p |
|---|---|---|---|---|
| Blue | Tile colour | 9 | 53.70 | <.005 |
| | Subjects | 7 | 14.32 | <.005 |
| Green | Tile colour | 9 | 634.10 | <.005 |
| | Subjects | 7 | 84.42 | <.005 |
| Off-white | Tile colour | 9 | 9.90 | <.005 |
| | Subjects | 7 | 0.40 | >.05 |

type. Individual differences between subjects were significant in the green and blue water types, but not in the off-white condition. Following the analyses of variance, a number of orthogonal comparisons were made to investigate the relative thresholds of specific colours. The results are shown in Table 4.6 The table confirms that the reduction in tile reflectance due to the neutral density filters had different effects in the three types of water. Against the green background, the thresholds of the yellow and red tiles were reversed when the yellow tile was made darker. The neutral density filter also made possible the reversal of the thresholds for the green and blue tiles when both tiles were made darker. Against the off-white background, the darker yellow tile was was significantly less recognisable than the red tile, although the standard red and yellow tiles were equally recognisable. The recognition threshold distances of the green and blue tiles decreased when they were made darker, although their relative thresholds were unaltered. Finally, against the blue background, the darker yellow had the same recognition threshold as the standard red tile, although the standard yellow was significantly more recognisable than the standard red. The darker blue was the least recognisable of all the tiles, and was significantly less recognisable than the green tile. The standard blue tile was also less recognisable than the standard green tile, and the darkerblue tile was sigificantly less recognisable than the darker green.

TABLE 4.6. Summary table of orthogonal comparisons for Experiment 4c (recognition threshold study).

| WATER COLOUR | TARGET COMPARISON | df | F | p | Direction of difference[1] |
|---|---|---|---|---|---|
| Blue | Red/yellow | 1/7 | 22.3 | <.005 | yellow |
| | Dark yellow/red | 1/7 | 0.5 | >.05 | - |
| | Blue/green | 1/7 | 13.5 | <.025 | green |
| | Dark blue/green | 1/7 | 328.5 | <.005 | green |
| | Dark blue/dark green | 1/7 | 263.4 | <.005 | green |
| Green | Red/yellow | 1/7 | 54.0 | <.005 | yellow |
| | Dark yellow/red | 1/7 | 21.5 | <.005 | red |
| | Blue/green | 1/7 | 32.0 | <.005 | green |
| | Dark blue/green | 1/7 | 222.0 | <.005 | green |
| | Dark blue/dark green | 1/7 | 88.3 | <.005 | blue |
| Off-white | Red/yellow | 1/7 | 3.8 | >.05 | - |
| | Dark yellow/red | 1/7 | 239.1 | <.005 | red |
| | Blue/green | 1/7 | 0.0 | >.05 | - |
| | Dark blue/green | 1/7 | 77.9 | <.005 | green |
| | Dark blue/dark green | 1/7 | 0.1 | >.05 | - |

[1] The named target is that which had the greater recognition threshold distance.

## 4.5 DISCUSSION - EXPERIMENTS 4a, b and c.

### 4.5.1. Comparisons of the present data with previous findings

4.5.1.1. General comparisons. The presence of a spectrally biased water background considerably complicates the experimental manipulation of the colour recognition task, because it is possible for the hue, saturation and brightness of the colour to interact with the same dimensions of the water background. Consequently, it is essential that clear specifications be made of the water background and target colours. Such specifications have been infrequently attempted, however. The failure to specify the luminance levels in the study of Kinney et al. (1967), for instance, restricts comparison with the present data to a general level. As an extreme example of the problems inherent in this type of comparison, one might note that a tile having chromaticity coordinates $x = 0.31$, $y = 0.31$ could appear black or white, depending on its luminance factor. Furthermore, caution is required in the interpretation of the chromaticity coordinates in the Kinney et al. study, because they were calculated from the laboratory measurement of a water sample, coupled with specification of the beam attenuation coefficient without reference to wavelength. Finally, the specifications of the targets in air in their study were ambiguous, because they were given in terms of chromaticity coordinates but without reference to an illuminant.

It is with these considerations in mind that comparisons are made between the test sites used in the study of

Kinney et al. and the present experiments. Figure 4.12 confirms that the chromaticity coordinates of the water backgrounds are generally comparable. The greatest difference would appear to be between the Gulf of Mexico and the Atlantic Ocean. The most likely reason for this is that the coordinates of the former are plotted for a pathlength of 34 metres (presumably calculated by adding the depth of 18 metres to the viewing distance of 16 metres), whereas the visual data were obtained at two depths (8.6 and 18 metres) and with two pathlengths. The 8.6 metre condition, which was not published, and which can be assumed to be more appropriate for comparison with the present data, would almost certainly plot closer to the Atlantic Ocean coordinates.

More importantly, however, Figure 4.12 also shows the chromaticity coordinates for the laboratory experiments in the present study. The correspondence between the data from the three laboratory water types and the field sites is closer than between the field data and the Kinney et al. field data. The luminance differences between the field and laboratory data are due to the difficulty of reproducing high levels of luminance in the laboratory, where high levels of attenuation are required. The luminances in all of the conditions in the present studies were above the photopic threshold, however, and it is probably reasonable to assume that the observers adapted to some approximately common level.

Given the approximate correspondences between the three sets of test conditions, it is interesting to note the similarities and differences between the psychophysical data, particularly in relation to the differences between the standard and 'dark' tiles. Comparing the two sets of field data first, it can be seen from Figures 4.2 and 4.6 that the green backgrounds of the Gulf of Mexico and the Atlantic Ocean confirm the superiority of the fluorescent colours (particularly the yellow) over the non-fluorescent standard colours of the same hue name. Of the standard colours, red was the least easily recognised, although this effect was less marked in the Atlantic Ocean. On the other hand, there were differences between the two sites and between the data obtained at the Atlantic Ocean site on different dates. Thus, although the relative recognition thresholds of the standard yellow and green tiles were reversed between the Gulf and the Atlantic on 17-7-79, the tiles were almost equally recognisable on 24-7-79.

A comparison between Loch Airthrey and Long Island Sound (Figures 4.5 and 4.2) revealed that there was close agreement between the data for the non-fluorescent standard tiles, although the relative recognition thresholds of the fluorescent green and yellow were reversed. Finally, in the two clear water conditions (Figures 4.7 and 4.2), the fluorescent and standard reds were much less recognisable than the other colours. Fluorescent yellow was the most recognisable colour. Standard blue and green were equally recognisable in Rainbow Springs, although the blue was more recognisable than the green in Morrison Springs.

The pyschophysical data obtained in the laboratory experiments also show similarities and differences with both sets of field data. In contrast with the data of Kinney et al. for the Gulf of Mexico, for example, Figure 4.13 shows that the standard blue was less recognisable than the other standard colours, and that standard red was equally recognisable with the standard green. On the other hand, standard yellow was the most easily recognised colour in both studies. The relative recognition thresholds of the standard colours in Long Island Sound and the off-white background (Figure 4.14) were also similar. Finally, a comparison of the data from Morrison Springs and Figure 4.15 confirms that the recognition thresholds of the standard blue and green were reversed in the two conditions. In both conditions, standard red was the least recognisable colour and yellow the most recognisable.

The data from the present field and laboratory data show the closest agreement of the three overall comparisons. Even so, for closely matched background chromaticities, the relative recognition thresholds of the tiles were not identical. Thus the thresholds of the non-fluorescent standard green and yellow were reversed between the Atlantic Ocean and the green laboratory condition, and the non-fluorescent standard blue and green thresholds were reversed between Rainbow Springs and the blue laboratory condition. Nonetheless, because different observers participated in the field and laboratory studies, it is possible that these small differences were partly a result of individual differences. These differences were found to be significant in the laboratory for both the green and blue water backgrounds. No reversals of the fluorescent colours were obtained.

At least three explanations can be proposed to account for the differences and similarities between the three sets of data. The first, which emphasizes the differences, ascribes importance to the methodological differences between the studies. For instance, in the Kinney et al. study, observers viewed all of the targets at the same distance (the mean recognition distance of all of the targets). The data were then analysed in terms of the percentage of targets correctly identified. Consequently, it is difficult to assess data such as those for the Gulf of Mexico (Figure 4.2), where four of the six fluorescent colours were recognised with 100 percent accuracy. Clearly, the effects of such methodological differences are difficult to quantify without further experimentation.

A second explanation considers the similarites between the present data and those of Kinney et al. as partly attesting to the robustness of the physical phenomenon of wavelength absorption by water and its impurities. This argument is supported by the fact that the reduction in the reflectance of tiles having a similar hue to that of the background had a disproportionate effect on the recognition thresholds of those tiles. In Figure 4.15 for example, against a blue background, a reduction in th reflectance of the blue tile caused an increase in the recognition threshold that was greater than that resulting from the reduction of the reflectances of the other tiles. Against a green background (Figure 4.13), the same effect was obtained for the green tile. In the off white water (Figure 4.14), on the other hand, which was almost spectrally neutral, no such disproportionate effects were observed. These results might be explained by assuming that a tile whose dominant wavelength is slightly offset from that of the background can remain recognisable by virtue of chromatic differences with the background in the absence of a brightness difference. For a tile similar in hue and saturation to the background, however, a reduction in the level of its reflectance, might result in it being indistinguishable from the background. The stability of the phenomenon is probably an important influence on the similarity between the findings of Kinney et al. (1965), Hemmings (1966) Luria et al. (1967), Lingrey (1968), Kinney and Miller (1974) and Fay (1976).

At the same time, it is clear from the present laboratory and field data that the reductions in the tiles' reflectances by the neutral density filters were sufficient to alter their relative recognition thresholds, even though the shapes of the reflectance curves remained the same. Consequently, the similarities discussed above must be considered to be limited to fairly specific target-background combinations. The present data therefore support the view that it can be misleading to generalise about 'the visibility' of colours on the basis of their hue names, and point to the crucial role of a target's brightness in determining its recognition threshold within a particular water body. On this view, therefore, the brightness differences between the targets in the Luria et al. study and the present experiments are considered to be an important influence on the relative recognition thresholds. Unfortunately, because the two sets of targets were not matched for hue and saturation, this hypothesis cannot be formally tested.

### 4.5.2. The case of red and yellow targets.

The complex relationship between a target and its background can be illustrated by the apparent discrepancy between the present and previous data for the standard red and yellow targets. Lythgoe (1969) and Lythgoe and Northmore (1973) have argued convincingly that yellow in clear blue water and red in green water would be particularly recognisable. This argument was based on calculations from the data of Tyler and Smith (1970), observations of fish colouration in different types of water, and experimental evidence. The present data suggest that the argument cannot be universally applied however. Comparison of Figures 4.6 and 4.13 with Figures 4.7 and 4.15 show that for the non-fluorescent colours, although the standard yellow is more recognisable than the standard red in the blue water of Rainbow Springs and the laboratory, the red is less easily recognised than the yellow in the green water of the Atlantic Ocean and the laboratory. The same result was obtained by Kinney, Luria and Weitzman (1967) in the Gulf of Mexico and Morrison Springs, and Hemmings (1966) in the Moray Firth and the Mediterranean Sea.

The likely explanation for this discrepancy can be inferred from the psychophysical data for the dark yellow tile. Figures 4.7 and 4.15 confirm that when the reflectance of the yellow tile was reduced, the recognition threshold distance was reduced relative to the red tile. In addition to the differences in reflectance at specific wavelengths, the targets differed in the total amount of energy reflected - the yellow tile having the greater reflectance at all wavelengths. The fluorescent red tile reflected more energy than the standard red, and approximately the same amount as the standard yellow. Figures 4.6 and 4.13 show that when the fluorescent red is compared with the standard yellow, Lythgoe's prediction is fully confirmed. The same result was obtained by Kinney et al. (1967) for red, fluorescent red and yellow targets in the Gulf of Mexico and Morrison Springs. It seems reasonable to conclude, therefore, that the full colourimetric specification of a target provides the most useful basis for the discussion of its recognition threshold. This might explain why the present data do not fully support the assertion of Lythgoe (1979, p. 184) that complementary colours should be approximately equally conspicuous within the same type of water (although it is also possible that the conspicuousness of a target is more appropriately a measure of its detection threshold rather than its recognition threshold).

At the same time, it is interesting to note that the present data lend support, in the domain of colour recognition, to the suggestion of Lythgoe and Northmore (1973) that for the detection threshold, the physiology of the eye is not a limiting factor. In their computer study, no combination of known visual pigments could reverse the visibility of a red and yellow target in blue water. In the present experiments, the change in target specification was sufficient to effect the reversal.

### 4.5.3. Fluorescent colours.

A further interesting feature of the data is the marked reduction in the advantage of fluorescent over comparable non-fluorescent tiles in the relatively clear blue water of Rainbow Springs and the laboratory, compared with the other conditions. The explanation for this effect was proposed by Kinney et al. (1967). The required exciting energy range for fluorescence (approximately 400 - 520 nm) is normally transmitted quite well under water, so that fluorescent targets should be highly recognisable at short ranges. At a shallow depth in Rainbow Springs, however, the fluorescence is lost before reaching the eye, and the fluorescent red, for example, is not much more easily recognised than the non-fluorescent red.

### 4.5.4. Individual differences between observers.

Apart from the brief consideration given by Hemmings (1966), individual differences have been largely omitted from consideration in underwater colour vision experiments. Subjectively, it might be anticipated that such differences would be rather great, given the individual differences in laboratory studies of colour vision. It might therefore be considered surprising that no significant differences were found between observers in four of the five field experiments (Table 4.4). In the laboratory experiments, on the other hand, these differences were significant in both the green and blue water types, but not in the off-white (Table 4.5). It is not immediately apparent how these data can be accounted for. The laboratory data suggest that the strongly chromatic backgrounds made the recognition task difficult and facilitated inter-individual variation. On the other hand the field data were probably influenced by the small number of observers who participated in the test sessions. Currently, therefore, it appears necessary to restrict comments on individual differences to merely indicating their presence and to pointing to the need for further research into this potentially important variable.

### 4.5.5. Difficulties for a model of colour detection and recognition.

The question also arises whether it might be possible to extend the visibility model outlined in Chapter 3 to include the detection and recognition of coloured objects. At the simplest level, the input requirements for such a model would be similar to those previously specified, namely target size, the beam attenuation coefficient (at several wavelengths), the adaptation luminance and the inherent spectral contrast between the target and the water background. For non horizontal sight paths, the diffuse attenuation coefficient would also be required on a wavelength basis.

**4.5.5.1. Chromatic discrimination.** A colour detection or recognition model is almost certain to be subject to the same problems of assessing chromatic discrimination as have been previously outlined (Appendix J). In the present studies, for instance, chromatic discrimination was certainly affected to some degree by blur. Other aspects of chromatic border discrimination would also complicate the prediction model. Differences in the red-green direction, for example, relate not only to colour, but can also support a contour between two fields of equal luminance. Differences in the yellow-blue direction, on the other hand, seem related to hue only (Boynton Hayhoe and McLeod, 1977). Although target size is not normally a limiting factor in underwater vision, an inherently small object in clear water might attain a size which could influence its perceived colour - as an extreme example, an object subtending 15' of arc at the retina is perceived as if the observer is tritanopic (Hunt, 1979). Colour discrimination is also impaired if the observer stares at a coloured field for a prolonged period (McCree, 1960), and will be influenced by the Ganzfeld-like conditions often encountered under water. Finally, in dynamic viewing conditions (with the observer or target moving), it would also be necessary to include the issue of colour discrimination in the peripheral visual field.

4.5.5.2. Chromatic adaptation. Although it is appropriate to discuss colour threshold differences under water in terms of the colour filter effect of water, various authors have pointed to the potential importance of chromatic adaptation. Kinney et al. (1967) found that the colour names given to a series of spheres viewed near the limits of visibiltiy often corresponded to the colour names given to the the same spheres in air. Lingrey (1968), Behan, Behan and Wendhausen (1972) and Fay (1976) have also reported differences between perceived and photographically recorded colour. Finally, Kinney and Cooper (1967) have confirmed the role of adaptation in such differences. To enable an estimate of the effects of such adaptation, some form of comparison between the eye and a non-adaptive colour meter is therefore required.

Clearly, colour naming, is not the most sensitive method for investigating chromatic adaptation. Nonetheless, some clear examples of such adaptation are shown in Figures 4.8 to 4.11. In Figure 4.8 for example, the physical specifications of the long wavelength tiles at threshold are outside the region of colour space normally associated with their hue names. Similar effects are present at the Atlantic Ocean site for the long and short wavelength colours (Figures 4.9 and 4.10), and for most of the tiles at the Airthrey Loch site (Figure 4.11).

The underwater studies that have found evidence for the presence of chromatic adaptation allow a general comparison with the present data. Thus, it is interesting to note that one aspect of the adaptation found by Kinney and Cooper (1967), namely the appearance in blue-green water of yellow-red colours, despite the absence of long wavelength energy in the target and the background, is also noticeable in Figure 4.8. Similarly, Kinney, Luria and Weitzman (1967) calculated a large physical shift in the colour of a blue sphere in the Gulf of Mexico, although some of the observers still reported it as blue. This finding is replicated with the shift in the specification of the blue tile in the Atlantic Ocean in Figures 4.6 and 4.9 and 4.10. Such colour shifts are also consistent with the recent laboratory data of Ware and Cowan (1982), who found that red, green and blue inducing stimuli caused test stimuli to shift their appearance away from the chromaticity coordinates of the inducing stimulus.

As indicated in Appendix J, a detailed, quantitative account of the chromatic adaptation process has yet to appear. That such an account might still be some way from realisation is suggested by the number of mathematical models available to explain the process. For a white target viewed against the red background of a peat loch, for example, the model proposed by Adelsen (1981) predicts two effects. First, the sensitivity of long wavelength cones should fall relative to middle and short wavelength cones, so that the target would appear less red and more blue-green. Second, the background would also add its own redness to the white. These effects would be approximately opposite. However, when the white patch is dim, the additive effect would dominate, and when the patch is bright the multiplicative effect would be the stronger; the hue would therefore change from reddish to blueish green as the patch intensity increased. Clearly, more psychophysical data are required to provide a base upon which an accurate colour recognition model could be constructed.

4.5.5.3. The role of background luminance. Another problem is that because relatively little attention has been paid to absolute energy levels, the issue of mesopic vision does not seem to have been considered in most discussions of colour visibility. Yet, as Lythgoe (1971) has shown, divers in turbid water can pass from full photopic vision at the surface to full rod vision at a depth of only 20 metres. Estimates of the minimum luminance level required for photopic vision vary; however a figure of 1 to 10 $cd/m^2$ is representative. Figures 4.7 and 4.8 confirm that a significant reduction in adaptation luminance can occur at a depth of only a few metres in natural water bodies. Consequently the potential applications of a colour visibility model that ignored the mesopic region would be limited.

Unfortunately, the visual data for the mesopic region are likely to add significantly to the complexity of a model of underwater visibility. Despite advances in our understanding of the spectral sensitivity curves in the mesopic region (Stabell and Stabell, 1975, 1976), the problem remains that they cannot be interpolated from the standard scotopic and photopic functions. No single nomogram exists for the mesopic region, so that it is necessary to know the relative amounts of rod and cone activity. To complicate the situation still further, rod intrusion can also occur when the field of view is greater than 2° (Trezona, 1976). The extent of the intrusion also varies with the luminance level (Judd and Wyszecki, 1975). Finally, it must be noted that when the intensity of the illumination changes, it is possible for the apparent hue and saturation to change also, even if the actual wavelengths presented remain the same (the Bezold-Brücke effect).

4.5.5.4. Limitations of colour measurement systems. Perhaps the most serious limitation to the construction of a colour visibility model is that because detection and recognition are tasks involving colour differences, their quantification is restricted by the level of accuracy with which such differences can be represented. Unfortunately, this level is currently not as high as might be hoped for.

The traditional treatment of colour as a three dimensional concept has led to attempts to represent the relationships between colours by distinct points in colour space. However, although a colour can be sucessfully located within a three dimensional colour space through the linear vector addition of three primaries (in accordance with Grassman's Laws), equal distances within the same colour space do not represent equal noticeable differences to the human eye.

Following Helmholtz, colour differences have been frequently represented by line element equations of various forms, of which some are quite complex (for example, Vos and Walraven, 1972a). The common feature of all line element equations important to colour science is that they relate to Riemannian space, within which the geodisic lines between points in space are curved. The three dimensions of tristimulus space, however, are Euclidean,within which all geodisics are straight. The question arises, therefore, whether a transformation exists between the two types of space that preserves the equality of distances required by line element equations. Two approaches can be taken. Either a line element equation can be modified until it sucessfully predicts tristimulus space, or the tristimulus space can be modified to represent equal perceptible differences.

According to Silberstein (1943), such a transformation is not possible. Furthermore, because of the Gaussian curvature of space, the mapping of Riemannian space in terms of Euclidean space might require as many as six Euclidean dimensions. To map one dimension into another and preserve distance, the two spaces must have the same Gaussian curvature. Euclidean space, therefore, having no curvature, can only be mapped without distortions by having considerably more dimensions. Despite this difficulty, there has been no shortage of attempts to reduce the discrepancies to an acceptable level. Those attempts dealing with transformation of colour space are particularly relevant to the present discussion. A useful historical perspective on these transformations has been given by Judd and Wyszecki (1975).

During the 1960's the CIE recommended the use of two colour difference formulae (CIELAB and CIELUV) in an attempt to promote some degree of uniformity of practice. More recently, it has been decided to recommend the adoption of the CIELAB system (Hill, personal communication). For most practical purposes, the colour spaces associated with these formulae are the closest approximation to a uniform colour space yet achieved. Indeed, the CIELUV system would have been an appropriate metric for the present data had it not been desired to compare them with those of Kinney et al. (1967). Unfortunately, even the best available colour difference formulae are poor predictors of colour appearance. Thus Kuehni (1976) found a correlation coefficient of only 0.68 between the visual acceptability and calculated colour difference using the CIELAB formula, and concluded that its use produced "a significant error in approximating visual colour differences by calculated colour differences (p. 499)." Furthermore, these findings relate to small colour differences. Over large colour spaces (greater than five j.n.d.'s.) it might be expected that different transformations would be required for different areas traversed. Accordingly, although the types of data presented in Figures 4.8 to 4.11 might be seen as a useful basis upon which to build a colour recognition and detection model (using colour difference formulae to quantify the threshold), it remains to be seen how accurately this method would be in predicting such thresholds. In addition the variable effects of chromatic adaptation evident in the figures suggest that much empirical data would need to be collected.

4.5.5.5. The definition of visibility. Finally, the data of Experiment 4a lend support to Lythgoe's suggestion that "the visibility of colours is a very broad phrase that needs more carful definition..." (Lythgoe, 1971, p. 133). The differential effect of increasing target brightness on the recognition and detection thresholds (Figure 4.3) emphasises that the potentially different requirements of visibility models will require specific sets of baseline data. For example, where efficient colour coding is required, the recognition threshold will be more relevant than the detection threshold, because the relative recognition thresholds of different colours may not be the same as their relative detection thresholds. Similarly, it would be important to establish in this example the nature of the colour confusions made by the observers (Kinney et al., 1967). In the future, it would be clearly convenient for investigators to adopt common defintions for the various aspects of visibility.

### 4.5.6. Conclusions

In the light of these difficulties, the prospects for the construction of an accurate detection or recognition model might appear poor. Nonetheless, it should also be considered that the utility of this or any model is partly determined by the requirements of the user. By adopting first order approximations and accepting wider margins of error, some of the limits implied by the above discussion can be removed. For example, by specifying 'standard' paints for underwater use, it might be possible to achieve the degree of generality implied by Kinney et al. (1967). If, on the other hand, a more rigorous model is required, it will be necessary to specify the chromaticities and brightnesses of both target and water background, and of the observers' responses to them. In view of the main conclusion to be drawn from the present experiments, that there is no fixed relationship between a target's hue name and its relative recognition threshold within a given water body, it would appear important to attempt to define the limits of such variation.

# CHAPTER FIVE - COLOUR APPEARANCE AND VIEWING DISTANCE

## 5.1 INTRODUCTION

### 5.1.1. Preliminary remarks.

The question has frequently been asked how the human eye can adapt to changes in the quantity and quality of the illumination to which it is exposed. For colour vision under water, this question is important, because a diver is often required to view under conditions of markedly biased chromatic illumination, which cause the reflection of spectral radiances from objects that are different from those that would be reflected by the same objects in air. The experiments to be described in the present chapter are concerned with the appearance of coloured objects under such conditions. Specifically, the aim was to investigate the relationship between the constancy of colour appearance and viewing distance.

The phenomenon of colour constancy has attracted the interest of researchers with differing theoretical orientations. Following Helmholtz and Hering, two major traditions have assigned importance to either the unconscious registration of illumination or to simultaneous colour contrast. Arguments relating to both viewpoints have been well documented and will not be repeated here. Useful summaries have been compiled by Graham and Brown (1965) and Hochberg (1971). A general survey of perceptual constancy that includes sections on brightness and colour has also appeared recently (Epstein, 1977).

### 5.1.2. Beck's theory of colour constancy.

Data from brightness and colour constancy experiments suggest that both elementary sensory processes and less specific higher order cognitive mechanisms are involved. Although the Helmholtzian concept of unconscious inference has been unpopular with both psychologists and physiologists, the possibility that illumination can provide cues which aid constancy has led some theorists to be reluctant to abandon the concept altogether. Beck (1972) explained how such cues might be used. He proposed that the perception of surface colour has two components, (a) sensory processes of transduction, enhancement and abstraction, such as adaptation, contrast, and contour formation, that determine a central neural pattern of the peripheral spectral distribution, and (b) 'schemata', trace representations of a surface colour, with which the sensory signals can be interpreted and compared. In particular, the observer was assumed to gain an impression of the illumination from such features as highlights and other non-uniform reflectances.

The concept that illuminance can be registered indirectly provides a clear similarity between Beck's position and that adopted by Helmholtz (1866, 1962), and apparently helps to explain a number of findings. For example, it could explain the breakdown of constancy when the stimuli are viewed through a reduction screen. Nonetheless, there is an important difference between the two theories. Whereas Beck implies only that cues to illumination may have an effect on perceived colour (Beck, 1965), Helmholtz assumed a precise covariance between the perception of illumination and colour (Hochberg, 1971). This difference is highlighted by the finding that good illumination judgements are difficult to obtain (Beck, 1974), and that lightness constancy occurs in the absence of accurate judgements of illumination (Beck, 1959, 1961). The validity of the Helmholtzian theory is further impugned by evidence reviewed in Hochberg (1971), that learning is not a prerequisite for constancy in children, and that it can be exhibited by animals to the same degree as found in humans (Burkamp, 1925; Locke, 1935).

For Beck, the perceptual system organises the sensory signals to minimise lightness changes. How the schemata are constructed depends on how the sensory signals are encoded - the cues to illumination being only one factor which may influence this process. Consequently, a changed impression of illumination is not regarded as a sufficient condition for a change in perceived lightness. The illumination cues that do affect perceived lightness create the impression of a special illumination.

To support his thesis, Beck cited research from several areas. First, he considered how changes in the relative size of a surface in the visual field can affect the perception of lightness. Second, he noted that perceived illumination also varied with the properties of contours delimiting the spatial region in which the surface is located. A constancy affect is typically found when there is a gradient in a contour, such as that caused by a penumbra (Macleod, 1947). The shadowed surface is seen as an area of reduced illumination.

In addition, sharp contours can give rise to a surface appearance (Koffka and Harrower, 1931; Fry, 1931; Wallach, 1963). Nonetheless, it is also possible that the constancy depends on the observer's attitude (Evans, 1948).

A third aspect of Beck's position was the emphasis given to perceived spatial position. Concomitant with this was the view that ratios of the luminances reflected from neighbouring surfaces in the field also change the impression of the illumination on a surface (Beck, 1961). Kardos (1934) was among the first to show the importance of the spatial arrangements of surfaces on lightness judgements. Several factors seemed to be involved. One of these, the object shadow effect, allows surfaces perceived to belong to an object to exhibit considerable lightness constancy (Katona, 1935; Beck, 1965). Similarly, Hochberg and Beck (1954) found that a change in apparent target position relative to the direction of illumination caused a change in perceived lightness. Beck (1965) interpreted these data as confirming that the cue properties of stimuli affect lightness perception by influencing the way in which sensory signals are assimilated into a schema.

Perhaps the most striking demonstration of the role of depth perception in lightness constancy has been given by Gilchrist (1977). Observers viewed targets whose apparent spatial position could be varied by the experimenter to lie in the plane of a distant wall or nearby. When perceived to lie in the nearby plane, the target was judged lighter than at the far distance, despite almost identical retinal stimulation. Simiar findings have been reported by Mershon and Gogel (1970), Metelli (1974), and Redding and Lester (1980). Gilchrist concluded that perceived lightness was determined primarily by ratios within perceived planes rather than by all retinal ratios regardless of perceived depth, and that "This result implies that lateral inhibition at the retina has little to do with everyday perception of lightness." (Gilchrist, 1977, p. 187). Significantly, this argument also implies that depth processing must occur before and be followed by the determination of surface lightness. Such a claim has not gone unchallenged (see, for example, Frisby 1979, p. 154), although formal experiments have not yet been undertaken.

As a further line of evidence in support of his thesis, Beck cited the phenomenon of memory colour. It was originally described by Hering (1874,1964), who suggested that the characteristic colour of an object becomes attached to it and is an important factor in constancy. Duncker (1939), for example, found that more green was required to match a comparison disc with a leaf than a donkey made from the same material, when both were viewed in red light (making the green material appear grey). It has also been noted that memory colour is particularly effective when the colour information is poor, such as when there is only a short period of time in which to view the stimulus (Herring and Bryden, 1970). The phenomenon has been treated with caution by some authors. Bolles, Hulicka and Hanly (1959), for example, proposed that memory colour effects were the result of response bias. At present it is unclear whether the observers in such experiments actually reproduce the colour as seen or how they think the colour should appear. In addition, the effects of memory colour are not always in the direction of the achievement of constancy. In the experiment of Bruner and Postman (1949), for example, the observer responded to incongruously marked playing cards with colours which were neither red nor black. Nonetheless, observers appear to be consistent in their choices in memory colour experiments (Bartleson, 1960), whether correct or not.

### 5.1.3. The effect of viewing distance.

Summarising his review of colour constancy, Beck (1972) stated that "There is as yet no general agreement on how an observer is able to perceive a stable colour with changes in the intensity and spectral composition of the illuminant," (p. 164). A decade later this statement remains essentially valid. Out of the complexities of recent studies, however, it can be seen that increased emphasis has been given to the role of viewing distance in brightness perception. The effect of viewing distance has been studied exhaustively for the perception of size, both because of the theoretical issues it raises (for example, the validity of the relative size-distance invariance hypothesis), and because of its relevance to practical viewing tasks. Changes of apparent colour with distance, on the other hand, are less obvious (at least in air), although changes in apparent brightness have been studied and linked with size and distance perception (Taylor and Sumner, 1945; Fry, Bridgman and Ellerbrock, 1949; Ross, 1967; Holmberg, 1972; Chatterjea, Saha and Biswas, 1974). Similar arguments for the role of brightness have been offered for the underwater situation (see Ross, 1971; Welch, 1978, for reviews). In brief, it has been suggested (Ross, 1971) that aerial perspective acts as a compelling cue to distance, both because of the large changes in contrast experienced over short distances, and because there are fewer distance cues under water than in air. The reduction of apparent contrast compels an overestimation of distance that varies linearly with the logarithm of the target's brightness contrast (Ross, 1968; Woodley, 1968), although near distances (up to 15 metres in clear water and 2 metres in turbid water) are underestimated.

Artists and interior decorators have long been familiar with the use of advancing and retreating colours to create the impression of distance. Similarly, formal research into the relationship between perceived colour and distance has been conducted from the premise that distance perception follows colour perception (for example, Mount, Case, Sanderson and Brenner, 1956). Nonetheless, it is only recently that the importance of colour contrast, rather than colour per se has been stressed - high contrast colours generally appearing closer than they really are (Farnè and Campione, 1976).

There have been several attempts to specify which colours maintain their appearance over long viewpaths in air. Studies by Holmes (1941), Hill (1947), and Sexton, Malone and Farnsworth (1952) have found that various colours can be conspicuous, depending on the background against which they are viewed. The only attempt to make quantitative predictions for the changes in apparent colour with changing viewing distance in air has been that of Middleton (1952), who calculated chromaticity coordinates for two colours as a function of distance in clear air. As Middleton further pointed out, the only directly related psychophysical experiment had been under taken by Hendley and Hecht (1949), who had observers make colour matches of natural objects using Munsell papers. In a delightful, if uncharacteristic example of bias, Middleton commented that "comparisons of this sort might be recommended as a hobby for thoughtful geophysicists on vacation (p.169)."

Under water, the effects of selective spectral attenuation can produce large changes in the spectral radiance of an object over short viewpaths. The effects on colour perception of such changes have been noted by previous investigators, but not separated from those of chromatic adaptation and simultaneous colour contrast. It would also appear that apart from colour naming studies, no direct measurements have been made of colour appearance under water, although Fay (1976) had his observers select colours from a chart in air to match colours seen immediately beforehand under water at various depths.

### 5.1.4. Hypotheses.

The experiments to be described were designed to investigate the effects of viewing distance on colour appearance under water. Such experiments are of theoretical interest to the extent that they can promote understanding of two potentially competing aspects of visual perception, namely the requirement to maintain stable colour appearance in the face of changing illumination, and to use the cue of aerial perspective to aid stable size perception (observers might be assumed to be capable of viewing in either mode). The relatively limited extent of spectral reflectance changes with viewing distance under normal conditions suggests that the balance between the two influences is tipped in favour of size constancy. For example, size-distance relations under water are more complex than in air (Welch, 1978). Second, the profound changes in spectral reflectance over even short viewing distances under water might be expected to provide greater scope for the presence of colour constancy effects. These effects might be further promoted by the presence of a mechanism such as that proposed by Gilchrist (1977), whereby depth perception would precede lightness and colour perception.

From the outset, it was appreciated that the accuracy of the quantitative assessment of the relative contributions of retinal and higher order factors to colour appearance would be limited by the fact that the CIE colourimetric system currently provides only moderately accurate formulae for the calculation of perceptual colour differences. Furthermore, comparison with other studies would be limited by the practical problems of underwater exerimentation - it would have been almost impossible, for example, to replicate the experimental conditions under which Gilchrist (1977) examined the influence of depth on lightness perception. Nonetheless, by requiring observers to make colour matches of the same targets at a number of distances and comparing the data with simultaneously obtained spectroradiometric measurements, it was hoped to provide a general description of possible constancy effects, over and above the effects of adaptation and simultaneous colour contrast.

It was considered useful to investigate possible variations in colour appearance with viewing distance due to changes in experimental instructions, changes in the type of target (for example a flat plaque of unknown size and colour, compared with a familiar object), and changes in the number of colour cues within the visual field. With size constancy, for example, Gilinsky (1955) and Jenkin and Hyman (1959) found that observers could provide separate judgements of objective and retinal size. Similarly, on the basis of Beck's (1972) theory of colour constancy, it was expected that observers might be able to provide alternative descriptions of a colour.

The investigation of the colour appearance of familiar objects was considered a useful opportunity to test the hypothesis that observers might be able to match the real colour of an object more closely to the appearance of the same object in air than if they matched its apparent colour to the air value. However, the experiment of Bruner, Postman and Rodrigues (1951) suggests that this is not necessarily the case. Nonetheless, it might be expected that the real colour of a familiar object would change less with changes of viewing distance than its apparent colour.

Finally, the present experiments were designed to investigate the possible effects of colour cues. The experiment of Holway and Boring (1941) on size constancy revealed that the degree of constancy was related to the amount of information about distance available to the observer. Thus the extremes of constancy were determined by the monocular artificial pupil and binocular viewing conditions. Likewise, colour perception appears to be more closely linked to retinal than cognitve factors the closer the viewing conditions approximate those of a reduction screen experiment. It was expected, therefore, that the presence in the visual field of familiar objects (of known colour) would promote colour constancy.

## 5.2 METHODS

### 5.2.1. Experiment 5a - Field study

5.2.1.1. Observers. Eight trained and experienced observers participated in the study. Their age range was 24-46 years, with a mean of 28.8 years. All had normal colour vision (on the Ishihara Colour Test), and all except one had normal uncorrected visual acuity (on the Snellen chart). One diver (H.H.) wore corrective lenses inside his facemask. All had previously participated in psychophysical experiments.

5.2.1.2. Apparatus. The stimuli were five aluminium tiles, each 0.09 $m^2$, having a dominant hue of blue, green, yellow, red or white. Their spectral reflectance curves are given in Appendix B. They were displayed against an unobstructed water background on either the aluminium frame described in Figure 3.4, or one of two smaller free standing frames of adjustable height, each designed to support a single tile . Four objects were also used as stimuli in two conditions at one of the experimental sites. These were a blue diving cylinder, a green lifting bag, a yellow lifting bag and an orange lifejacket. It was not possible to measure their spectral reflectances. However, their chromaticity coordinates under illuminant 'A' were assessed with the colourimeter described below, and are given in Appendix N. A number of familiar objects were also included in one condition, to act as colour cues. These were: blue diving cylinders, a yellow lifejacket, a red lifting bag, a green lifting bag, and a Kodak Colour Control Card (enclosed in transparent plastic).

Light readings were taken with the underwater photometer described in Figure 3.5, and the spectroradiometer described in Figure 4.4.

Visual colour matches were obtained with a Burnham-type colourimeter (Figure 5.1, (a)), which was designed and built for the present study. The colourimeter was supported on an aluminium frame, 56 x 56 x 70 cm. The waterproof

Fig. 5.1. (a and b). Burnham type underwater colourimeter.

(a) External structure - The observer viewed into window W1 while adjusting the potentiometers to achieve colour matches. The matches were recorded from window W2 by the Experimenter.

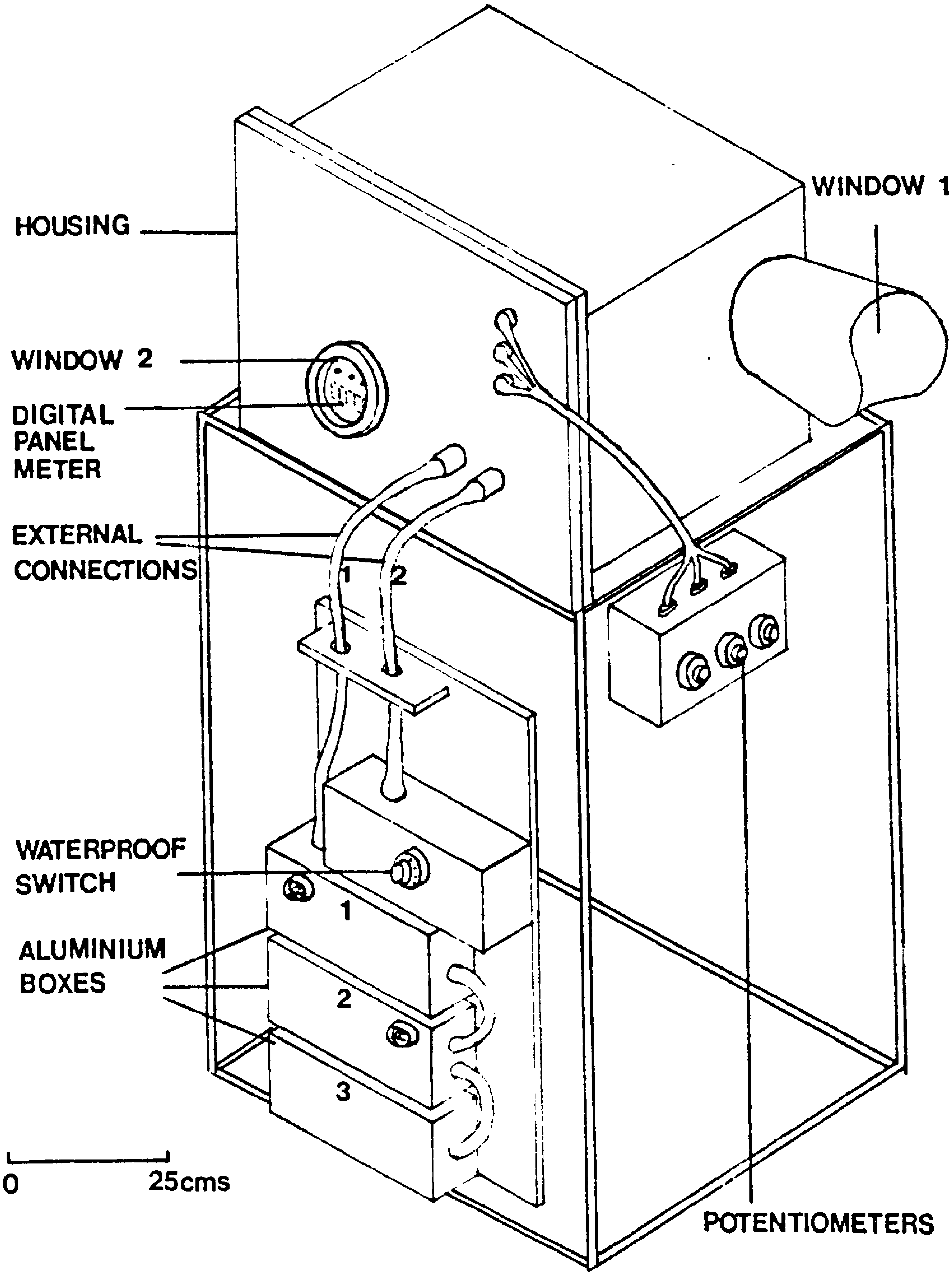
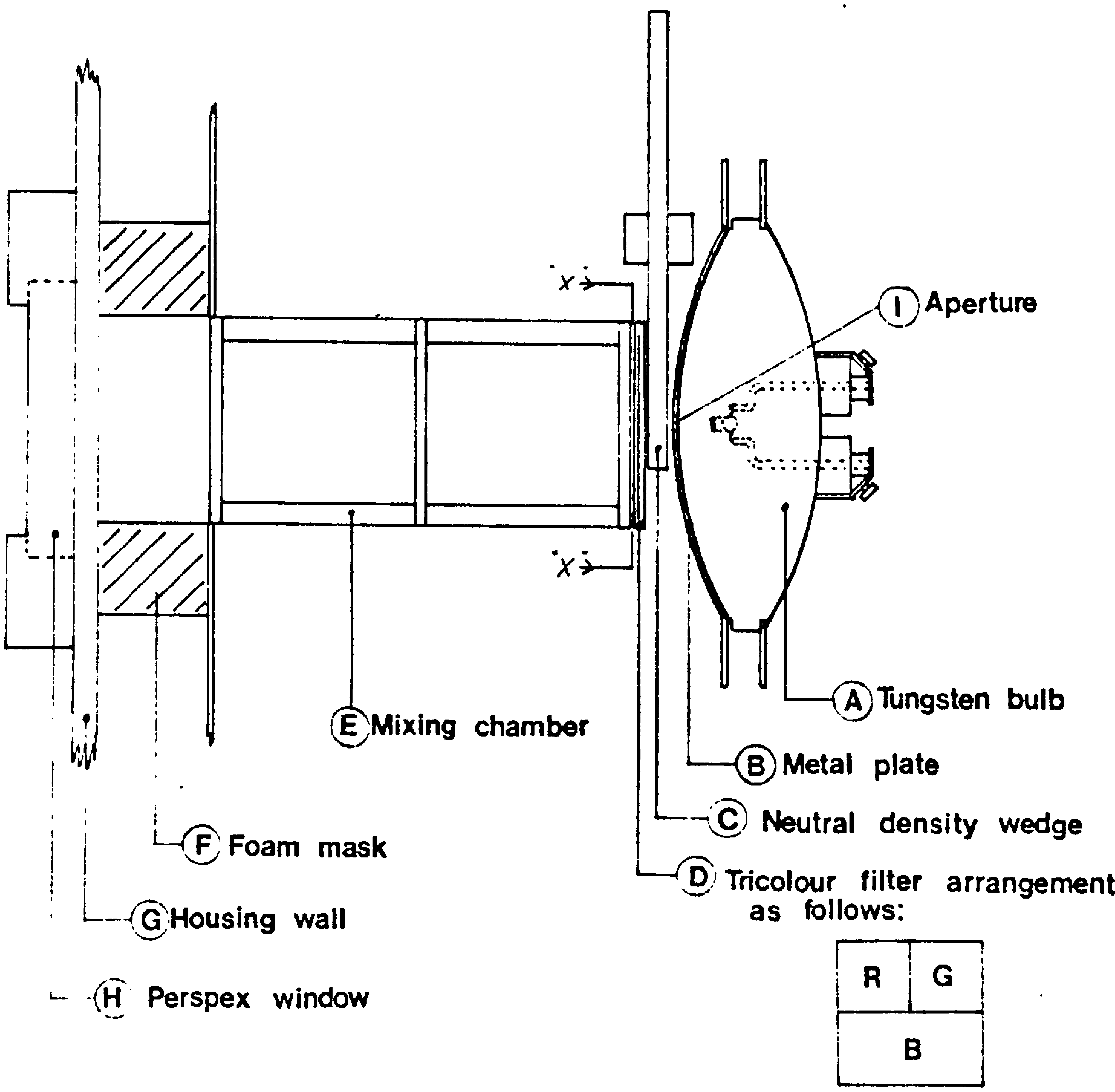


Fig. 5.1. (b). Optical arrangement of the underwater colourimeter - Light from the bulb passed through the aperture, neutral density wedge and tricolour filter before being mixed in the chamber. The perspex window at which the colour was produced is window W1 in Fig. 5.1. (a).



housing was an aluminium box, 42 x 30 x 34 cm., with two perspex windows, each 1.27 cm. thick and two external connections. The housing was sealed with an 'O' ring and a number of brass nuts and bolts. Inside the housing, the optical arrangement was that shown in Figure 5.1 (b). A prefocused sealed beam tungsten bulb (GEC, 4.7 V, 0.5A) operating at a constant 2700°K illuminated a tricolour filter through an aperture, 3.96 mm. in diameter, in a 0.381 mm. thick metal plate, and a 140 mm. diameter graded circular neutral filter wedge (Barr and Stroud Ltd). The optical density of the neutral filter increased linearly from 0.035 at an angle of rotation of 75° to 0.325 at 360°. The tricolour filter was made from three Kodak Wratten gelatin filters (numbers 26, 48 and 61), cemented together as shown in Figure 5.1 (b), and enclosed within a photographic slide frame, 50 x 50 mm. The filter slide was mounted rigidly on a stage, whose movement was controlled in the horizontal and vertical planes by two servomotors in response to two potentiometers, set into a diecast box with their exposed control knobs modified for underwater use. Adjustment of the potentiometers varied the voltages between known limits and allowed the relative contributions of the gelatin filters to be determined (see below). The system was able to detect changes in the horizontal and vertical direction of 0.0213 mm. A third potentiometer controlled the neutral density filter through a third servomotor. The mixing chamber, 14.29 x 5.72 x 5.72 cm, comprised a number of mirrors arranged as recommended by Cavonius (1974).

Their internal reflections produced a uniform distribution of light on the opal glass which formed the end of the chamber. A foam mask separated the chamber from the housing and window W1. A section of black rubber was attached to the front of the window into which fitted the diver's mask. Black adhesive tape on the outside of the window reduced the angle subtended by the opal glass to 4°.

Power was supplied via an underwater cable (Swift Aqua Supplies) by Nickel Cadmium NCC 400 and NCC 200 rechargeable batteries, housed in aluminium boxes as used for the photometer. The circuit diagrams are given in Appendix M. The plug-in connectors enabled the power pack to be recharged without breaking the seals of the diecast boxes (the recharging unit was wired to a matching socket). Because the plugs could be disconnected under water, it was possible to remove the power pack for recharging without disturbing the housing or supporting frame. A waterproof switch, operated by the experimenter, controlled the display of the lamp and servomotor battery conditions, as well as the positions of the tricolour filter and the neutral density wedge, on the digital panel meter in window W2. As a safeguard, three L.E.D's inside the window indicated the correct functioning of the lamp and servomotors. The whole colourimeter unit, which is slightly negatively bouyant at the water surface, has been successfully tested at a pressure of four Ats.

To calibrate the colourimeter, a Spectra Spotmeter, model UBD (0.25° field) was used to measure the tristimulus values X, Y and Z of the colours produced in the exit window at the extreme filter settings (i.e. the maximum amount of red only, green only and blue only, with maximum transmission through the neutral density filter), thereby determining the corners of the triangle within which lay all the chromaticity coordinates that could be obtained. This procedure, recommended by Kaiser (1974), avoids the assumptions involved in integrating the contributions of the individual components of the optical system. The Spotmeter was then used to determine the chromaticity coordinates at a number of additional settings of the colourimeter. The chromaticity coordinate calculations were then repeated, based on the proportions of the three filters involved in the mixture. The latter procedure, recommended by White and Wolbarsht (1975), is a modification of that originally suggested by Burnham (1952) for a four filter colourimeter. Given the filter arrangement in Figure 5.1 (b), a filter position hv (proportion of the total travel horizontally and vertically) was transformed into the relative contribution of each filter from the following equation:

$$\begin{aligned} P_r &= v(1-h) \\ P_g &= hv \qquad\qquad (5.1) \\ P_b &= (1-v) \end{aligned}$$

The location of each colour in CIELUV space could then be calculated, as previously described for the spectroradiometer. The chromaticity coordinates u', v' for the triangle corners are given in Table 5.1. The CIELUV system was chosen for these experiments because it was considered to provide a more accurate specification of colour differences than the 1931 CIE system, and unlike in the colour recognition experiments it was not intended to make detailed comparisons with previous data. Most importantly, unlike the CIELAB system, CIELUV also has an associated chromaticity diagram. The chromaticity coordinates u', v' of various settings of the colourimeter as calculated from the proportions of filters exposed and as measured by the Spotmeter are given in Table 5.2. To obtain an accurate colour match for some stimuli of high reflectance, it was necessary to estimate the lightness using a Kodak 24-Step Neutral Density Guide, enclosed within clear perspex. To achieve uniform data, a lightness estimate was requested for all matches made.

The area within the colourimeter supporting frame was enclosed on three sides by thin aluminium sheets, painted matt black. A Munsell Limit Colour Cascade arranged into eight waterproofed pages (each approximately $0.09m^2$) was placed in this area. Each page consisted of sections from the Cascade cemented between thin transparent perpex sheets (of negligible spectral bias). The Cascade, which comprises colours of high saturation from the region close to the spectrum locus, contains 768 different colours, arranged in 48 hues and 16 degrees of lightness. The chromaticity coordinates of the colours were calculated from their published Munsell specifications.[1] The samples

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[1] The chromaticity coordinates for the Cascade were generously made available by the Tintometer Ltd. (U.K.).

TABLE 5.1. Chromaticity limits u',v' of the underwater colourimeter.

The coordinates indicate the boundaries of the area of the chromaticity diagram within which colour matches were possible. The illuminant was source 'A'.

| FILTER | CHROMATICITY COORDINATES | |
|---|---|---|
| | u' | v' |
| Red | 0.530 | 0.520 |
| Blue | 0.149 | 0.177 |
| Green | 0.081 | 0.576 |

TABLE 5.2. CIE Chromaticity coordinates u',v' measured by a Spectra Spotmeter for various settings of the underwater colourimeter.

| CHROMATICITY COORDINATES | | | |
|---|---|---|---|
| u' | | v' | |
| Spectra Spotmeter | Visual Colourimeter | Spectra Spotmeter | Visual Colourimeter |
| .246 | .248 | .531 | .528 |
| .315 | .313 | .544 | .546 |
| .381 | .379 | .531 | .531 |
| .168 | .168 | .557 | .555 |
| .345 | .346 | .529 | .527 |
| .167 | .163 | .477 | .475 |
| .102 | .105 | .547 | .549 |
| .409 | .406 | .521 | .524 |
| .186 | .185 | .507 | .507 |
| .401 | .398 | .534 | .534 |

were illuminated from a distance of 30 cm. by an underwater lantern (ACR/L6, Avionics Systems Ltd.) attached to the colourimeter supporting frame. The lantern was fronted by a Kodak Wratten gelatin filter (80 A), enclosed within Transpaseal, which resulted in approximately daylight illumination of 47,000 lux. The lantern's 6 V battery provided approximately ten hours continuous illumination without a noticeable brightness decrement.

<u>5.2.1.3. Procedure</u>. Details of the two experimental sites are given in Table 5.3. The order in which the experimental conditions were presented is summarised in Table 5.4. Prior to the first laboratory test, the observers were shown how to operate the colourimeter, then each was allowed a practice period of about 15 minutes. Each observer was then required to match the five coloured plaques (binocular viewing, under approximately Illuminant A) presented singly, in random order, at a distance of 0.5 metres, and to match the lightness of each plaque with one of the patches on the Neutral Density Guide (illuminated by the underwater lantern).

In the underwater conditions, the observers were required to match the colour of each of the targets, presented singly, in random order, at each of three distances (given in Table 5.4). Two types of colour match were required. The 'apparent' match was intended to represent the colour of the target as it appeared to the observer. Under the 'real' match instruction, observers were to indicate the colour of the target as it would

# TABLE 5.3. Field sites for colour matching studies (Experiment 5a).

| LOCATION | WATER TYPE | DATE | TIME | DEPTH (Metres) | BOTTOM | SKY[1] |
|---|---|---|---|---|---|---|
| A. Rainbow Springs, headpool, Florida, U.S.A. | Extremely clear freshwater spring | (a) 14-5-80<br>(b) 16-5-80 | 11.00-14.00<br>11.00-14.00 | 3<br>3 | Flat, sandy. | 0/8<br>0/8 |
| B. Dunstaffnage, off S.M.B.A. Oban, Argyll, Scotland. | Turbid inshore coastal seawater. | (a) 9-10-79<br>(b) 10-10-79<br>(c) 11-10-79<br>(d) 23-10-79<br>(e) 24-10-79 | 09.30-12.15<br>09.30-12.45<br>09.30-12.30<br>09.30-12.30<br>09.30-12.30 | 7<br>8<br>8<br>8<br>8.5 | Flat, sandy | 6/8<br>5/8<br>1/8<br>6/8<br>8/8 |

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[1] The range is from 0/8 (no cloud) to 8/8 (totally overcast).

# TABLE 5.4. Experimental conditions in field colour matching studies (Experiment 5a).

| | LOCATION | DATE | CONDITION[1] | OBSERVER-TARGET DISTANCE (Metres) |
|---|---|---|---|---|
| A. | Laboratory/<br>University of Florida | 10- 5-80 | PAC | 0.5 |
| | Rainbow Springs | 14- 5-80 | PAC | 0.5, 13.5, 29.0 |
| | Rainbow Springs | 16- 5-80 | PRC | |
| B. | Laboratory/Oban | 6-10-79 | PAC | 0.5 |
| | Oban | 9-10-79 | PAC | 0.5, 2.8, 4.0 |
| | Oban | 10-10-79 | PRC | 0.5, 2.8, 4.5 |
| | Oban | 11-10-79 | PRC plus cues | |
| | Oban | 23-10-79 | OAC | |
| | Oban | 24-10-79 | ORC | |
| | Laboratory/Oban | 25-10-79 | OAC | 0.5 |

1. Abbreviations: P = Plaques
AC = Apparent colour match
O = Objects
RC = Real colour match

normally appear in the laboratory (i.e. in air). As a further variation, observers at the Oban site were also required to make real and apparent matches of familiar objects.

At both sites, the main frame was positioned on the bottom, and the height of the perspex cross-section adjusted until the targets could be viewed against an unobstructed water background. The two samll frames were then placed approximately in line with the colourimeter, at distances determined by the visual range. At the Oban site the apparatus was set down on the day before the first test session. Two experimenters were required. One changed the targets on the frames, in a predetermined random order (read from a a formica slate), while the other was stationed at the colourimeter and recorded the observers' colour matches on a formica slate. The observers were not informed that they were viewing the same targets at different distances. In the 'cue rich' condition at Oban, the cues were placed at random in the visual field. Each observer was also given a Kodak Colour Control Card, which could be viewed as required. Each observer had access to the cards for a short period of time immediately before submerging. When the last observer had completed the task, light readings were taken with the photometer and spectroradiometer, as described in Chapters 3 and 4. At the Oban site, the observers then returned to the laboratory and made apparent colour matches for the familiar objects, under the same viewing conditions as for the plaques.

### 5.2.2. Experiment 5b - Laboratory study.

5.2.2.1. Observers. Four observers, three males and one female took part in the study. Their ages were 21, 23, 24 and 26. Three had normal uncorrected visual acuity (on the Snellen Chart). Observer J. A. had normal corrected visual acuity. All had normal colour vision (on the Ishihara Colour Test), were experienced divers, and had previously participated in psychophysical studies.

5.2.2.2. Apparatus. Most of the apparatus has been described previously. The stimuli were five aluminium tiles, 6.45 cm.$^2$, having identical spectral characteristics to those used in the field study. Several familiar objects also served as either experimental stimuli or colour cues. The former were: a white plastic beaker (70 mm. high, 40 mm. in diameter); a section of the (blue) cover of the Oxford Dictionary (80 x 70 mm.), covered with Transpaseal; a (green) squash ball; a (yellow) Kodak film box, covered with Tranpaseal; a miniature (red) post box (60 mm. high, 10 mm. in diameter). The cues were: a (white) golf ball; a (blue) bottle of a common household cleaner (Domestos); a photograph of a standard traffic light set at green, covered with Transpaseal; a plastic (yellow) banana; a plastic (red) tomato; a Kodak Colour Control Card (sealed as previously). It was not possible to determine the spectral reflectances of the familiar objects. However, their chromaticity are coordinates under illuminant 'A' were assessed with the colourimeter and are given in Appendix N.

The aquarium and illumination system used to view the targets was that described in Figure 3.1. Instead of the perspex presentation frame, however, the targets were presented on scaled models of the frames used in the field study, made from Meccano. The floor of the aquarium was covered with a thin layer of sand. The colourimeter, Munsell Colour Cascade and Kodak Neutral Density Guide were as described on page 150. The Cascade was illuminated by the underwater lantern as in the field study. The solutions in the aquarium were prepared as described in Chapter 4 to provide either a blue or green background. The addition of Aluminium Hydroxide Gel required the presence of an electric stirrer. The tristimulus values of the stimuli were measured with the Spectra Spotmeter.

5.2.2.3. Procedure. The procedure in the laboratory followed that in the field study as closely as possible. The conditions tested were the same as at Oban (Table 5.4), except that the familiar objects were as described above, and the viewing distances were 5,25 and 50 cm. Each observer participated in all 12 conditions, which were tested at the rate of one per day, at about the same time for each observer. The conditions were presented at random, except for the two 'air' matches, which were made first and last for each observer, as at the Oban site. In the 'cue rich' conditions the Kodak Colour Control Card was positioned adjacent to the near wall of the aquarium.

Light readings were taken at the beginning of the study. The readings were repeated at random intervals. No significant changes were recorded over the experimental period (six days for each water colour). Because the acceptance angle for the light meter was always smaller than the angle subtended by the target, CIE tristimulus values could be measured directly, without the extrapolation required for the field data. The background luminance was measured with the underwater photometer.

## 5.3 RESULTS

### 5.3.1. Qualitative description

The mean (N=4) visual matches for the coloured targets in the different experimental conditions at the three viewing distances in the laboratory and field studies are given, with the simultaneously obtained spectroradiometric data (the 'instrumental colours'), in Appendix N. Chromaticity diagrams (u', v'), showing some sample comparisons between instrumental and visual matches are presented in Figure 5.2 (a-d). For each site, the figure shows the chromaticity coordinates of the visual and instrumental colour at each viewing distance for specific targets under different experimental conditions, together with the visual and instrumentally measured background chromaticities. Four classes of visual response are illustrated, corresponding to either a small or approximately equivalent change relative to the instrumental colour change as viewing distance increased, under either the 'apparent' or 'real' match instruction.

Fig. 5.2.(a-d). Sample comparisons of visual and instrumental colour matches (Experiments 5a and 5b).

Examples are given of the chromaticity coordinates u',v' (CIELUV colour space) of tiles in two laboratory and two field studies. The tiles were measured spectroradiometrically ( ▲ ) and assessed visually (binocular viewing) by the observers ( o ) (the visual matches represent the means of the four observers) at the three distances under water and in air ( unlabelled triangles and circles) under illuminant 'A'. The apparent ( ♦ ) and instrumental ( ◊ ) chromaticity coordinates of the water background in the horizontal plane are also shown.

Four types of visual response are demonstrated for each site ; (a) apparent colour match instruction, instrumental and perceived colour changes with changes of target distance approximately equal, (b) colour match instruction as for (a) but where the apparent colour change was less than the instrumental change, (c) as for (a) but with the real colour match instruction, and (d) as for (b) but with the real colour match instruction.

The continuous lines are for visual clarity only, and bear no fixed relationship to the actual change of chromaticity coordinates between the data points.

The five experimental conditions were :

1. PAC : Plaques, apparent colour
2. PRC : Plaques, real colour
3. PRCC : Plaques, real colour with cues
4. OAC : Objects, apparent colour
5. ORC : Objects, real colour

Fig. 5.2. (a). Green background (Oban).

Viewing distances: 1 = 0.5 m
2 = 2.8 m
3 = 4.5 m


(i) Experimental condition : OAC
Target colour : Green
0·55
0·53
0·51
0
0·10
0·15
0·20
U'
1
2
3
1
2
3
(ii) E.C. OAC
T.C. Red
0·60
0·55
0·50
V'
0
0·10
0·20
0·30
0·40
U'
3
2
1
3
2
1
(iii) E.C. ORC
T.C. Green
0·57
0·55
0·53
0
0·10
0·15
0·20
U'
1
23
3
2
(iv) E.C. ORC
T.C. Yellow
0·60
0·55
0·50
0
0·10
0·20
0·30
0·40
U'
3
2
1
2
3
1

Fig.5.2. (b). Green background (laboratory).

Viewing distances: 1 = 5 cm
2 = 25 cm
3 = 50 cm


(i) E.C. PAC
T.C. Blue
0·525
0·500
0·475
0
0·10
0·15
0·20
0·25
U'
1
2
3
(ii) E.C. PAC
T.C. Red
0·60
0·50
0
0·10
0·20
0·30
0·40
U'
V'
1
2
3
(iii) E.C. PRC
T.C. Green
0·55
0·53
0·51
0
0·10
0·15
0·20
U'
1
2
3
(iv) E.C. ORC
T.C. Yellow
0·58
0·54
0·50
0
0·10
0·20
0·30
U'
1
2
3

Fig. 5.2. (c). Blue background (Rainbow Springs).

Viewing distances: 1 = 0.5 m
2 = 13.5 m
3 = 29.0 m


(i) E.C. PAC
T.C. White
(ii) E.C. PAC
T.C. Red
(iii) E.C. PRC
T.C. Blue
(iv) E.C. PRC
T.C. White
V'
U'
0·1
0·2
0·3
0·5
0·6
0·4
0
1
2
3

Fig. 5.2. (d). Blue background (laboratory).

Viewing distances: 1. 5 cm
2. 25 cm
3. 50 cm


V'
(i) E.C. PAC
T.C. Blue
0·48
0·46
0·44
0
0·10
0·15
0·20
U'
1
2
3
(ii) E.C. PRCC
T.C. Green
0·54
0·49
0·44
0
0·10
0·20
0·30
U'
1
2
3
(iii) E.C. PRC
T.C. Blue
0·48
0·44
0·40
0
0·10
0·20
0·30
U'
1
2
3
(iv) E.C. ORC
T.C. Yellow
0·55
0·50
0·45
0
0·10
0·20
0·30
U'
1
2
3

From Figure 5.2 it can be seen that the instrumental colour changes are approximately exponential with distance, and confirm the shift of the inherent target colours towards the colours of the backgrounds against which they were viewed (the same is true of the luminance measurements, given in Appendix N). The sizes of the instrumental colour shifts are partly determined by the relative spectral characteristics of the target and background. In Figure 5.2 (a), for example, the changes with distance for a green target (i) and (iii) are small compared with those for the yellow target (iv).

The chromaticity changes for the visual matches in Figure 5.2 confirm that there were unequal differences between the magnitudes of instrumental and visual colour changes for the same target in different experimental conditions. In Figure 5.2 (c), for example, the changes in apparent colour of the white target (i) were only marginally smaller than the instrumental colour changes, whereas under the real match instruction (iv) the visual changes were much smaller than the instrumental changes. Similarly, there was a marked variation in the magnitude of the difference between instrumental and visual matches for different targets at a given site under a specific experimental condition (compare, for example, Figure 5.2 (b) (i) with (ii)). The differences between the visual and instrumental matches for the water backgrounds in the horizontal plane of the target confirm the presence of selective chromatic adaptation. This adaptation is generally in a direction away from the hue of the inducing (background) colour. The joint effects of chromatic adaptation and simultaneous colour contrast are given by the difference between visual and instrumental matches in experimental condition one (apparent match) for viewing distance one under water and in air.

### 5.3.2. Quantitative assessment.

Perceptual constancy is often quantified in terms of a ratio measurement. Several such measures have been suggested, of which the most widely used are those of Brunswik (1982) and Thouless (1931, a and b). Brunswik's formula is:

$$R = 100(s-p)/(r-p) \qquad (5.2)$$

where R is the degree of constancy (percent), r is the dimension of the distal object functioning as the stimulus, p is the corresponding dimension of the proximal stimulus, and s is the phenomenal dimension of the object. Thouless's ratio is almost identical, substituting the logarithms of these quantities. The assessment of constancy in this way is not universally accepted, however (Leibowitz, 1956; Hurvich and Jameson, 1960). Furthermore, it was not immediately obvious how a three dimensional concept such as colour could be so quantified. The procedure for the quantification of colour constancy used in the present experiments derived from the fact that colour change can be represented by a single dimension ($\Delta E$). Three changes were to be assessed, namely that between the target colour in air and at the closest underwater viewing distance (1) and those between viewing distance (1) and the middle and far distances (2 and 3) under water. The formula used for colour change was that given by Robertson (1977):

$$\Delta E^*_{uv} = [\ (\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{\frac{1}{2}} \qquad (5.3)$$

where $\Delta L^*$, $\Delta u^*$ and $\Delta v^*$ indicate the differences in $L^*$, $u^*$ and $v^*$ respectively between the two colours. For each colour change, the ratio of visual to instrumental change was calculated and expressed as a percentage, then subtracted from 100. This resulted in a scale that ranged from 100 (for perfect constancy) through 0 (zero constancy) to negative values (for underconstancy).

The mean constancy ratios for the four observers calculated by the above method are given in Appendix O for each site, experimental condition, and change of viewing distance. These data have been rearranged in Figure 5.3 (a-d), which shows the constancy ratios for individual observers for each experimental condition in the four water types, averaged over target colour and viewing distance. The main features of the data presented in Appendix N and Figure 5.3 can be summarised as follows:

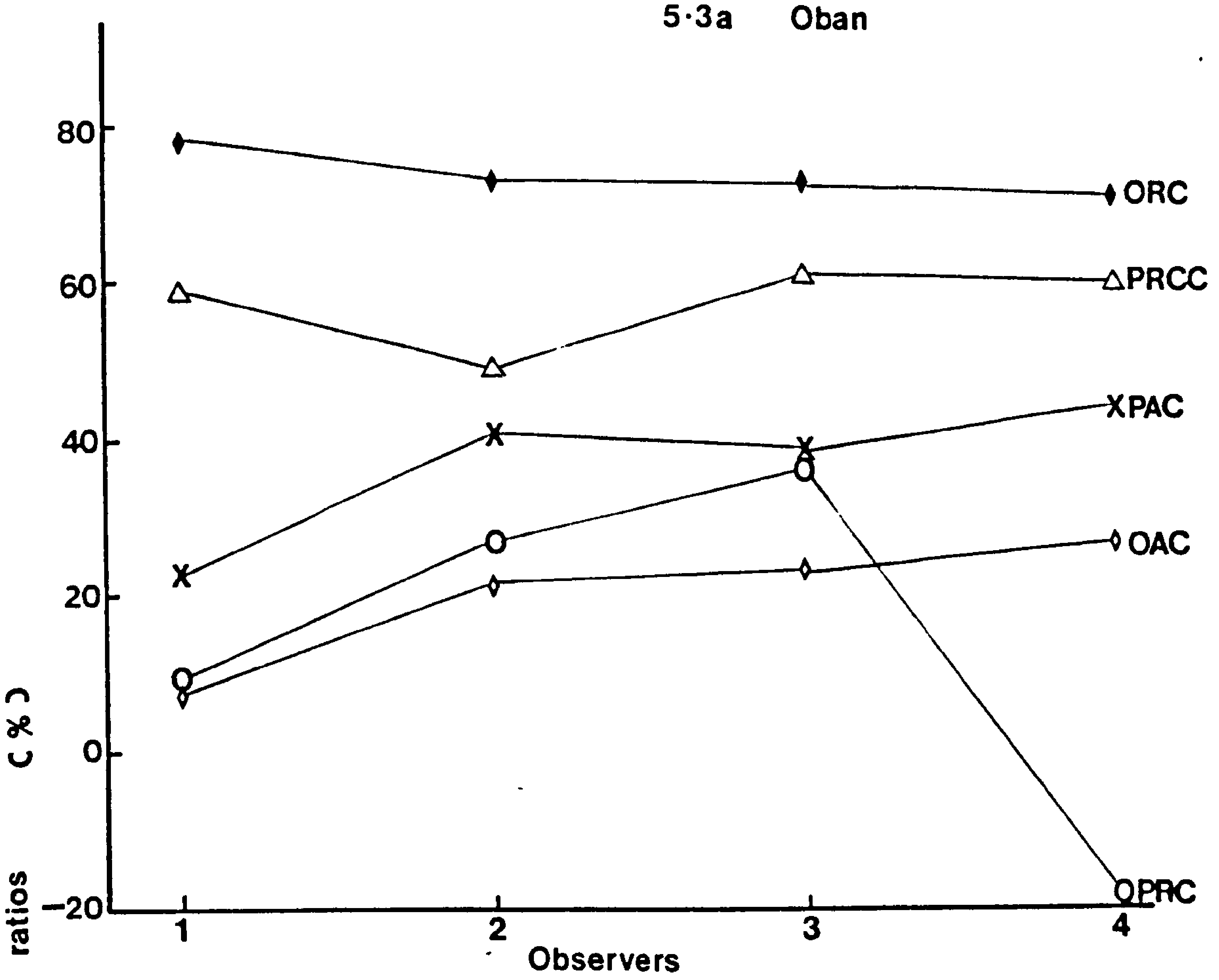
(a) Differences between experimental conditions. - Friedman two-way analyses of variance confirmed that there were significant differences between the constancy ratios in the five experimental conditions at Oban ($\chi_{\underline{r}}^2$ = 14.8, $\underline{df}$ = 4, p<.01) and in the laboratory (blue background, $\chi_{\underline{r}}^2$ = 11.8, $\underline{df}$=4, p<.01; green background, $\chi_{\underline{r}}^2$ = 22.9, $\underline{df}$ = 4, $\underline{p}$<.001). At Rainbow Springs, a Sign test confirmed that the difference between the ratios for the two conditions tested was insignificant ($\underline{L}$ = 10, $\underline{T}$ = 15, $\underline{p}$>.05, two-tailed). Exclusion of the data for the object, real colour condition

Fig. 5.3.(a-d). Individual constancy ratios for various types of colour match (Experiments 5a and 5b).

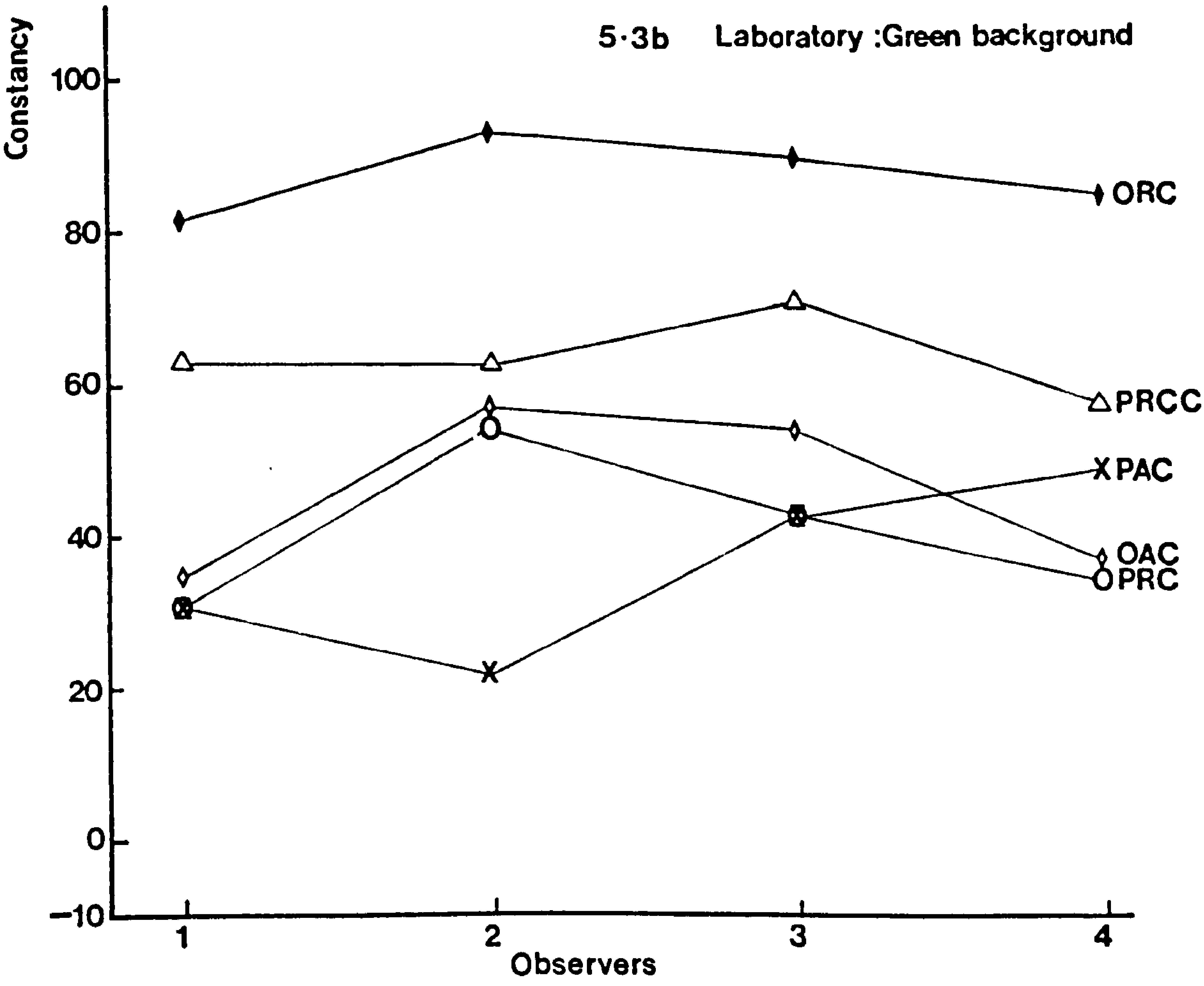
The colour constancy ratios (binocular viewing) are given for four observers in four types of water, averaged over target colour (white, blue, green, yellow and red, in air) and viewing distances 1-2 and 1-3 (as given in Table 5.4 for Oban and Rainbow Springs, and for 5-25 and 5-50 cm for the laboratory). The same four observers participated in both of the laboratory studies, but for practical reasons different observers participated in the Oban and Rainbow Springs studies. The ratios represent the changes in visual and instrumental colours over the specified distance. A ratio of 100 represents perfect constancy.
The experimental conditions were :

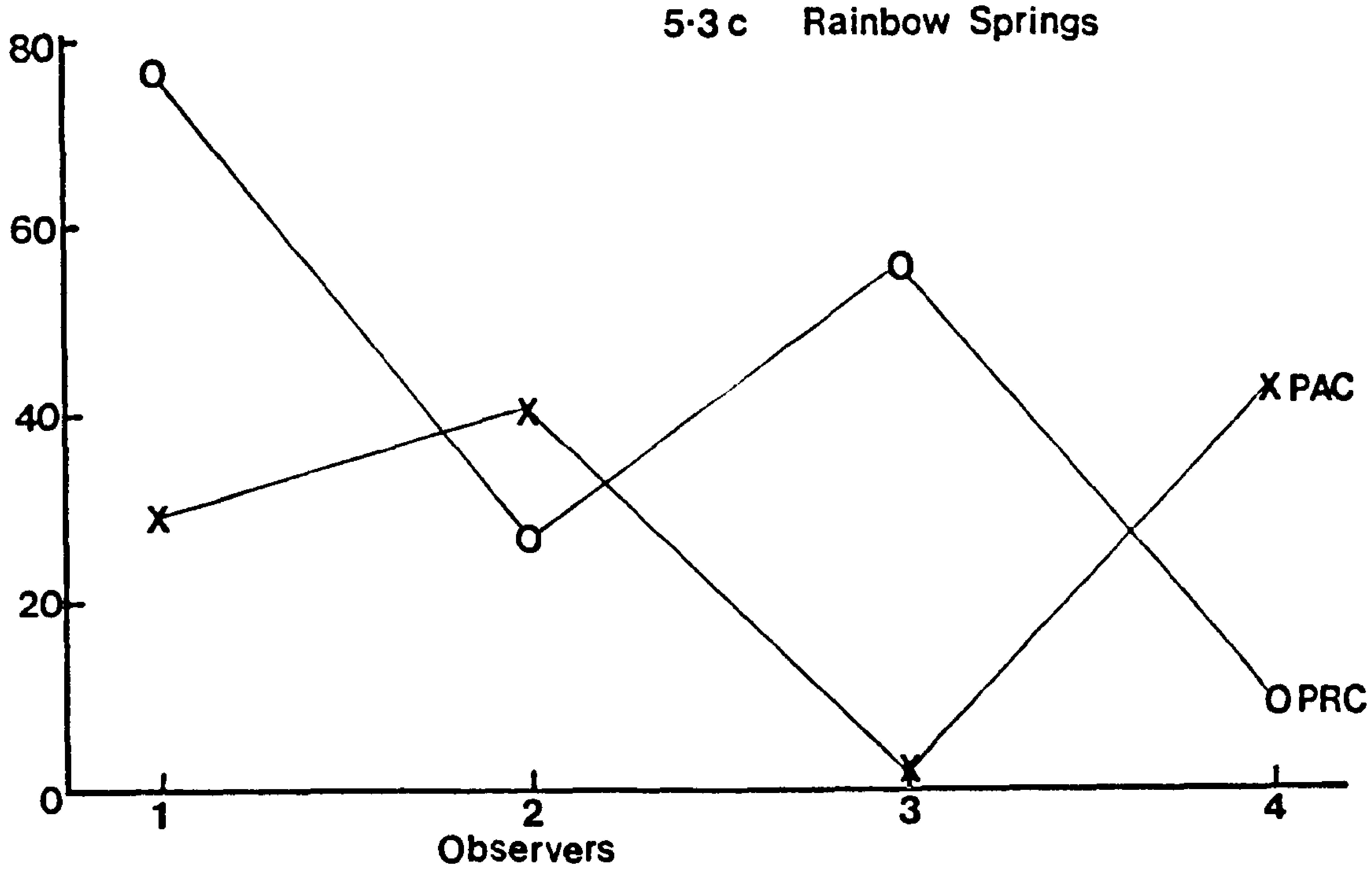
1. x - x PAC : Plaques, apparent colour
2. o - o PRC : Plaques, real colour
3. △ - △ PRCC : Plaques, real colour with cues
4. ◊ - ◊ OAC : Objects, apparent colour
5. ♦ - ♦ ORC : Objects, real colour

5·3a Oban

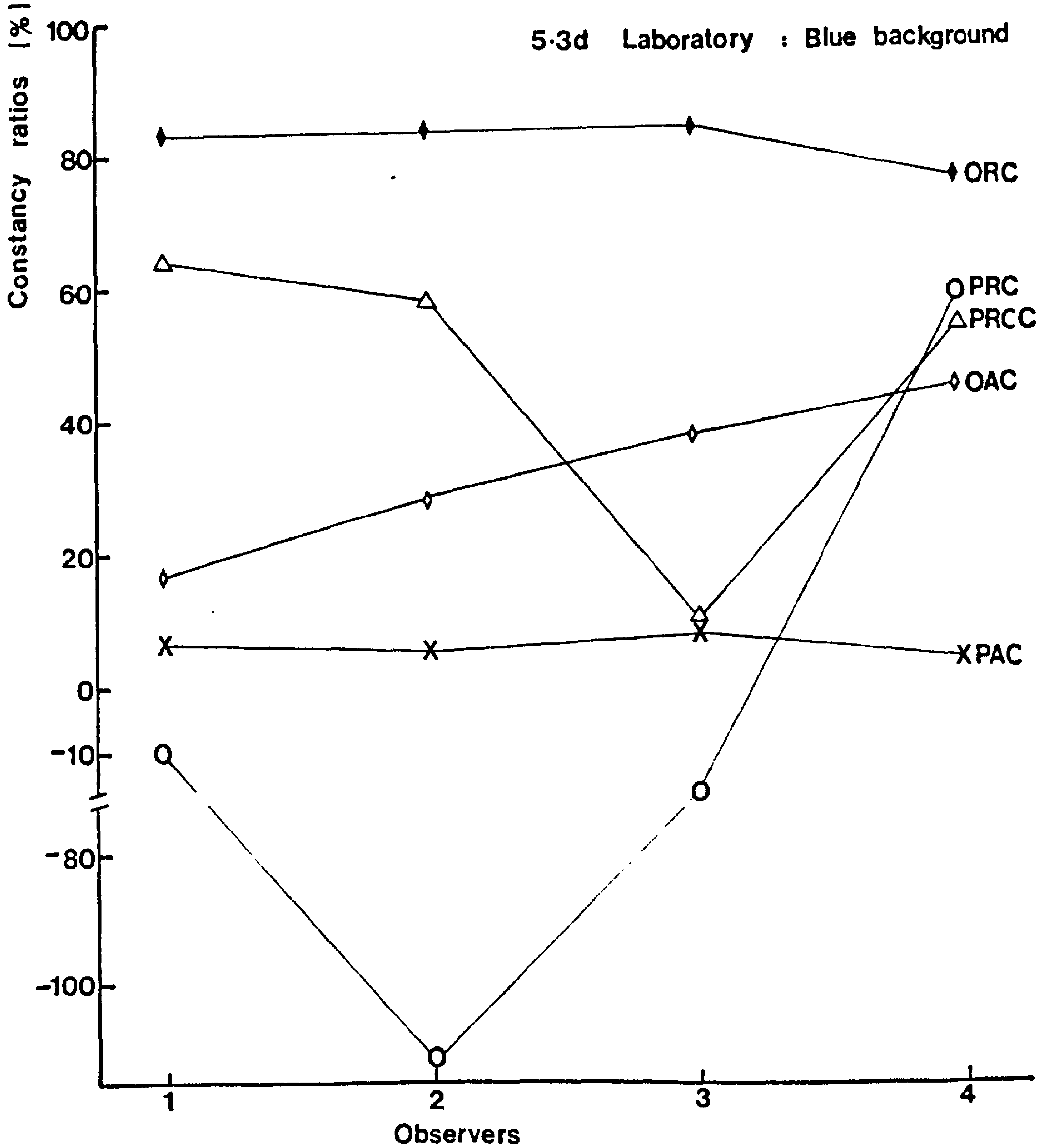


5·3b Laboratory :Green background





5·3c Rainbow Springs



5·3d Laboratory : Blue background

from the Friedman analysis of variance reduced the differences between conditions to an insignificant level for the Oban and blue laboratory experiments (Oban, $\chi_r^2 = 3.9$, $df = 3$, $p = 0.324$; laboratory, blue background, $\chi_r^2 = 1.95$, $df = 3$, $p = 0.677$), implying that this condition was the major contributant to the initial observed difference. Against the green laboratory background, the overall difference between conditions was still significant when the object real colour condition was excluded ($\chi_r^2 = 9.3$ $df = 3$, $p = 0.012$), but not when the plaque apparent colour with cues condition was excluded ($\chi_r^2 = 3.5$, $df = 2$, $p = 0.273$). The fact that there was still a significant difference when the plaques, real colour with cues condition was excluded but the objects, real colour condition was included ($\chi_r^2 = 9.3$, $df = 3$, $p = 0.012$) confirms that the latter condition also contributed to the initial significant difference.

The effect of instructions was examined by comparing the differences between the constancy ratios for the plaque apparent and real colour, and object apparent and real colour conditions. For the plaque conditions, Sign tests indicated that there were no significant differences in either green or blue water (green background, $L = 3$, $T = 8$, $p = 0.726$; blue background, $L = 3$, $T = 8$, $p = 0.290$, both tests two-tailed). For the object conditions, the differences in green water were significant ($L = 0$, $T = 8$, $p = 0.008$, two-tailed). The same analyses could not be undertaken for the blue water because there were insufficient data. For the plaque real colour conditions, there was no significant difference between the green and blue laboratory backgrounds (Sign test, L = 2, T = 8, p = 0.290, two-tailed). For the plaque apparent colour with cue conditions, there were no significant differences between the blue and green backgrounds (Sign test, L = 3, T = 8, p = 0.726, two-tailed).

(b) Differences between viewing distances 2 and 3. The relationship between colour constancy and viewing distance is shown in Figure 5.4. The laboratory studies did not reveal any significant differences between the constancy ratios at viewing distance two compared with viewing distance three, either when averaged over all five experimental conditions (Sign test, L = 3, T = 8, p = 0.726, two-tailed) or when averaged over the plaque apparent colour and plaque real colour conditions (Sign test, L = 3, T = 8, p=0.726, two-tailed). For the field experiments, although a slight decrease in constancy with increasing viewing distance is suggested in the plaque apparent and plaque real colour conditions, these differences were not statistically significant (Sign tests: Rainbow Springs, L = 3, T = 8, p = 0.726; Oban L = 1, T = 8, p = 0.070, both tests two-tailed). In the plaque apparent colour condition alone, two-tailed Sign tests confirmed that the differences in the green and the blue laboratory water types were insignificant (green background, L = 10, T = 20, p = 1.00; blue background, L = 9, T = 20, p = 0.824). In the field studies, the difference between distances two and three was insignificant at Rainbow Springs (Sign test, L = 10, T = 20, p = 1.00,

Fig. 5.4. Colour constancy as a function of viewing distance (Experiments 5a and 5b).

The colour constancy ratios (binocular viewing) obtained in four types of water and under different experimental conditions are plotted as a function of the change in viewing distance from a reference position (0.5 m for the field experiment, 5 cm for the laboratory experiment). The ratios are means for four observers viewing white, blue, green, yellow and red (in air) targets. The same four observers participated in both of the laboratory studies, but for practical reasons different observers participated in the Oban and Rainbow Springs studies. The ratios represent the changes in visual and instrumental colours over the specified distance. A ratio of 100 represents perfect constancy.
The experimental conditions were :

1. x - x PAC : Plaques, apparent colour
2. ◦ - ◦ PRC : Plaques, real colour
3. △ - △ PRCC : Plaques, real colour with cues
4. ◊ - ◊ OAC : Objects, apparent colour
5. ♦ - ♦ ORC : Objects, real colour


Lab. blue background
80
60
40
20
0
-20
-40
ORC
PRCC
OAC
PAC
PRC
Air - 5cm
5- 25cm
5- 50cm
Lab. green background
80
60
40
20
ORC
PRCC
OAC
PRC
PAC
Air - 5cm
5- 25cm
5- 50cm
Constancy ratios [%]
Change of viewing distance
Rainbow Springs
100
80
60
40
20
PAC
PRC
Air - 0.5m
0.5 - 13.5 m
0.5 - 29m
Oban
100
80
60
40
20
ORC
PRCC
PAC
OAC
PRC
Air - 0.5m
0.5 - 2.5m
0.5 - 4.5m
Change of viewing distance

two-tailed), but at Oban, the constancy ratios were lower at the further viewing distance ($L = 2$, $T = 20$, $p = 0.001$, two-tailed). Corresponding tests for the plaque real colour condition revealed no significant differences between the ratios at the middle and far distances in the laboratory (Sign tests: green background, $L = 8$, $T = 20$, $p = 0.504$; blue background $L = 7$, $T = 20$, $p = 0.264$, both tests two-tailed) or at Oban (Sign test, $L = 7$, $T = 20$, $p = 0.264$, two-tailed). There was, however, a significant difference at Rainbow Springs (Sign test, $L = 5$, $T = 20$, $p = 0.042$, two-tailed). For the plaque apparent colour with cues condition, there were no significant differences between the middle and far viewing distances (Sign tests: Oban, $L = 9$, $T = 20$, $p = 0.824$; laboratory, green background $L = 6$, $T = 20$, $p = 0.116$; laboratory, blue background, $L = 9$, $T = 20$, $p = 0.824$, all tests two-tailed).

(c) *Differences between green and blue water backgrounds* - Two-tailed Sign tests confirmed that in the laboratory the green background produced a higher constancy ratio than the blue background ($L = 4$, $T = 20$, $p = 0.012$). In the field experiments, for the two comparable conditions (plaque apparent colour and plaque real colour), the difference between Oban and Rainbow Springs was insignificant (Sign test, $L = 4$, $T = 8$, $p = 1.00$, two-tailed).

(d) *Differences between laboratory and field experiments* - Because the objects and colour cues in the laboratory and field experiments were different, the only valid comparisons were those between the plaque apparent and real colour conditions. Against both blue and green backgrounds, the differences between laboratory and field experiments for the two conditions were insignificant (Mann-Whitney test: green background, $\underline{u} = 2$, $N_{\underline{A}} = 4$, $N_{\underline{B}} = 4$, $\underline{p} > 0.05$; blue background, $\underline{u}' = 2$, $N_{\underline{A}} = 4$, $N_{\underline{B}} = 4$, $p > 0.05$ two-tailed). For the apparent condition alone, the difference between Oban and the laboratory green background was insignificant (Mann-Whitney test, $\underline{u} = 8$, $N_{\underline{A}} = 4$, $N_{\underline{B}} = 4$, $\underline{p} > 0.05$ two-tailed), although the Rainbow Springs condition produced higher constancy ratios than the blue laboratory condition (Mann-Whitney test, $\underline{u}' = 0$, $N_{\underline{A}} = 4$, $N_{\underline{B}} = 4$, $\underline{p} < 0.05$, two-tailed).

(e) Differences between target colours - Caution is required in the interpretation of differences between target colours, because they can vary along more than one dimension. At the gross level of colour classification by dominant hue name it was found that there were significant differences between the constancy ratios for the target colours in the laboratory for both the green and blue water backgrounds (Friedman two-way analyses of variance: green background, $\chi_{\underline{r}}^2 = 14.2$, $\underline{df} = 4$, $\underline{p} < 0.02$; blue background, $\chi_{\underline{r}}^2 = 13.4$, $\underline{df} = 4$, $\underline{p} < 0.02$). In the field studies, the corresponding analyses confirmed that there was a significant difference between colours at Oban ($\chi_{\underline{r}}^2 = 11.1$, $\underline{df} = 4$, $\underline{p} = 0.0009$) but not at Rainbow Springs ($\chi_{\underline{r}}^2 = 6.8$, $\underline{df} = 4$, $p > 0.05$), where only two conditions were tested.

When the analyses were repeated for the plaque apparent colour and real colour conditions, significant differences between colours were obtained at all three sites (blue laboratory background, $\chi_{\underline{r}}$ = 13.0 <u>df</u> 4, $\underline{p} < 0.02$; green laboratory background, $\chi_{\underline{r}}$ = 11.6 <u>df</u> = 4, $\underline{p} < 0.02$; Oban, $\chi_{\underline{r}}$ = 13.0, <u>df</u> = 4, $\underline{p} < 0.02$). The data for the plaque apparent colour condition alone also resulted in significant differences between colours ($\chi_{\underline{r}}$ = 13.4, <u>df</u> = 4, $\underline{p} < 0.01$).

Examples of differences between specific colours are shown in Figure 5.5, which confirms that against the blue water background, the lowest constancy ratio was that of the blue (in air) target, and the highest constancy ratio was that of the red target. Against the green background, the green target produced least constancy, and the red target the most (for these comparisons, the plaques and objects of the same hue name have been classified together).

## 5.4 DISCUSSION

### 5.4.1. Introduction.

Two aspects of the data from the laboratory and field experiments can be usefully separated for the purposes of discussion. The location in CIE colour space of the visual colour matches at the nearest underwater viewing distance can be assessed in terms of previously reported data for chromatically adapted observers. Secondly, the relative changes with distance of instrumental and visual matches can be assessed in terms of the colour constancy ratios in the various experimental conditions.

Fig. 5.5. Constancy ratios for various colours in blue and green water (Experiments 5a and 5b).

The constancy ratio is an expression of the mean ratio of visual (binocular viewing) to instrumental colour change for four observers and two changes of viewing distance (5-25 cm and 5-50 cm in the laboratory (┌╌┐); distances 1-2 and 1-3 as given in Table 5.4 for the field experiments (┌┐)). The data for the five experimental conditions given in Table 5.4 have been averaged. A ratio of 100 represents perfect colour constancy.


5·5a Water background colour : blue
100
80
60
40
20
0
-40
-70
blue
green
yellow
red
white
Target dominant hue name
Constancy ratios ( % )
5·5b Water background colour : green
100
80
60
40
20
0
blue
green
yellow
red
white
Target dominant hue name

Both comparisons are essential to enable unequivocal specification of the effects of viewing distance on colour constancy to be made; it is important to be certain that the constancy ratios calculated from the visual match data result in the perceived colour being closer to the instrumental colour in air than the instrumental colour under water. With information about the CIE specification of both visual and instrumental colour, it is possible to determine whether or not this was the case.

### 5.4.2. The effects of chromatic adaptation and simultaneous colour contrast.

The instrumental colour data for both green and blue water types in the laboratory and field experiments represent the results of the filtering action of the water on the targets, and follow from the principles of radiative transfer under water. In their general form the data can be regarded as similar to those presented in Chapter 4 for Rainbow Springs and Shirkin Island. Thus in green coastal water at Oban, there were large colour shifts for the long wavelength targets (Figure 5.2 (a) (ii) and (iv) but small colour shifts for the green target (Figure 5.2 (a) (i)). Against a blue background, long wavelength targets were similarly markedly altered (Figure 5.2 (d) (iv)), and blue targets were less altered than green targets (Figure 5.2 (d) (i) and (ii)). It can be added, parenthetically, that Figure 5.2 confirms the non-linearity of chromaticity changes with changing viewing distance, as described by Middleton (1952, p. 169).

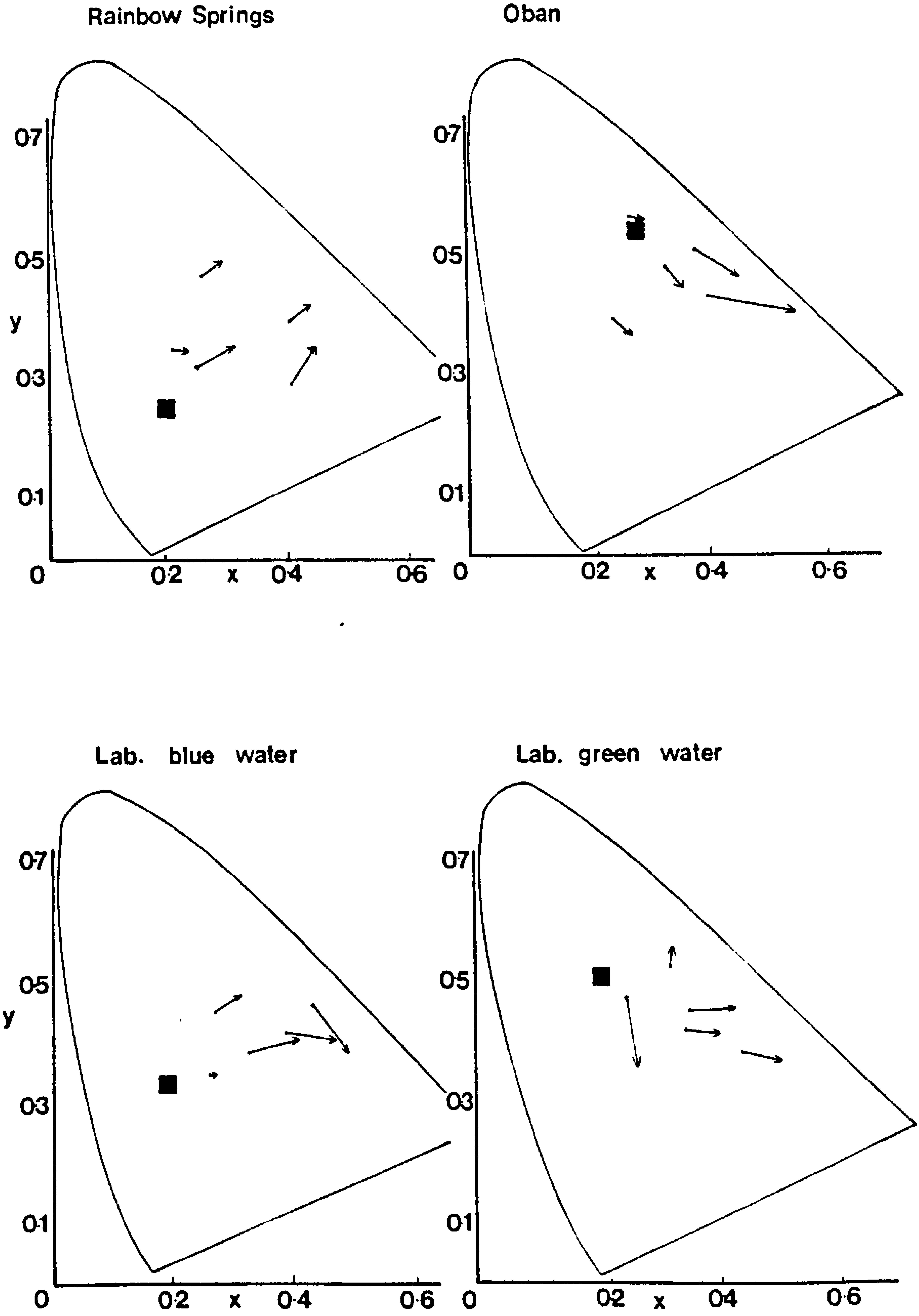
In the present context, it has been assumed that the most reliable measure of the observers' chromatic adaptation can be taken from the data for the plaque, apparent colour match condition (Condition One) at the nearest underwater viewing distance. It is suggested that in this condition the major effect of chromatic adaptation is mediated through the sensitivities of the three receptor types, as experienced by altered weights of the receptors' spectral sensitivities. In general, the changes in perceived colour represented in Figure 5.2 are as one might expect from the operation of an opponent system that signals simultaneous colour contrast Thus, adaptation to the blue and green backgrounds (for example, Figure 5.2 (a) (ii)) results in enhanced sensitivity to long wavelengths. It is also evident that in Condition One perceived colour is closer to the instrumental and perceived colour in air than is the instrumental colour under water. This suggests that the direction of the constancy effect is towards the maintenance of stable colour perception around the perceived colour in air. Nonetheless, as Lythgoe and Northmore (1973) have pointed out, there are limits to such compensation, such that, for example, at depths below about 30 metres in clear water reds are identified as shades of grey.

Previous studies have used a variety of methods to determine perceived colour in water, and only the most general comparison with the present data is possible. The most significant feature of such studies has been the reported enhanced sensitivity to long wavelengths when viewing against blue and green water backgrounds (for example Lythgoe and Hemmings, 1967; Radloff and Helmreich, 1968; Behan, Behan and Wendhausen, 1972; and Fay, 1976). Comparisons with relevant studies of chromatic adaptation in the laboratory are complicated by the fact that for experiments conducted in air, the inducing background does not influence the instrumental colour match, whereas target colours are physically changed by the intervening water. Consequently, to enable comparison with previous data to be made, the instrumental colour matches at the closest viewing distances in the various water types have been used to approximate the visual matches. Mindful of this approximation, the present data can be compared to those of Ware and Cowan (1982). In the latter study, the appearance of test stimuli shifted away from the chromaticity coordinates of the inducing stimuli. For a blue inducing background, as the chromaticity difference from the stimulus increased, and as the distance to the red-green spectrum locus decreased, the shift away from blue was replaced by a shift towards red. For a green background, stimuli close to the red-green spectrum locus moved towards red, and those near the green-blue locus shifted towards blue.

The present data for the plaque, apparent match condition at the closest viewing distance at the four sites have been converted to CIE 1931 chromaticity coordinates, using standard equations (Hunt, 1978), and are shown in Figure 5.6.

Fig. 5.6. Apparent colour shifts of targets viewed in air and in blue and green water (Experiments 5a and 5b).

The chromaticity coordinates x,y (1931 CIE colour space) are plotted for the means (N=4) of the observers' colour matches (binocular viewing) for various tiles in air under illuminant 'A' (tails of the arrowed lines) and at the closest viewing distances in the apparent colour match condition (heads of the arrowed lines). The viewing distances were 0.5m in Rainbow Springs and at Oban, 5 cm in the laboratory. The water background chromaticities at each site (measured instrumentally) are also given ( ■ ).



Rainbow Springs

Oban

Lab. blue water

Lab. green water

Compared to Figures 3 and 5 of Ware and Cowan (1982), the present data for the blue background do not show the same degree of colour shift towards the red region of the chromaticity diagram. Rather, both laboratory and field data suggest a more directly opponent response, in the direction of the yellow-green region of the diagram. For the green background the data do not show as marked a shift towards red wavelengths as that found by Ware and Cowan. In both cases, the differences between the two studies are small, however.

The likely explanation for the differences is that Ware and Cowan examined the effect of highly saturated inducing stimuli. Some adaptation studies have found that a neutral stimulus takes on a complementary colour appearance to the inducing stimulus (Kinney, 1962; Valberg, 1974), whereas others have found that a blue surround induces the appearance of a colour more red than the complementary of blue (for example, Oyama and Hsia, 1966; Hasegawa, 1977). The inducing stimuli in the present experiments were less saturated than those of Ware and Cowan. It is possible, therefore, that saturation plays an important role in the adaptation process. Unfortunately, it is not possible to separate the effects of saturation and hue in Figure 5.6 to enable analysis of their relative importance. At the same time, it is also likely that the observed differences between the two studies were influenced by the fact that the luminances in the Ware and Cowan experiments were artificially equated, whereas the present study included stimuli with different luminances. For example, accepting that a two process model of adaptation provides a reasonable working explanation of adaptation data, less adaptation might be expected for dim objects. On Shevell's (1979) model, for bright objects the multiplicative effect of a reduction in the gain of the cones sensitive to the adapting light would dominate; for dim objects, the additive process would dominate, merely copying the addition of background colour to that of the target. In the former case, against a blue background, constancy would be favoured by the addition of long wavelength light to the target colour, partially compensating for the presence of additional short wavelength light. In the latter case, however, the perceived addition of short wavelength light to that already present would cause the target to appear to contain even more short wavelength light. Clearly, the classification of colours as bright or dim is open to interpretation. Nonetheless, it would seem possible that in the present experiments those targets having a low reflectance were subject to such effects.

It is also unfortunate that in the study of Kinney and Cooper (1967), which incorporated less saturated inducing stimuli than Ware and Cowan and with which a more direct comparison might have been made, insufficient colour matches were investigated for any conclusions to be drawn (only white was matched). In addition, because the observers were asked to reproduce the appearance of the concept of white rather than match a white that was physically present in the visual field, the only valid comparison with the present data would be that with the object, real colour conditions.

### 5.4.3. Constancy effects with viewing distance.

5.4.3.1. Introduction. Estimation of the degree of adaptation was introduced into the present experiment partly in order to provide a basis upon which to measure the degree of colour constancy as a function of viewing distance. Unlike the case for the near viewing distance, the observed constancy effects at the middle and far distances in Condition One (plaque, apparent colour match) cannot be so confidently referred to current models of the visual system. For example, it might be considered that there are no compelling physiological reasons why perceived contrast should depart from physical contrast purely as a function of viewing distance. It is known that physical contrast decreases linearly with the logarithm of viewing distance under water. Similar findings have also been reported for the contrast to the human eye, at least in the absence of significant edge degradation effects (Hemmings and Lythgoe, 1965). In air, also, perceived contrast varies linearly with stimulus contrast over a wide range of conditions (Hamerly, Quick and Reichert, 1977; Ginsburg Cannon and Nelson, 1980). Nonethless, it must be noted that such a relationship might hold even if the absolute values of physical and apparent contrast or the slope of their functions differed. In such cases spurious constancy calculations would result.

Apparent and physical contrast do sometimes differ. Nonetheless, many of the factors known to contribute to such differences are probably either absent from the present experiments, or not differentially affecting the data at the various viewing distances. First, constancy effects were obtained at the Rainbow Springs site, where it can be safely assumed that no significant target edge degradation due to optical blur occurred. Furthermore, the targets' reflectances were quite low, and would therefore be minimally affected, even where edge degradation was possible (at Oban and in the laboratory). Second, other errors of measurement of physical contrast, such as that resulting from the use of the Vλ function for calculating brightness, are minimised by the recent CIE colour space (in this case the L* function). Finally, although the presence of a differential simultaneous contrast effect due to the smaller visual angle subtended by the targets at the Rainbow Springs site cannot be excluded (this change for the angles subtended at viewing distances one and three was seven times greater than for the comparable change at Oban, where the smallest angle subtended was 4°), the Oban data suggest that the changed target size is not a necessary condition for the constancy effect.

In the remainder of the present discussion, a tentative theoretical framework will be suggested for the constancy ratios obtained in the five experimental conditions of the laboratory and field studies. Brief comments will also be made about more general aspects of the data which became evident through the data analysis.

5.4.3.2. Plaques, apparent colour matches. An explanation for the obtained mean constancy ratio of 30 for the apparent colour matches of the plaques at the middle and far viewing distances in the four water types was sought in the role of distance perception in the determination of colour appearance. The general finding has been that observers overestimate far distances underwater, where targets typically have low contrasts with their backgrounds. Near distances, on the other hand, are underestimated, although the reason for this is a source of controversy ( Welch, 1977). Theory pertaining to underwater distance judgements has been well summarised by Ross (1971). The judgements are influenced by numerous cues. In general, the more cues that are available the more veridical the judgement. The most frequently cited cues are: accommodation and convergence; binocular disparity, linear and size perspective, texture gradient and object interposition; movement parallax; aerial perspective and knowledge of the direction of the illumination. Of these, the first two are effective only over short distances, while that of binocular disparity is relatively ineffective when either visual contrast is low (Ross, 1967(a); Luria, 1968) or peripheral stimulation is absent (Luria, 1969).

The suggestion that depth perception can precede lightness perception (Gilchrist, 1977) raised the possibility that depth cues could be important in the determination of colour appearance. On the other hand, in situations where depth information is substantially reduced, brightness and colour contrast might determine the estimation of distance.

Support for the latter statement can be found in the experiment of Ross (1971), which required observers to view targets presented in isolation in an aquarium filled with a turbid white solution. In that study, where viewing conditions were similar to those with a reduction screen, targets of low brightness contrast were judged to be further away than targets of high contrast presented at the same physical distance. Indirect evidence for the former statement is suggested by the fact that aerial perspective is not a necessary condition for the overestimation of distance under water. For example, Luria and Kinney (1968) found that overestimation of distance may occur as a result of a reduction in the number of distance cues other than aerial perspective.

The mechanism here proposed to account for the constancy in the plaque, apparent colour condition is one that involves high level cortical interactions. When sufficient visual information is available to permit depth perception to precede lightness and colour perception, the mechanism might respond by eliciting a colour appearance that would represent the same target at a much closer distance. The overestimation of distance which is typical for objects located at far distances from the observer under water might therefore promote greater constancy than situations where perceived distance was veridical. Similarly, because the underestimation of perceived distance decreases with increasing viewing distance at near distances, this situation might also promote constancy. In both of these situations, near and far refer to relative distances (less than and greater than half the total visual range). Nonetheless, the fact that the constancy ratios for the Oban site showed a significant decrease from the middle to far viewing distance suggests that an additional factor, the absolute viewing distance, is also important in the determination of perceived colour.

The effect of the absolute viewing distance does not appear to be a simple one. If a target presented at a fixed physical distance was made to appear at two different perceived distances by the alteration of distance cues in in the visual field, one might expect an increased constancy ratio as perceived distance increased. This is clearly an impossible situation, because apparent target colours would regress towards their inherent colours as viewing distance increased. It is therefore necessary to further assume that the magnitude of the constancy effect decreases as the absolute perceived target distance increases. At the Oban site, the decrease in constancy from the middle to far distance might be explained by assuming that the constancy reducing effect of the increased viewing distance was not balanced by the constancy inducing effect of distance overestimation. In the laboratory experiments, where the constancy ratios remained equal with increasing viewing distance, it might be assumed that the effect of the decreasing underestimation of distance with increasing viewing distance balanced the effect of the increasing absolute viewing distance.

Because distance overestimation tends to increase with increasing viewing distance, the short viewing distances at Oban might not be expected to produce as much constancy as at Rainbow Springs - in effect the colour constancy mechanism would be assumed to have been swamped by the large colour change over a short distance. The inherent ambiguity of a direct comparison between the constancy ratios obtained at Oban and Rainbow Springs is indicated by the fact that more constancy was obtained in the green than blue water laboratory experiments. That this latter finding was most likely an experimental artefact is suggested by the observation that the instrumental colour changes were also greater in the green water. Indirect evidence for the former argument is strong, however. Whereas there was no difference between the constancy ratios obtained in the green laboratory water and at Oban, the ratios at Rainbow Springs were higher than in the blue laboratory water. If the increased constancy obtained from testing in the green water at Oban (compared with blue water) was approximately balanced by the increased constancy obtained from the long viewpath at Rainbow Springs (compared with Oban), one might expect equal constancy ratios at both sites. This in fact occurred.

In summary, the proposed explanation for the data implies that depth perception and colour perception may be related in a complex way. The tentative explanation outlined above emphasises the importance of perceived target distance, in a a manner analagous to the relative size-distance invariance hypothesis. In general, if the target looks further away than it really is, cognitive constancy will overcompensate when determining the apparent object colour, and if the object looks too near, it will undercompensate.

Clearly, in future experiments it would be useful to obtain distance estimates in addition to colour matches, so that the precise effect of distance estimation could be assessed. Because the number of distance cues can be reduced under water to the point at which conditions approximate those of a Ganzfeld, there must be a distance at which aerial perspective becomes dominant over other distance cues, and at which one might expect a decrease in colour constancy. Similarly, it would be interesting to investigate whether observers are able to override the predominant temporal ordering of depth and colour perception in the absence or presence of depth information.

If the proposed interpretation of the data is valid, it implies that greater consideration should be given to the role of depth information processing in the assessment of colour appearance. It further implies that purely retinal explanations of the constancy effect are inadequate. The complexity of distance estimation under water has been noted previously. More generally, in a recent review of the metric of visual space, Gogel (1977) stressed the importance of both egocentric and exocentric factors. He argued that when physical (exocentric) factors are few in number, the observers' own (egocentric) influence acquires increased importance. Such a view resembles the theory of Taylor (1962), that the visual system gives more weight to information as it becomes more precise. Accordingly, at far distances, where the relative importance of cues is diminished, there is more scope for cognitive correction.

The data therefore appear will fitted to the theoretical framework offered by Beck (1965), whereby the cue properties of stimuli affect the way in which the sensory signals are assimilated into a schema. Unfortunately, but perhaps predictably, such descriptions are sometimes met with scepticism outside the field of psychology, mainly because of the nebulous terms in which schemata have been described. Nonetheless, significant changes have recently been made to the concept of schemata as originally proposed (by, for example, Bartlett, 1932). For present purposes, a schema can be understood to be the portion of the entire perceptual cycle that is internal to the observer, modifiable by experience, and specific to what is being observed. In biological terms, it is an active array of physiological structures and processes- an entire system that incorporates receptors, afferents, feed-forward units and efferents. An elegant summary of one recent approach to the concept of schemata that stresses the interaction between an active observer and the information offered by the environment has been given by Neisser (1976). For Neisser, perception is regarded as the observer building anticipations of specific types of information that enable him or her to accept it as it becomes available. The information picked up modifies the original schema, and directs further exploration. The optical information is considered to include the specification of objects and events at various levels of abstraction and meaning, as well as the traditional patterns in the light over time and space.

5.4.3.3. Plaques, real colour matches. The framework outlined above appears equally useful in interpreting the data from the other experimental conditions of the present studies. When real colour matches for the plaques were requested, it was found that the change in experimental instructions was insufficient to significantly alter the overall degree of constancy from that found in the plaque, apparent colour condition, in either laboratory or field experiments. Nonetheless, the real colour match condition was clearly a more difficult task. As a result, the variability of the matches was higher in this condition, (Figure 5.3). This might be explained by assuming that the way in which the observers' schemata were constructed depended less on information in the environment and more on his or her own concept of how the targets ought to appear. Under these circumstances, Neisser (1976) prefers to describe the schemata as being detached from the cycles in which they were originally embedded, and the process as one of imagining rather than perceiving.

Although memory colour effects are more effective when the stimulus colour is ambiguous, most memory colour experiments have employed targets with meaningful shapes, whereas the plaques in the present study provided no clear information that the observers could use to assist them. Indeed, the data support the assertion of Bruner, Postman and Rodrigues

(1951), that the request for the observers to make real matches sometimes leads to a less accurate assessment of colour than when apparent matches are required. For example, there is now no significant difference between the constancy ratios obtained in the blue and green water types in the laboratory. It is also to be noted that the decrease in constancy with increasing viewing distance obtained at Rainbow Springs but not the other sites for this condition suggests that the task is more difficult at greater distances This concurred with the informal comments of the observers, who indicated that they found the matching task more difficult when the target was in the distance than when it was nearby.

5.4.3.4. Plaques, real colour matches in the presence of cues. The presence of cues to colour, in the form of objects with familiar, distinctive colours, resulted in a marked increase in the mean constancy ratios over those obtained in the previous two conditions (Figure 5.3) This effect was greatest in the green laboratory water. Furthermore, there was no difference for this condition in the constancy ratios between the green and blue water in the laboratory studies, or between the ratios obtained at the middle and far viewing distances at any of the sites (this condition was not tested at Rainbow Springs, however). In terms of Neisser's framework, it could be argued that the schemata were exerting their influence by promoting the selective acquisition of information from the visual field. That is, a contribution to a colour match from information in the visual field could be made from the colour cues. The data also confirm that the constancy ratios were relatively stable in this condition.

5.4.3.5. Objects, apparent colour matches. The results for this condition were the most difficult to anticipate. If the observers were able to match the object colour without the influence of a memory colour effect, the constancy ratios might have been expected to approximate those obtained in the plaques, apparent colour condition. Figure 5.3 suggests that a slightly higher constancy ratio was obtained for the object matches in the laboratory, but not in the Oban experiment. This was probably because different colour cues were used in the field and laboratory studies. Nonetheless, the fact that there was no significant difference between the constancy ratios at the middle and far distances at Oban further implies that even at this site the matches were subject to influences not present for the plaque matches.

5.4.3.6. Objects, real colour matches. The highest constancy ratios were obtained in this condition. The data strongly suggest that the matches were mainly a product of the observers' imagining processes, and that the perception of the targets' shapes preceded their colour identification. This finding might imply that target shape is a more useful visual code to use than colour for underwater recognition tasks. The results parallel those obtained by Woodley and Ross (1969), who found that the perceived distance of familiar objects was almost as accurate under water as in air, whereas the distance of unfamiliar objects was under or overestimated, depending on the physical distance involved. It had been expected that an exact correspondence with the real colour in air would not be obtained. Kinney and Cooper (1967) reported that when observers were requested to reproduce the appearance of an ideal white their matches were shifted in the direction of the blue inducing background, indicating an enhanced sensitivity to long wavelengths. In the present experiments, similarly, although the observers were aware of the real colours of the objects, their matches confirm that the effects of adaptation were also present.

The small amount of variability in the colour matches between observers confirms Bartleson's (1960) finding that colour matches of familiar objects are consistent between observers. It is difficult, however, to comment usefully on Bartleson's other major conclusion, that compared to instrumental matches, most memory colour matches exhibit increased saturation and a hue shift in the direction of what is the most impressive chromatic attribute of the object.

Finally, it can be noted that the potential for modifying colour appearance by improving the observers' knowledge might facilitate the improvement of colour recognition under water. This is suggested by the fact that there was a significant difference between the constancy ratios obtained between the two object colour matching conditions (for the green backgrounds). It would be unrealistic, perhaps, to expect that a factor such as the small colour card used in the present experiment would enable perfect recognition to be achieved under water. It might be possible, however, to use such a device to reduce the number of gross errors of colour judgement. The training of observers in visual tasks is not difficult. For example, it has been found that provided enough training is given, substantial improvement can be obtained in the accuracy of distance estimation under water (Ferris, 1973). However, it is difficult to maintain the improvement over time. Several investigators have also found "instantaneous adaptation" to optical distortion under water by experienced divers, compared with novices (Ross, 1967(b); Luria, Kinney and Weissman, 1967; Luria and Kinney, 1970; Ross, Franklin, Weltman and Lennie, 1970). This type of improvement is presumably more resistant to decay. For brightness perception, Smith, McNeill and Clark (1979) have suggested that brightness contrast (in air) can be influenced by the amount of practice an observer has had on a particular task. In this context, it would be interesting to investigate the possibility of improving colour recognition through training. For example, it might be hypothesised that for the real colour matches, improved observer knowledge about the colour filtering effects of the water, coupled with an accurate estimate of distance, could lead to increased constancy.

<u>5.4.3.7. General effects</u>. From an initial inspection of the data (Figure 5.2) it was clear that there were differences between the constancy ratios for the various target colours at the different sites. The statistical analysis carried out on the data, averaged over the various experimental conditions confirmed that these differences were significant. Because this effect might

have been related to the ease of recognition of some of the objects, a more accurate constancy estimate was obtained from the plaque, apparent and real colour conditions only. The analysis confirmed that for all except the Rainbow Springs site there were significant differences between colours. At the latter site, differences between colours were significant when only the plaque, apparent colour matches were assessed. Qualitatively, the highest constancy ratios were obtained for the yellow and red targets, which also exhibited the largest instrumental colour changes. These differences could not be quantified, however, because there were insufficient data.

The explanation for such differences is not immediately obvious. Perhaps a more useful way to consider them is in terms of the fact that less constancy was obtained for targets whose dominant wavelength was close to that of the background against which they were viewed. One might then speculate that the schema upon which the perceptual process operates is more ambiguous than when the target hue is clearly different from the background. Carefully controlled experiments would be required to enable more defensible statements to be made about differences between target colours, however. In the light of the data presented in Chapter 4, close attention would have to be given to the control of brightness and saturation.

### 5.4.4. Summary.

The results of the present experiments confirm that a number of processes are involved when an observer assesses the colour appearance of a target. It is suggested that the relation between perceived and instrumental colour is similar to that described by Leibowitz and Harvey (1967) for size and distance, that "There is no unique function relating... (matched size) to distance, but rather a family of functions whose parameters are particularly sensitive to variables such as instructions, the nature of the object, and the environment" In summary, the two frameworks within which the data have been discussed are quite general. The first assumes that constancy at the nearest viewing distance in Condition One represents the effect of chromatic adaptation, whereas when greater distances are involved a more useful explanation is offered by including the concept of cognitive schemata.

Given the current level of uncertainty about both the nature of chromatic adaptation (for example Ware and Cowan, 1982) and the status of cognitive explanations in visual science (for example Neisser, 1976), the frameworks have probably been elucidated to the limit of their practical utility. Despite this generality, it is clear that the data lend strong support to the thesis that the prediction of colour appearance under water from hydrological and human performance data is a far from simple task. For close viewing distances, under the instruction to match the apparent colour of an object, it might be possible to estimate colour appearance from adaptation data. For most other situations, however, such predictions are likely to be complicated by some of the factors discussed above.

# CHAPTER SIX - EXTENDING THE VISIBILITY MODEL.

## 6.1. INTRODUCTION

### 6.1.1. Preliminary remarks.

The issues raised in the previous chapters present a number of problems that could restrict the application of current approaches to predicting underwater visibility in fairly simple viewing situations. In the present chapter, brief consideration will be given to the difficulties of predicting visibility at threshold under more realistic viewing conditions, such as when the observer or target is moving, and when the observer must search the visual field.

In recent years, threshold detection models have become increasingly complex. It would be unfair to use hindsight to criticise early attempts by Duntley and his colleagues to extend the Scripps visibility model. Rather, the aim of the present chapter is to attempt to indicate the type of factor which must be incorporated into any model of visibility that is intended to be applied to practical search tasks.

### 6.1.2. The engineering approach to visibility modelling.

In his introductory comments about the general requirements of visibility models, Duntley (in Duntley et al., 1964) recognised the importance of having libraries of visual and photometric data, preferably stored on computer for ease of access. His own model, for example, owed a considerable debt to Blackwell (1946) for psychophysical contrast threshold data, and to various members of staff at the Scripps Institute of Oceanography for data relating to the structure of the underwater light field. Nonetheless, there were significant lacunae in the psychophysical data for conditions other than those originally specified by Blackwell. These gaps set narrow limits to the range of the model's applications. Even so, Taylor (in Duntley et al., 1964) considered that it was only a question of time before the data were available which could allow any visibility problem to be solved. Although the absence of all the relevant data was thought to be only a temporary deficiency, the demand to extend the current model to a wide range of conditions remained. The proposed solution was the introduction of field factors - multipliers which could be directly applied to the basic data when expressed in terms of contrast.

Two types of conversion were introduced. To account for the well established statistical nature of target detection, it was considered useful to be able to specify alternative probabilities of detection. The probability of detection rises with stimulus magnitude in accordance with an ogival curve, and due to the almost invariant relationship between the threshold and steepness of the curve (Blackwell, 1963), it was possible to apply a conversion factor to yield any desired probability level. The confidence with which this may be done depends on the original level of data collection, being most satisfactory for forced choice data ( Taylor, in Duntley et al., 1964).

Secondly, a more complicated type of conversion was related to the nature of the visual task (Taylor, in Duntley et al., 1964). At one level, there was the effect of such variables as lack of knowledge about the target location, size, duration and time of occurrence. At a higher level there were such influences as individual differences in the levels of observer training, fatigue, physiological state and psychological variables. When improved visibility nomograms were published (Duntley, 1960), little was known about these effects. Nonetheless, largely as a result of the work of Blackwell (1959) it was considered possible to account for at least some of them. Thus a field factor of 1.90 was introduced for the effect of lack of observer training, 1.31 for lack of knowledge of target location ($\pm 4^{\circ}$), and 1.40 for lack of knowledge of when the target was to be presented.

A fundamental feature of the approach taken by Duntley and his colleagues is that the modelling process is essentially an engineering problem which can always be solved if adequate input data are available. Although this view is logically defensible, it is not certain that such information can be readily obtained. Indeed, although the number of field factors has grown considerably in recent years, most have had an <u>ad</u> <u>hoc</u> origin (Akerman III and Kinzly, 1979). A concomitant problem is that the field factored model tends to predict well for only a limited number of situations. To apply to other situations a different field factor becomes necessary.

### 6.1.3. Problems of input specification to visibility models.

**6.1.3.1. Search theory - the concept of visual detection lobes.** When a target can appear anywhere in the visual field, it is necessary to treat the detection problem as one of visual search. Models of visual search are based on the estimated probability of target detection at each possible retinal position. Differential sensitivity across the retina, coupled with the statistical nature of visual thresholds, results in a variation in the probability of carrying out a given visual task as a function of radial angular distance from the fovea. This is known as a visual lobe (Davies, 1968; Overington, 1976). It is a three dimensional surface, associated with a specific observer position in space and a specific orientation of fixational centre. It normally incorporates the features of target, background, atmosphere and visual system.

**6.1.3.2. Basic laboratory data.** The basic input data to the detection lobe relate the visual contrast threshold to the brightness contrast, size and retinal position of the target, and the observer's adaptation luminance. Unfortunately, there are discrepancies between some of the data reported by different investigators. Whereas the foveal data of Blackwell (1946) are statistically well fitted by a normal ogive of the form $N(1, 0.39)$, an ogive $N(0.97, 0.27)$ is required to fit the data of Lamar, Hecht, Shlaer, Hendley (1947). Large differences in peripheral thresholds are also reported (compare, for example, the data of Sloan (1961) with those of Lamar, Hecht, Shlaer and Hendley (1947). Furthermore, the angular limit of the fovea is considered to be greater by the Lamar group (0.7°) than Blackwell (0.54°). Clearly, clarification of these differences and their causes is required - it is known, for example, that peripheral acuity is particularly sensitive to variations in test conditions (Grether, 1963).

6.1.3.3. Target and observer motion. Outside the laboratory target detection will normally occur while the target, observer, or both are in motion. Considerable attention has been given to the foveal response to temporally modulated, spatially periodic stimuli (for example, Tolhurst, Sharpe and Hart, 1973). Two thresholds have been proposed one indicating the smallest contrast at which a grating can be perceived, and a lower one for the detection of flicker or brightness changes in the visual field. A second group of experimenters (Pantle, 1970; Breitmeyer, 1973; Tolhurst, 1973) have proposed one type of response mechanism sensitive to low spatial frequency and high temporal frequency, and another sensitive to patterns of higher spatial frequency and low temporal frequency. Sharpe (1974), Koenderink et al. (1978) and Barbur and Ruddock (1978) have confirmed that the peripheral retina specialises in the detection of large, fast moving stimuli.

The collection of such data is not without problems. Barbur (1979) has pointed out that non spatially periodic, moving stimuli produce results which cannot be predicted from studies employing periodic test patterns. A more serious difficulty, perhaps, is the fact that the relationship between an observer's performance under such artificial conditions and in the real world has yet to be determined. Kaufman (1974, Ch. 10) has presented evidence which suggests that motion perception can be influenced by a number of variables absent from the laboratory studies. The effect of including the third spatial dimension is of particular importance, because it highlights the possible discrepancy between the physical speed of the target and its perceived velocity due to speed constancy (for example Ross and Rejman, 1972). Such a difference casts doubt on the attempt by Petersen and Dugas (1972) to introduce a field factor for target movement based on target speed.

6.1.3.4. Search strategy. A particularly cogent example of the problem of specifying the input to a search model is given by the possibility that observers adopt different search strategies. Observers might search systematically, so that for each glimpse the detectability of any object in the visual field could be computed. Second, they might search randomly, so that the probability of detection would depend on chance as well as an object's specific properties. Third, search might depend on the objects in the search field, and be entirely predictable, given adequate description of the entire visual field. Although most search models involve the second approach because it leads to a mathematically tractable solution, Brown (1979) has pointed out that any of the strategies may apply in certain instances.

Several indirect lines of evidence lend support to this view. Bartlett (1932) and Neisser (1976), for example, have emphasised the active role of the observer in attending to preliminary representations of stimulus properties, and constructing from them a higher level representation. From this viewpoint, search performance would be seen as a joint product of the representations made by the observer and the stimulus characteristics. More direct support for Brown's assertion has been given by Megaw and Richardson (1979), who found that even when the scan time and probability of target detection were known, it was impossible to predict search time under conditions of target uncertainty without data for the payoff between scan time and the probability of detection, because observers employed a compromise strategy with the introduction of target uncertainty. Even a small amount of uncertainty can exert a relatively large influence on target detection (Cohn and Lasley, 1974). Target detection can also be influenced by the rewards and costs involved (Green and Swets, 1966) although in a largely unpredictable manner (Craig, 1979). Nor is behaviour during and between search trials constant (LLewellyn- Thomas and Lansdown, 1963).

6.1.3.5. Type of visual field. Search time is significantly affected by the type of field the observer scans. Unfortunately, the diver cannot be assumed to be always looking horizontally against a uniform background. It is therefore necessary to account for the fact that search time increases with the number of elements in the display and the number and type of cues (Smith, 1961). Nor is the influence of field type only determined by external factors. Johnston (1965) reported that observers have different sized visual fields - typically, observers with large fields found targets significantly more rapidly than those with small fields. On the other hand, when the visual field is empty, observers are likely to experience myopia (Luria, 1980). This effect, which relates to the resting state of accommodation, is subject to wide individual differences. It is also influenced by target size, making the prediction of its magnitude more difficult, because when visibility is poor large targets become visible not as a whole, but in small segments (Luria, 1980).

6.1.3.6. Underwater effects. The difficulties encountered in generalising from laboratory studies to the real world have been well illustrated by Akerman III and Kinzly (1979). Although they were able to calibrate their visibility model against field data by introducing a field factor, they were forced to conclude that "one still cannot completely account in a scientific manner for the differences between the parameterized thresholds and the underlying laboratory data." (p. 288). For the underwater situation, the multifarious effects which might contribute to such differences result both from an environment which is fundamentally more complex than that of the laboratory, and from the observers' responses to it.

One of the more obvious environmental effects is that due to the change in atmospheric pressure. For many practical diving purposes, the direct effect can be discounted if the partial pressures of oxygen and nitrogen remain at or near the atmospheric pressure at sea level (Kelly et al., 1968). On the other hand, the indirect effect can be quite marked. The narcotic effect of breathing air at depth is a good example. Occurring in even relatively shallow water (in some instances less than 30 metres), this effect is mainly concerned with changes in mental ability and mood. However, nitrogen narcosis can impair visual performance on any task involving these functions (Ross and Rejman, 1974).

In the present context, it is interesting to note the potential effects of perceptual narrowing, the reduction in an observer's ability to assimilate sensory information. Although often associated with a reduction in peripheral sensitivity, it is more likely to reflect a redistribution of attention under stress; the observer concentrates on the most important aspect of the task, which usually coincides with the centre of the visual field (Hockey, 1970). Weltman and Egstrom (1966) demonstrated its occurrence in novice divers at a depth of only eight metres in the open sea. On the other hand, Ross and Rejman (1974) found no clear evidence for it in a chamber test at 60 metres with experienced divers. That the effect is related to anxiety and does not only occur in the sea is evidenced by the fact that it was found at a simulated depth of 20 metres in a mock pressure chamber, where the observers were tricked into believing that the pressure was being increased (Weltman, Smith and Egstrom, 1971).

The quantification of individual differences may also be important when attempting to predict visual performance under water. Large individual differences have been found on a number of more complex visual tasks under water (for example, Ross, 1965, 1967; Ross, Dickinson and Jupp, 1970; Ross, 1970). An important influence on such differences is undoubtedly the observer's diving experience. The perceptual judgements of experienced divers tend to be less variable than those of novices, and more similar to their judgements in air (Weltman and Egstrom, 1966; Luria, Kinney and Weissman, 1967; Nichols, 1967; Ross, 1967, 1970). It is difficult to envisage how such differences could be readily incorporated into a visibility model.

On a more general level, the construction of visual detection lobes for the underwater environment will be complicated by the fact that the perceived changes in stimuli upon immersion are not always related to the physical changes in a simple manner. Many investigators (reviewed in Adolfson and Berghage, 1974; Ross, 1971) have shown that the relationship between the perceived size and distance of underwater objects is such that knowledge of the retinal image size by itself is insufficient to allow the prediction of perceived size. Speed perception is similarly affected.

Ross (1974, p. 33) cites the case of an object in turbid water whose apparent speed will be greater than its actual speed. The effect is more complicated in clear water because there will be different speed distortions depending on the line of travel. It is also likely that veering tendencies will affect the search performance of a free-swimming diver (Ross, Dickinson and Jupp, 1970). These problems are compounded by the adaptation that takes place to such distortions (reviewed in Welch, 1978).

6.1.3.7. Interaction effects. The field factor approach relies on the possibility of combining task element probabilities together in a simple (mulitplicative) manner. In most dynamic search situations, however, factors exist that modify all the elements comprising the task. Too long spent looking in one area of the visual field, for example, will reduce the time available for the remaining areas and modify the probability of detection in those areas. Under conditions of heavy mental loading (as might well be the case for the diver), individuals may adopt alternative strategies to achieve the goal of maintaining output at a constant level (Sperandio, 1978). Such common mode effects are the rule rather than the exception when modelling human behaviour (Embrey, 1979), and considerably reduce the possibility of accurately synthesising task elements to allow prediction of perforance. As the number of documented interactions increases, analysis of their effects will require increasingly ingenious experiments.

### 6.1.4. Experimental aims.

Clearly, the detailed assessment of the influence of the factors currently considered to be relevant to visual search represents a formidable task, and one which is beyond the scope of the present study. Nonetheless, in view of its importance in search models, it would be useful to identify some of the limits of the field factor approach to visibility modelling.

The Duntley model was primarily concerned with the maximum theoretical sighting range of a static target for a static observer. From the preceding discussion, it would appear that in real search situations the detection threshold is subject to a number of influences not considered by the model. The main aim of the present experiment, therefore, was to investigate the effects of having a non-static target or observer. Two questions merited attention. It was important to discover whether the visual range of a moving target or observer could be predicted from the basic model. It followed that if a correction was necessary, it would also be useful to determine whether a field factor could serve this purpose. Given the complex nature of movement perception, no precise predictions were made of the size or direction of the target-observer motion. Nonetheless, it seemed reasonable to consider that because the detection threshold varies with velocity (Barbur and Ruddock, 1978), if the data required correction, a single factor could not account for the wide range of possible velocities; consequently it would be necessary to determine velocity in each particular viewing situation.

A second method of assessing the field factor approach is to consider the possibility of interactions between the variables. The presence of such interactions considerably weakens the argument favouring field factors because it is usually assumed that the factors are independent. On the other hand, it seems likely that in real search situations the variables cannot be treated in this way. A second aim of the experiment was to investigate the possibility of one type of interaction, namely that between the effects of target-observer motion and the size of the search area.

## 6.2 METHODS AND RESULTS

### 6.2.1. Experiment 6a - Laboratory study.

6.2.1.1. Observers. Four trained and experienced divers, three males and one female, volunteered for the experiments. Their age range was 23-29 years, with a mean of 25 years. All had normal colour vision (on the Ishihara Colour Test) and three had normal uncorrected visual acuity (on the Snellen Chart). One observer, P. G. was myopic and wore corrective lenses. All of the observers had previously participated in psychophysical experiments.

6.2.1.2. Apparatus. The stimuli were two grey aluminium tiles (one of low reflectance (12%) and one of high reflectance (83%), each having a surface area of 6.45 sq. cm., as used in Experiment 3 a. The basic experimental arrangement was that shown in Figure 3.1

with two perspex cross-sections added to the frame. To enable the stimuli to be presented at different velocities, the perspex frame was attached to a four wheeled chassis, which ran along the wooden support. The chassis was driven by a small geared motor (Meccano Ltd.) connected to a stabilised power supply. Two switches were incorporated into the circuit. One allowed the observer to stop and start the motor, the other allowed the experimenter to control the direction of the frame's travel. An electronic timer (Forth Instruments Ltd.) monitored the interval between the motor being switched on and off.

6.2.1.3. Procedure. The aquarium was filled with a solution of Riboflavin, Methylene Blue and tap water, to produce a green coloured background. The background luminance was then measured through the facemask, as in Experiment 3 a. In a repeated measures design, each observer took part in one practice session and two test sessions, at the same time on consecutive days. In both sessions (one for each stimulus), after an adaptation period of five minutes, the visual range was determined for the stimulus (binocular viewing) using a modified method of limits (to correspond with the method of Experiment 3a the ascending series was omitted). Following ten practice trials, each observer was given twenty test trials in random order, under each of five conditions. In the four dynamic conditions, the stimulus was presented at either three or eight cm/s, and on either the middle of the centre cross-section of the frame, or in a random position on one of the three cross-sections. The observer was informed which condition was about to be presented and was instructed to indicate in which position on the frame the stimulus appeared.

On each trial, the observer switched the motor on, and the stimulus moved towards the facemask until he or she could just detect it. The Experimenter then recorded the distance travelled and the time taken. The initial distance was varied to prevent the observer expecting the stimulus to appear after a constant time interval. In the fifth condition, the visual range was determined for the static stimulus, in a known location, following the procedure in section 3.2.1.3. Twenty trials were given for each condition. The blackbody distance was also determined for each observer, on each day of testing, with the blackbody used in Experiment 3a.

Although the observers' adaptation levels were maintained as far as possible, rest periods were allowed at any time on request. These were followed by a further period of adaptation. Before each test session, which lasted approximately 90 minutes, a blackbody estimate was made by the Experimenter. No changes were reported during the experimental period.

### 6.2.2. Experiment 6b - Swimming pool study.

6.2.2.1. Observers. The observers were the same as in Experimenter 6a.

6.2.2.2. Apparatus. The experiment was undertaken in the swimming pool at the University of Stirling. The pool measures 25 x 11 m., with a constant dept of 1.3 m. The stimuli were two aluminium tiles, each 200 sq. cm., having the same spectral reflectance characteristics (in air) as the tiles used in the laboratory study. They could be suspended on one of nine laboratory retort stands, which were arranged one meter apart across the pool floor, towards one end. A surveyor's tape measure was laid along the pool floor, perpendicular to the stands, directly in line with the central stand. The tape was weighted to prevent it from becoming misaligned.

SCUBA gear was worn by the observers according to personal preference, although they all wore facemasks of the recessed kidney type. In the clear water, it was necessary to artificially reduce the visual range so that the stimuli were not visible along the full length of the pool, by attaching a semi-opaque piece of colourless perspex to the front of the observers' masks. The observers also carried small formica slates, which informed them of the order of the experimental conditions and on which they recorded their own data.

6.2.2.3. Procedure. Each observer took part in two test sessions (one for each tile), each lasting approximately ninety minutes. The experimental design was similar to that in the laboratory experiment. After an adaptation period of five minutes, the visual range of the tile was measured using a modified method of limits, as before. Following five practice trials, each observer was given six test trials, in random order, under each of the five experimental conditions tested in the laboratory study. On each trial, the observer swam towards the central stand until the tile was just visible (binocular viewing), using the tape as a guideline, and keeping the faceplate as close as possible to it. He or she then recorded the distance on the formica slate, swam back to a position where the tile was no longer visible (a marker on the tape) and repeated the procedure.

In the small search field condition, the tile appeared on the central stand. In the large search field condition, it was randomly positioned by the Experimenter on one of the nine stands. In this condition, the observer also noted on the slate the position of the tile. In the high velocity condition, the observers swam with the aid of fins (flippers); they were instructed to swim at an even, moderate pace on each such trial. The same instruction was given for the low velocity condition, in which the fins were removed. The static visual range for each tile in a known position was determined in the same way as that described in section 3.2.2.3. The blackbody distance was also determined for each observer, using the open end of a black plastic bucket lined with black cloth.

The test sessions were undertaken at night, under artificial illumination, at the same time on consecutive days. The background luminance in the horizontal plane of the observers' eyes was measured before both test sessions, using the underwater photometer (Fig. 3.5). No difference was found between the two readings. To minimise the time taken to complete the experiment, the observers were tested in pairs. All of the observers had rehearsed the procedure in the swimming pool on a previous occasion.

### 6.2.3. Results - Experiments 6a and 6b.

The mean visual ranges for each observer for the two tiles in the four dynamic (two velocities, two sizes of search field) and one static condition are shown in Figures 6.1 and 6.2. The distances in the dynamic conditions in the laboratory were obtained by multiplying the time taken by the tile velocity and subtracting the product from the initial distance of the tile from the facemask. This was more accurate than measuring the distance moved along the frame, because at the higher velocity, the forward momentum of the chassis caused it to continue beyond the distance at which the motor was switched off. The figures also show the values of the predicted visual ranges. They were calculated as follows: first, the observers' blackbody distance estimates were averaged to calculate the beam attenuation coefficient. Assuming a contrast threshold value of 0.02, it was then possible to calculate the inherent contrast for each tile from formula 2.12. The contrast threshold was then multiplied by the field factor of 2.71 for uncertain stimulus location and time of occurrence (Taylor, in Duntley et al., 1964). These values were then

Fig. 6.1. The effect of target velocity and search area on visual range (Experiment 6a).

The mean (N=20) threshold detection distances (binocular viewing) are given for each of four observers (identified by their initials). The targets were a bright (B ) and dark (D) tile, presented in a small (S) or large (L) search area, at a low ( ♦ ) or high ( ◊ ) velocity. The threshold detection distances for the static targets are also given ( O ). The threshold distances predicted from the Duntley visibility model ( X ) refer only to the moving tiles. Adaptation luminance was 10 cd/$m^2$.


P.B.
D.T.
J.A.
Y.W.
54
50
46
42
38
34
30
55
51
47
43
39
35
31
54
50
46
42
38
34
44
40
36
32
28
24
Mean visual range (cm)
B S D B L D
O
X
Tile brightness - Bright / Dark
Search area - Small / Large

Fig. 6.2. The effect of observer velocity and search area on visual range (Experiment 6b).

The mean (N=6) threshold detection distances (binocular viewing) are given for each of four observers (identified by their initials). The targets were a bright (B) and dark (D) tile, presented in a small (S) or large (L) search area, with the observer moving at a low ( ♦ ) or high ( ◊ ) velocity. The threshold detection distances for the static targets are also given ( ○ ). The threshold distances predicted from the Duntley visibility model ( X ) refer only to the moving observers. Adaptation luminance was 3 cd/$m^2$.


P.B.
D.T.
J.A.
Y.W.
Mean visual range ( m.)
21
19
17
15
13
11
18
16
14
12
10
8
6
B
S
D
L
Tile brightness – Bright / Dark
Search area – Small / Large

used to calculate the predicted visual range for each tile from equation 3.1.

From the figures it is clear that target-observer motion influenced the visual range of both targets in both sizes of search field. The range is shorter in the high velocity conditions; it is also shorter for the larger search area. The obtained ranges for both targets and both velocities were greater than those predicted for a static condition when the search area was small. In the laboratory study (Figure 6.1) the obtained ranges were also greater than predicted for the low velocity, large search area condition. In the swimming pool study (Figure 6.2), the predicted range was greater than the obtained range in the high velocity condition, although this effect was less marked for the bright tile. In the low velocity condition, the obtained range was slightly greater than predicted.

Statistical analyses were undertaken with GLIM, a computer based interactive modelling procedure, that uses a combination of linear regression and analysis of variance techniques to differentiate treatment effects. From the raw data of each experiment a linear regression model was established, fitting the data (T) with an equation:

$$Y = a + bT \tag{6.1}$$

where $a = 0$ and $b = 1$. Then, as successive factors were added to the equation the deviance from each best-fit line was calculated. For example, taking account of the predictions from the addition of field factors to the Duntley visibility model required the data to be fitted with an equation:

$$Y = a + bT + bP \qquad (6.2)$$

where P is the predicted value. The magnitude of the increase or decrease in deviance from the equation when successive factors were added indicated whether additional correction factors to the predicted values were required.

The results of the analyses are summarised in Tables 6.1 and 6.2. It is clear that for both experiments the Duntley model significantly improved the predictability of the data, compared with when there was no model ($p<.005$). Similarly, the effects obtained for target-observer motion and search field area were also significant (both $p$'s$<.005$). In the laboratory (Table 6.1) there was a significant reduction in variance when subjects were treated as a separate factor ($p<.005$). The tables further show that the effects of tile brightness and the numerous possible interactions were insignificant ($p>.05$). In the swimming pool study (Table 6.2) the effect due to subjects was also insignificant ($p>.05$).

Intra-individual threshold variations in the two experiments are given in Tables 6.3. and 6.4, as coefficients of variation. Two-tailed sign tests confirmed that the small search field conditions resulted in significantly less variation than the large search field (laboratory: $L = 0$, $T = 16$ $p<.01$; swimming pool: $L = 3$, $T = 16$. $p<.01$). In the laboratory experiment, the variation in the high velocity condition was significantly greater than in the low velocity condition ($L = 2$, $T = 16$, $p<.01$).

TABLE 6.1. ANOVA summary tables for Experiment 6a derived from GLIM analysis (visual range study).

| SOURCE | SS | df | MS | F | P |
|---|---|---|---|---|---|
| Reduced model: | | | | | |
| Duntley model prediction | 714.7 | 1 | 714.7 | 541.44 | < .005 |
| Target velocity | 178.6 | 1 | 178.6 | 135.30 | < .005 |
| Target search area | 126.4 | 1 | 126.4 | 95.76 | < .005 |
| Subjects | 119.3 | 3 | 39.8 | 30.20 | < .005 |
| Residual | 33.0 | 25 | 1.3 | | |
| Full model: | | | | | |
| Full model | 1158.6 | 18 | 64.4 | 62.50 | < .005 |
| Omitted variables[1] | 19.7 | 12 | 1.6 | 1.60 | > .05 |
| Residual | 13.3 | 13 | 1.0 | | |
| TOTAL | 1191.6 | 31 | | | |

1. Omitted variables were:
(a) Tile velocity x target search area
(b) Subjects x tile velocity
(c) Subjects x target search area
(d) Tile brightness
(e) Tile brightness x tile velocity
(f) Tile brightness x target search area
(g) Tile brightness x subjects.

## TABLE 6.2. ANOVA summary tables for Experiment 6b derived from GLIM analysis (visual range study).

| SOURCE | SS | df | MS | F | P |
|---|---|---|---|---|---|
| Reduced model: | | | | | |
| Duntley model prediction | 146.1 | 1 | 146.1 | 168.32 | <.005 |
| Subject velocity | 33.58 | 1 | 33.58 | 38.69 | <.005 |
| Target search area | 48.51 | 1 | 48.51 | 55.89 | <.005 |
| Residual | 24.31 | 28 | 0.868 | | |
| Full model: | | | | | |
| Full model | 242.86 | 18 | 13.49 | 18.18 | <.005 |
| Omitted variables[1] | 14.67 | 15 | 0.978 | 1.32 | >.05 |
| Residual | 9.64 | 13 | 0.742 | | |
| TOTAL | 252.5 | 31 | | | |

1. Omitted variables were:
   - (a) Subjects
   - (b) Tile brightness
   - (c) Tile brightness x subject velocity
   - (d) Tile brightness x target search area
   - (e) Subject velocity x target search area
   - (f) Subjects x tile brightness
   - (g) Subjects x subject velocity
   - (h) Subjects x target search area.

TABLE 6.3. Coefficients of variation in Experiment 6a (visual range study).

| OBSERVER | TILE VELOCITY | TILE BRIGHTNESS | | | |
|---|---|---|---|---|---|
| | | Dark | | Bright | |
| | | SEARCH AREA | | SEARCH AREA | |
| | | Small | Large | Small | Large |
| P.B. | Static | 0.03 | | 0.03 | |
| | Low | 0.04 | 0.08 | 0.03 | 0.05 |
| | High | 0.07 | 0.09 | 0.05 | 0.05 |
| J.A. | Static | 0.02 | | 0.03 | |
| | Low | 0.03 | 0.06 | 0.02 | 0.05 |
| | High | 0.05 | 0.08 | 0.04 | 0.05 |
| D.T. | Static | 0.04 | | 0.03 | |
| | Low | 0.06 | 0.07 | 0.04 | 0.04 |
| | High | 0.03 | 0.08 | 0.04 | 0.06 |
| Y.W. | Static | 0.04 | | 0.05 | |
| | Low | 0.05 | 0.08 | 0.04 | 0.05 |
| | High | 0.05 | 0.07 | 0.06 | 0.09 |

TABLE 6.4. Coefficients of variation in Experiment 6b (visual range study).

| OBSERVER | OBSERVER VELOCITY | TILE BRIGHTNESS | | | |
|---|---|---|---|---|---|
| | | Dark | | Bright | |
| | | SEARCH AREA | | SEARCH AREA | |
| | | Small | Large | Small | Large |
| P.B. | Static | 0.03 | | 0.03 | |
| | Low | 0.05 | 0.11 | 0.07 | 0.06 |
| | High | 0.07 | 0.15 | 0.03 | 0.14 |
| J.A. | Static | 0.03 | | 0.03 | |
| | Low | 0.04 | 0.09 | 0.08 | 0.07 |
| | High | 0.05 | 0.09 | 0.07 | 0.07 |
| D.T. | Static | 0.03 | | 0.03 | |
| | Low | 0.03 | 0.05 | 0.05 | 0.10 |
| | High | 0.07 | 0.16 | 0.03 | 0.11 |
| Y.W. | Static | 0.03 | | 0.05 | |
| | Low | 0.08 | 0.06 | 0.08 | 0.08 |
| | High | 0.05 | 0.12 | 0.07 | 0.10 |

In the swimming pool experiment, however, there was no significant effect of velocity ($L = 5$, $T = 16$, $p > .05$).

## 6.3 DISCUSSION

The present data confirm that even with the addition of field factor corrections, the Duntley visibility model does not accurately predict visual range when the target or observer is moving. In both the laboratory and swimming pool, it was possible to significantly increase the accuracy of the predictions made by the model by taking into account both the velocity of the observer or target and the size of the search area. In the laboratory, it was also necessary to account for the variation between observers.

The finding that the model does not accurately predict the visual range when the target or observer is moving does not by itself impugn the model, because the model applies strictly to the maximum theoretical visual range of static targets and observers. Rather, the major implication of the data is that the number of field factors required to accurately predict visual range under realistic search conditions is likely to be high. The greater the number of field factors required to predict visual range, the less useful they become.

The general finding that target or observer motion is an important variable in visual detection tasks lends support to the previous findings of Petersen and Dugas (1972). However, in their experiment, it was found that the effect of target motion could be accounted for by modifying the exponent in the detection probability function with a squared term. This type of correction is unlikely to be of great advantage in the present situation because the visual angle subtended by the target was not constant, whereas in the Petersen and Dugas experiment the target moved across a two dimensional surface. Secondly, Petersen and Dugas found that the detection rate improved as the target speed increased up to a rate of about 5 degrees per second, after which it remained fairly constant. In the present experiments, on the other hand, when the target or observer velocity increased, the visual ranges of the two tiles also increased. Thus, although it was possible to significantly reduce the variance due to the effect of velocity by altering the linear regression equation in the GLIM analysis, it must be considered that the present data support the claim that it is highly unlikely that the detection threshold changes linearly with changing velocity (Baker and Steedman, 1961). Furthermore, there is the additional practical problem of determining the velocity of the target, because in the underwater environment the physical and perceived velocities are not necessarily equal.

When analysing the perception of movement in the third dimension, account must be taken of the variation in speed of an object across the retina with distance. In general this is slower at far distances, because it traverses a smaller retinal area in the same time. Under water, the observer experiences distortions of apparent size and distance, which vary in a complex manner with water clarity and the actual distance of the target from the eye (Ross, 1965, 1967; Luria et al., 1967; Kinney et al., 1969; Kinney and Luria, 1970; Ferris, 1972). In clear water, for example, a diver's facemask makes nearby objects appear too near and enlarged. Because distances across the line of sight normally appear enlarged, objects appear to be travelling faster than they actually are. The distortion along the line of sight is less straightforward, as near distances appear foreshortened (Ono et al., 1970) but far distances appear extended (Luria et al., 1967; Ross, 1967) Consequently, at near distances objects appear to travel too slowly, but they should appear to speed up in the distance. The adaptation that takes place to these distortions is also complex (Ross and Rejman, 1972). Although these effects have not been studied at threshold, it would seem likely that they should also be present there. This would imply that for the calculation of visual range the perceived velocity of a target is a more relevant datum than the physical velocity. This amounts to a further variable to be accounted for in the construction of the visual lobe.

A field factor approach to the present data would also need to account for the observers' reaction times. In most laboratory detection threshold tasks, the observer reports only the absence or presence of the moving stimulus. In the present experiments, however, and in many real search tasks, reaction time is also involved. Its effect will vary with velocity-for example a high velocity stimulus will move further in the time taken to react to its presence than a low velocity stimulus (assuming a constant reaction time). Nor is reaction time itself always constant, having been found to vary with such factors as stimulus luminance (Pollack, 1968 and the amount of temporal uncertainty (Klemmer, 1957). Unfortunately, reaction time is impossible to calculate for the present data because the exact distance at which the moving target was first detected is unknown. Nonetheless, because its effect has been shown to vary with velocity, it is suggested that the field factor for lack of knowledge of time of occurrence, used to calculate the predicted visual range in the present experiments, can only be validly applied when such a distance is known.

A further problem introduced by the presence of target-observer motion is that the location of the target on the retina at the time of detection can vary. Consequently, any correction for the effect of movement will require account to be taken of the variation in sensitivity across the retina. The complexity of this effect has been demonstrated by Barbur and Ruddock (1978), who found that the detection threshold at different retinal locations varies with target size, field structure and target velocity. For example, although the fovea is more sensitive than the periphery for target speeds up to 25°/s, for sufficiently high speeds and sizes the periphery is equally sensitive, if not more so. Similarly, for a given stimulus speed, the detection threshold can be either above or below the static threshold, depending on retinal location.

Figures 6.1 and 6.2 also show that increasing the size of the search area resulted in a decreased visual range, and that the shortest ranges were obtained in the high velocity, large search area conditions. This was probably because in these conditions the distance to the target decreased more rapidly while the stimulus remained undetected (relative to the low velocity conditions), and there was a higher probability of looking in the wrong location on each glimpse (relative to the small search area). Considering that the target location was not well defined in either size of search field, this finding suggests that the division of search areas into those in which the stimulus location is known (to within plus or minus four degrees of visual angle) and unknown (Taylor, in Duntley et al., 1964), is too simplistic. Given the range of possible search fields, as determined by the visual range, a number of field factors appear to be necessary.

Table 6.1 confirms that in the laboratory experiment, there were statistically significant differences between the four observers. This finding further complicates attempts to predict visual range from field factor modifications to the Duntley model, because it implies that the predicted threshold would need to be weighted differently for different observers. That the effect did not occur in the swimming pool study could have been due to the greater intra-individual variation there than in the laboratory (Table 6.3 and 6.4). A tentative explanation of the inter-individual variation is suggested through a consideration of the nature of the visual task. The observers were confronted with a dim, fog-like visual world, devoid of frames of reference, in which focusing was difficult. In this world rapid systematic visual search is likely to have been impeded, with the result that the observers had the opportunity to adopt different strategies. In the large search area conditions, for example, some observers might have adopted different strategies from those adopted in the small search area conditions. One observer commented after the experiment that he had not scanned the visual field at all in the large search field condition in the laboratory, but preferred to fixate the centre of the aquarium and "Let the target find me". This is of some theoretical interest because it provides indirect evidence that a form of perceptual narrowing occurred. The phenomenon is usually associated with more extreme forms of environmental stress, such as cold narcosis, or fatigue (Ross, 1974, p. 32). In the present experiments, however, no obvious form of such stress was present. It seems possible, therefore, that perceptual narrowing might occur whenever the demands of the task exceed the mental resources to perform it. This would support the claim of Hockey (1970), that the effect refers to a redistribution of attention to enable the observer to concentrate on the most important aspect of the task, rather than to a physical reduction in peripheral sensitivity. It would clearly be useful to determine the conditions under which the observer no longer considers it possible to search the visual field.

Against the difficulties involved in modelling underwater visibility using a field factor approach can be set the failure to find significant interaction effects between the variables examined in the present experiments. This finding is encouraging because the problem of threshold prediction is made much more complex if the field factors cannot be treated independently. At the same time, it should be noted that this argument cannot be automatically applied to other experimental conditions - it is possible, for example, that different target or observer velocities produce interaction effects that depend on the size of the search area. It is also possible that interactions took place in the present experiments that were not included in the analyses. In particular, the present analyses exclude the potential modifications to the visual detection lobe due to the interaction between the size of the search area and the observers' search strategies. For example, the preceding comments about perceptual narrowing suggest that only the gross effects have been extracted from the data.

Taken together, the results from the present swimming pool and laboratory experiments suggest that the field factor approach to underwater visibility modelling when the target or observer is in motion might be inappropriate. Such a finding lends support to the contemporary view that the field factor approach is outdated, and that a more accurate model of the probability of target detection might be obtained by exploring the possibility of defining detection lobes under particular conditions. Akerman III and Kinzly (1979) provide a good example of this approach. Their visual search model for predicting aircraft detectability has four components: a liminal contrast threshold, a frequency of seeing curve, a soft shell search representation, and discrete cumulation of single glimpse detection probabilities. By comparing three sets of data from their own search experiments with those of five existing models, they were able to derive a model that was a better predictor of visual range than any of the other models.

Perhaps the most appropriate future research strategy might be to include current theories of visual search and underwater performance into the design of experiments to be carried out under realistic conditions. Given the complexity of the factors influencing underwater performance and the sophistication of search theory, such a task might prove to be formidable. Nonetheless, the existence of powerful modelling techniques such as GLIM offers the opportunity to make significant advances towards the development of a model that will accurately predict visual range. The failure to obtain data that might confirm or question the validity of field factors represents an important shortcoming of the Duntley approach. It is suggested that greater emphasis should be placed on the collection of such data. Armchair speculation should be only a part of the scientific process.

## CHAPTER SEVEN - GENERAL CONCLUSIONS AND PROSPECTS.

If science can be described in terms of the search for patterns in Nature, the most important scientific conclusion to be drawn from the present study concerns the pattern of the relationship between the response of a human observer to a visual stimulus and the physical specification of that stimulus. For target detection and recognition, as well as for supra-threshold appearance, it was found that the specification of the fundamental physical aspects of the stimulus was often insufficient to predict the response of the observer. Thus, it would appear that some current models of human visual performance oversimplify the visual response.

Examples of this mismatch were obtained in each experimental section. For target detection, for example, it was observed that the Duntley visibility model erred in stressing the importance of luminance contrast as a correlate of visual contrast. For the recognition of colours, it was indicated in Chapter 5 that the failure to achieve a perceptually uniform colour space restricted the assessment of chromatic discrimination. At the same time, attention was drawn to the importance of considering colour as a three dimensional concept, and to the potential role of high order cognitive factors in colour perception. The size of the mismatch appeared to be related to the nature of the visual task. In general, as the task became more complex, the available models became less accurate. The most serious discrepancy appeared to be that obtained for the data of Chapter 6, which was concerned with visual search under dynamic viewing conditions.

Criteria for assessing the adequacy of available models of visual performance should reflect the interests of the researcher. For some practical purposes, the establishment of 'rules of thumb' to govern underwater operations is all that is required. From this viewpoint, the present data confirm some previous data with respect to target detection and recognition. For example, general agreement has been obtained with the finding of Kinney et al. (1967) that fluorescent colours are particularly visible under water. On the other hand, from a less 'applied' viewpoint, the present data reveal important deficiencies in contemporary theory - the data from the colour matching experiments (Chapter 5) suggest the involvement of higher mental processes for which no adequate model exists. Visual search theory is also still in its infancy.

A second conclusion to be drawn from the present study relates to the possibility of simulating underwater vision studies in the laboratory. In general, the trends in the data are encouraging. For all experiments, the relative responses to the various targets were fairly consistent between laboratory and field. Undoubtedly, the field data were influenced by the fact that the experiments were conducted with highly trained and experienced observers, in diving conditions that minimised the psychological and physiological stresses frequently encountered under water. Once again, the question of whether the observed discrepancies imply that laboratory data should not be used to predict performance in the field is slightly ambiguous. As the desired level of precision increases, the prospect for immediate success appears to decrease. Similarly, as the field conditions become less quantifiable, they become more difficult to simulate, and where it might be necessary to induce psychological anxiety or physical discomfort, the researcher is faced with the additional burden of making ethical decisions. Nonetheless, the present data suggest that for simple visual tasks, it might not be necessary to conduct all of the experiments under field conditions. It might be advantageous, for example, to use the laboratory for extensive experimentation and then to replicate one or two of the conditions in the field.

The third conclusion from the study concerns the practical aspects of the specification of input data to models of visual functioning. At the simplest level, the present experiments have attempted to measure some of the important optical characteristics of the target and background, as well as to specify the appearance of the target to the observer. It is encouraging that diver operated instruments were able to provide such data (even if their accuracy was limited by the colour specification problem) because simultaneous visual and physical measurements are essential for the prediction of the visual response. Furthermore, the relatively low cost of the instrumentation used in the present study suggests that underwater vision research need not be the sole province of research groups with substantial financial support. Similarly, future attempts at visibility modelling are likely to be enhanced by the increasing availability of powerful data storage devices. The storage of large quantities of hydrological optical and human performance data on portable instruments would make in situ visibility calculations a real possiblity.

Further experiments suggest themselves in each area of the present study. Of greatest theoretical interest, perhaps, would be the extension of the experiments concerned with colour constancy as a function of viewing distance. Such a finding does not appear to have been reported previously, and it would be interesting to repeat the experiments using a greater number of viewing distances, so as to examine more closely the shape of the functions relating viewing distance to the degree of constancy. Similarly, it would be useful to extend the investigation to allow the assessment of other potential influences on the constancy function (for example by comparing monocular with binocular viewing). Because the colourimeter provides a fairly rapid method for colour matching, it might also be possible to examine the time course of chromatic adaptation under field conditions, by requiring divers to open their eyes at different depths and make colour matches at given time intervals.

If progress is to be made towards the improvement of visibility models, future studies must concentrate on data collection, because in this area theory far outstrips the available data. It has been suggested that errors have been made in the field of visibility modelling because the actual performance of human observers under realistic viewing conditions has been neglected. It appears to the author that it would be particularly useful to acquire such data, with which to test the sophisticated models of search and visibility now available. The data should certainly be extended to include situations such as where the observer or the target is in motion. They might also eventually even include situations such as when the search task must be undertaken in relatively dangerous circumstances (for example, searching for explosives).

Whereas the present study has focused on the underwater environment, an obvious extension of the research would be towards the modelling of atmospheric visibility. Numerous theoretical and applied studies have been undertaken following the impetus given by Middleton's (1952) excellent survey, many of which deal directly with the problems of detection and recognition. It has been unfortunate that greater importance has not been given to the simultaneous measurement of optical and psychophysical variables (normally in these studies physical measurements were limited to a simple assessment of the background adaptation luminance). Now that the technology is available to accurately measure light in the atmosphere, there should be no reason for this shortcoming to be a feature of future work. (Although it should be noted that the problem of colour specification will still require a solution). In particular, it would be interesting to investigate the possible presence of a constancy mechanism to compensate for changes of luminance contrast (and less crucially, of hue and saturation) with changes in viewing distance.

Finally, with regard to methodology, reference might be made to the statement in the Prolegomena concerning the the nature of psychological research. Little defence has been offered for the present experimental designs and methodologies. To the purist, many underwater performance studies must appear crudely conceived. Nonetheless, through previous and, hopefully, the present studies, it has been shown that progress can be made by setting realistic goals.

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# APPENDIX A. Hydrological optics - fundamental processes and the theory of radiative transfer.

## A.1. Global radiation incident on the water surface.

The description begins with the assumption that irradiation on the water surface is of solar origin. As light (defined as radiation to which the human eye is sensitive) passes through the atmosphere it is subject to the effects of absorption (conversion into alternative forms of energy) and scatter (redirection), the latter being the dominant process.

When the particles involved in the scattering process are much smaller than the wavelength of incident light, the intensity of the scattered light is proportional to the reciprocal of the fourth power of the wavelength. This is generally referred to as Rayleigh scattering. As particle size increases, light becomes scattered almost equally at all wavelengths. This explains the shift in apparent colour of the sky from blue on a clear day to grey on a misty day. McCartney (1976) has given a comprehensive summary of scattering in the atmosphere. Absorption is also somewhat selective, mainly due to the presence of water vapour, which causes absorption in the red region of the spectrum to exceed that in the blue.

The distribution of radiation changes with solar altitude and cloud and haze cover (Sastri and Das, 1968; Condit and Grum, 1964; McFarland and Munz, 1975 a and b). Intensity variations are minimal while the sun is $30^{\circ}$ or more above the horizon, but can be seven log units of luminance between $20^{\circ}$ above and $20^{\circ}$ below if there is no moon (Lythgoe, 1979, p.10). Normal cloud cover reduces daytime irradiance by 0.3 log unit, heavy storm clouds by about one log unit. Although direct energy from the sun is unpolarized, skylight is plane polarized to a degree which is dependent on the part of the sky under observation, the solar elevation and the air turbidity (Sekera, 1957, cited in Jerlov, 1976). Maximum polarization occurs at about 90° from the sun in the vertical plane through the observation point and the sun.

## A.2. The air-water interface.

### A.2.1. Reflection.

Jerlov (1976) considered it good methodology to distinguish sky radiation from global radiation (from sun and sky) when discussing the air-water interface. Sky radiation is considered to have a directed and a diffuse component; the directed radiation from the sun (assumed to be unpolarized) has a reflection value (for a flat surface) equal to the mean of the reflection parallel and perpendicular to the plane of incidence :

$$\rho_s = \frac{1}{2}\left|\frac{\sin^2(i-j)}{\sin^2(i+j)} + \frac{\tan^2(i-j)}{\tan^2(i+j)}\right| , \qquad (A.1)$$

where i is the angle of incidence, j is the angle of refraction and $\rho_s$ is a percentage. The reflected ray is in the plane of incidence, and the angle of reflection is equal to i.

The diffuse component is approximated by :

$$\rho_d = \frac{2\pi \int_0^{\frac{1}{2}\pi} \rho(i) L \sin i \cos i \, di}{2\pi \int_0^{\frac{1}{2}\pi} L \sin i \cos i \, di} = \int_0^{\frac{1}{2}\pi} \rho(i) \sin 2i \, di , \qquad (A.2)$$

where i is the reflectance for the angle of incidence and L is the radiance. The derivation of this equation is given in Jerlov (1976). The reflection of global radiation is then given by :

$$\rho = \rho_s(1-n) + \rho_d n , \qquad (A.3)$$

where n is the significant ratio of sky radiation to global radiation. Unfortunately the water surface is rarely calm. Theoretically, therefore, small elements of waves should be considered as individual air-water interfaces, each with its own refractive index. In practice this means that it is usually easier to measure reflection directly than to calculate it. A further complication is that for solar elevations below 30° reflection depends on wavelength. Sauberer and Ruttner (1941) have discussed this effect.

### A.2.2. Refraction.

An electromagnetic wave incident on a water surface decomposes into a wave which is refracted and passes through the surface, and one which is reflected back into the air. The law of refraction for a flat surface is :

$$\frac{\sin i}{\sin j} = n , \qquad (A.4)$$

where i and j are the angles that the incident ray and refracted ray make with the normal and n is the refractive index of water relative to air (taken as 1.333 for fresh water and 1.341 for sea water).

## A.3. Absorption of light under water.

Within the hydrosphere, light is again subject to the effects of absorption and scattering. In his analysis of absorption, Williams (1970) set out to establish a relationship between the absorption coefficient (a) and transmittance (T). He began by considering the radiant flux, $F_o$, incident on an imaginary sample of absorbing (but non-scattering) fluid of length $\Delta l$. For this case $F_o - F\Delta l$ will be lost in the sample through absorptance (A). If $F\Delta l$ represents the radiant flux leaving the sample, A can be defined :

$$A = \frac{F_o - F\Delta l}{F_o} \quad . \qquad (A.5)$$

The absorption coefficient is then defined in terms of the absorptance of an infinitely thin layer of water divided by the layer thickness :

$$a = - \frac{A}{l} \quad . \qquad (A.6)$$

Substitution of equation (A.5) into equation (A.6) results in :

$$a = \frac{-\dfrac{F_o - F\Delta l}{F_o}}{\Delta l} = - \frac{F_o - F\Delta l}{\Delta l F_o} = - \frac{\Delta F}{\Delta l F_o}$$

so that :

$$-a\Delta l = \frac{\Delta F}{F_o}$$

or, in differential form :

$$-adl = \frac{\Delta F}{F} \quad . \qquad (A.7)$$

Integration of equation (A.7) between the limits of $F_o$ and Fl for a path length of one unit results in :

$$- \int_0^1 adl = \int_{F_o}^{Fl} \frac{dF}{F} \quad . \qquad (A.8)$$

Equation (A.8) can be integrated on the assumption of a homogeneous medium :

$$-al = \ln Fl - \ln F_o = \ln \frac{Fl}{F_o} = \ln T \ , \qquad (A.9)$$

or :

$$\exp(-al) = T \ , \qquad (A.10)$$

an expression usually referred to as Lambert's law. As water is a selective absorber, T is wavelength dependent. Pure distilled water, for example, has a peak absorption towards the red end of the visible spectrum (Clarke and James, 1939).

## A.4. Scattering of light under water.

### A.4.1. Particulate matter.

Kullenberg (1974) has distinguished various methods of classifying particulate matter, of which the most important (and the one used in the present description) is size distribution. At one extreme, the water molecules themselves are significantly smaller than the wavelength of incident light; at the other, some organic scatterers can exceed one mm. in diameter. In general, however, light scattering is dominated by particles above 1-2 µm. (Gazey, 1970). This method of classification is not without its problems, because the measurement techniques can be equivocal. For example, Baler's (1970) proposed hyperbolic distribution for marine particles holds only for the middle of the particle size range (Kullenberg, 1974).

### A.4.2. Scattering by pure water.

Because water molecules are smaller than the wavelength of incident light, they can be considered to produce scattering in accordance with Rayleigh's law. One approach is to consider this process in terms of a dipole being induced by a homogeneous electrical field.

Given certain restrictive assumptions of this method an alternative approach is commonly preferred. The Einstein-Smoluchowski theory attributes the scattering to fluctuations in density or concentration which occur in small - volume elements of the fluid independently of fluctuations in neighbouring volume elements. Here, however, the density of the medium requires the change of refractive index with pressure to be measured directly. Morel (1974) has given an advanced treatment of this topic.

In general, molecular scattering from the water itself and the dissolved salts form only a minor part of the total amount of scattering, their effect being at a minimum in turbid water and for scattering angles of more than 45$^{\circ}$ (Kullenberg, 1974).

### A.4.3. Mie scattering.

When the size of the scattering particles approaches the wavelength of incident light, the resonance problem is best approached through the electromagnetic theory of Gustav Mie (1908). The complexity of the problem requires a number of simplifying assumptions, of which the following are the most important :

1.) The particles are spherical, monodisperse and non-absorbing.

2.) There is no multiple scattering ( so that total scattering relates only to the number of particles ).

3.) The particles are independent ( so that the intensities scattered by individual particles can be added ).

4.) Scattered light has the same wavelength as the incident light.

In essence the theory considers the perturbation of the plane of a monochromatic wave by particles which resonate electromagnetically and reradiate energy in a manner determined by particle size relative to the wavelength of incident light. The total scattered radiation is considered to be equal to the sum of two vectors, $i_1$ and $i_2$. These refer to the intensity scattered in the direction $\theta$ (a) perpendicular to and (b) in the plane of the observation.

The quantity scattered in the direction $\theta$ from a randomly polarized beam of unit intensity will be :

$$i(\theta) = \frac{\lambda^2}{8\pi^2} (i_1 + i_2) \qquad (A.11)$$

and the total scattered radiation found by integrating $i(\theta)$ with respect to $\theta$ becomes :

$$I = 2\pi \int_0^\pi i(\theta) \sin\theta \, d\theta = \frac{\lambda^2}{4\pi} \int_0^\pi (i_1 + i_2) \sin\theta \, d\theta \quad . \qquad (A.12)$$

For practical purposes, a dimensionless term, V, the efficiency factor (representing the cross-sectional area of the particle) is preferred so that :

$$V = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} \frac{n^2 (n + 1)^2}{2n + 1} \left(|A_n|^2 + |B_n|^2\right) \quad , \qquad (A.13)$$

where $\alpha = \pi D/\lambda$ and the functions $A_n$ and $B_n$ involve the Riccati-Bessel and Riccati-Hankel functions (see Jerlov, 1976, p.29). If the assumption of monodispersal is dropped, minor alterations are necessary. Enlarging the treatment to include absorbing particles is also possible, but rather more complex.

Mie theory implies that as particle size increases, the intensity of scattering first increases, levels off, and then oscillates about a value of 2. The theory can be used even when the particles are non-spherical provided that the total cross-sectional areas are the same (Holland and Cagne, 1970). Difficulties arise, however, in its application to turbid water, because assumption 2 above becomes invalid (see also section A.4.7.).

### A.4.4. Scattering in the region of geometric optics.

When the scattering particles are considerably larger than the wavelength of incident light normal geometric optics applies- the ratio of the actual scattering cross-sectional area to the geometric cross-sectional area is unity. Light can deviate from rectilinear propagation by the action of the particles themselves (diffraction), it can penetrate the particles and emerge with or without one or more internal reflections (refraction), as described in A.2.2., or it can be reflected externally. Both particle size and shape are important. For irregular, non-absorbing, randomly oriented particles, the diffraction pattern should resemble that of spherical particles with the same projected area. Similarly, external reflections will be changed very little, because there will be an equal probability of reflection at all angles. The first refraction by irregular particles will be similar to that for spheres, whereas the second may show significant angular deviations. Opaque irregular particles thus behave in the same way as opaque spheres (Jerlov, 1976). Most scattering in natural water can be estimated by the methods of geometrical optics (Mertens, 1970).

### A.4.5. Non particulate scattering.

It is important to note that actual physical particles need not be present for scattering to occur. Incomplete mixing of water samples of different refractive indices can produce noticeable effects at very small scattering angles and can be responsible for significant loss of detail in optical images.

### A.4.6. Angular distribution of scattered light.

Measurement of the intensity of scattered light as a function of scattering angle produces the volume scattering function ($\beta$). A sample volume of water is irradiated by a beam of light and the amount of scatter measured at various angles (for example, Hishida, 1966). In general, the pathlength must be short enough to exclude multiple scattering (Hodara, 1973). Alternatively, measurement of the modulation transfer function and the point spread function can be used as an indirect method (Yura, 1971; Hodara, 1973; Duntley, 1974), although this technique is not without its critics (Hodgson and Caldwell, 1972).

For a small illuminated volume dV, and scattering defined in terms of polar coordinates $(\theta,\phi,)$, the measurement of $\theta$ from the incident light and $\phi$ in a plane perpendicular to it results in symmetry with respect to $\phi$, and intensity is a function of just $\theta$. Given that the attenuation of light is determined by the sum of absorption and scattering, and is exponential with respect to distance,

$$dFs = b\ dV\ E(l) \quad , \qquad (A.14)$$

where dFs is the total scattered energy , b is the total scattering coefficient and E(l) the illumination of the incident beam. The luminous intensity dI produced by scatter within dV equals dFs when integrated over the total solid angle, hence :

$$2\pi \int_0^\pi dI\ \theta \sin\theta\ d\theta = dFs = b\ dV\ E(l) \quad . \qquad (A.15)$$

Combining equations (A.14 and A.15) :

$$b\ dV\ E(1) = 2\pi \int_0^{\pi} dI\ \theta\ \sin\theta\ d\theta \quad . \tag{A.16}$$

Dividing both sides by dV E(1) results in :

$$b = 2\pi \int_0^{\pi} \frac{dI\ \theta}{dV\ E(1)} \sin\theta\ d\theta = 2\pi \int_0^{\pi} \beta(\theta)\sin\theta\ d\theta \quad , \tag{A.17}$$

where $\beta(\theta)$ is the volume scattering function. An expression which better conveys the sense of the total solid angle involved is :

$$b = \int_{4\pi} \beta(\theta)\ d\omega \quad . \tag{A.18}$$

For Rayleigh scattering, which is relatively independent of the scattering angle :

$$\beta = C\ (1 + \cos^2\theta) \quad , \tag{A.19}$$

where C equals $(3/16\pi)x$, ($x$ being the scattering coefficient for Rayleigh scattering).

Hodara (1973) has presented a useful analysis of the relative contributions of diffraction and refraction to scattering at various angles. Refraction (due to large transparent mineral particles) was considered dominant at large ($10^{\circ} \lesssim \theta$) angles, diffraction at small ($\frac{1}{2}^{\circ} \lesssim \theta \lesssim 10^{\circ}$) angles, although refraction by organic and biological material may also contribute. The role of temperature and salinity inhomogeneities at very small ($\theta \lesssim \frac{1}{2}^{\circ}$) angles was also noted. Few data are available for this region, although some progress has been made in recent years (Sprinrad, 1978).

### A.4.7. Multiple scattering.

The single-scatter approximation considered thus far is applicable to only a few, clear water viewing conditions. In even moderately turbid water, irradiation of the volume elements comes from light scattered by other particles as well as light from the original illuminating beam, and the necessary mathematics involves several approximations.

One such approximation, made by Woodward (1964), assumes a succession of parallel layers of particles of unbounded extent, through which parallel and scattered light passes. In this scheme, the first layer receives only parallel light, and the second layer receives both parallel light which passed through the first layer and light which was scattered from it. The following expression is given for scattering into the forward direction $\theta < \pi/2$ :

$$Q_k\ (x) = \left[\frac{(NFx + \alpha x)}{k}\right]^k \exp - (NF + \alpha)x , \qquad (A.20)$$

where k represents the order of scattering, x the distance, N the number of scattering particles per unit volume irradiated by the parallel light from the source to the plane of observation, F the quantity of light scattered by a single representative particle illuminated by a quantity of light $Q_k = 1$ according to any general angular distribution $f_k\theta$, and $\alpha$ the light absorption coefficient of the particles. The angular distribution is given by :

$$f_k\ (\theta) = \frac{1}{4\pi} \sum_{n=0}^{\infty} 2n + 1 \left[\frac{A_n}{A_o(2n + 1)}\right]^k P_n(\cos\ \theta) , \qquad (A.21)$$

where $P_n$ (cos $\theta$) are the ordinary Legendre polynomials, $A_n$ and $A_o$ are constants dependent upon wave number, particle diameter and refractive index, and n is an integer. It is to be emphasised that such equations are only approximations, and that the mathematics of higher order scattering becomes difficult, if not intractable, after only a few orders of scattering. Nonetheless, the potential importance of these equations is underlined by Gazey's (1970) comment that for the North Sea, assuming a mean particle diameter of 2.5 μm. and a concentration of 6 mg/l., the single scatter range limit is only 16 cm. Wells (1973) has considered multiple scattering through analysis of the modulation transfer function.

## A.5. Polarization.

Only brief consideration will be given to polarization. The basic formula for calculating the degree of polarization is :

$$p = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} , \qquad (A.22)$$

where $I_{\parallel}$ and $I_{\perp}$ are the intensities of light scattered parallel and perpendicular to a plane through the incident and scattered beams. Various modifications are necesssary in calculations related to underwater light polarization; these have been discussed by Waterman (1974) and Timofeeva (1974).

## A.6. The Radiance Model of The Visibility Laboratory. Scripps Institute of Oceanography.

### A.6.1. Introduction.

Radiative transfer theory, the analysis of the penetration and distribution of underwater radiant energy, builds directly on the fundamental processes described thus far. Development of a formal general theory of radiative transfer in a scattering-absorbing medium was already well advanced when Shuleikin (1933) first applied it to the marine environment (see, for instance, Weiner, 1900; Schuster, 1905; Schwarzschild, 1906; King, 1913). Following Shuleikin, Le Grand (1939), Takenouti (1949), Mukai (1959), Jerlov and Fukuda (1960), Lenoble (1961) and Schellenberger (1963) proposed models containing assumptions about scattering which were too simplistic.

In 1964 Preisendorfer summarized the radiance model that had been developed at the Scripps Institute of Oceanography. The model had evolved almost simultaneously with research into underwater visibility undertaken at the same laboratory by S.Q. Duntley, and the same optical properties are central to both investigations. In the following brief outline, emphasis will be given to these properties and their interrelationships.

A.6.2. The general equation of transfer for radiance.

A useful starting point is to trace a packet of photons as it traverses a path through the neighbourhood of a point in a scattering-absorbing medium (Preisendorfer, 1961). The equation of transfer for radiance L is given by :

$$\frac{n^2}{v}\frac{D(L/n^2)}{Dt} = -cL + L^* + L\eta \quad , \qquad (A.23)$$

where n is the index of refraction, v the speed of light at the point instantaneously occupied by the packet, c the total attenuation coefficient (the sum of absorption and scattering), $L^* = \int_{4\pi} L\beta \, d\omega$ , and $L\eta$ the emission source function. A rigorous derivation of this equation has been given by Preisendorfer (1957).

If $L/n^2$ is invariant along a path which exhibits no scattering, absorption, or sources of radiant flux, equation (A.23) reduced to :

$$\frac{1}{v}\frac{D(L/n^2)}{Dt} = 0 \quad . \qquad (A.24)$$

Including scattering and absorption results in :

$$\frac{1}{v}\frac{D(L/n^2)}{Dt} = -c\frac{L}{n^2} + \frac{L^*}{n^2} \quad , \qquad (A.25)$$

which accounts for the increase in the streaming photon population due to scattering into the direction of travel.

Further development of the analysis requires the introduction of five simplifying assumptions (Preisendorfer, 1964) :

1) Light fields under water are in the steady state (or quasi-steady state).

2) Zero emission functions.

3) Unpolarized, monochromatic energy.

4) A constant source of radiance at the surface.

5) A constant refraction function within the water body.

Under these conditions equation (A.23) becomes, for $L(z,\theta,\phi)$ (that is, for direction $\theta,\phi$, about point z) :

$$\frac{dL(z,\theta,\phi)}{dr} = -cL(z,\theta,\phi) + L^*(z,\theta,\phi) , \qquad (A.26)$$

where :

$$L^*(z,\theta,\phi) = \int_{\phi'=0}^{2\pi} \int_{\theta'=0}^{\pi} \beta(\theta,\phi;\theta',\phi')L(z,\theta',\phi')\sin\theta' \, d\theta' d\phi'$$

$$= \int_{4\pi} \beta(z,\theta,\phi;\theta',\phi')L(z,\theta',\phi')d\omega(\theta',\phi')$$

and $z=r\cos\theta$, so that $\theta$ is the angle between zenith and the direction of motion of the flux. The first term on the right in equation (A.26) specifies the space rate loss of radiance $L(z,\theta,\phi)$ by attenuation along a direction of travel; the second term gives the space rate of gain of $L(z,\theta,\phi)$ by backscattering.

It is possible to rewrite equation (A.26) :

$$c = \frac{L^*}{L} - \frac{1}{L} \cdot \frac{dL}{dr} \qquad (A.27)$$

and, when $L^*$ is minimised (for example, where radiance attenuance is measured over a fixed distance) :

$$c = -\frac{1}{L} \cdot \frac{dL}{dr} \quad . \tag{A.28}$$

### A.6.3. Formal integration of the equation of transfer.

When the equation of transfer is given in the following form :

$$\cos\theta \, \frac{dL(z,\theta,\phi)}{dz} = -c(z)L(z,\theta,\phi) + L^*(z,\theta,\phi) \tag{A.29}$$

integration over all directions about the point z results in :

$$\frac{d}{dz} \int_{4\pi} L(z,\theta,\phi)\cos\theta \, d\omega = c(z)\int_{4\pi} L(z,\theta,\phi)d\omega + \int_{4\pi} L^*(z,\theta,\phi)d\omega, \tag{A.30}$$

where $d\omega = \sin\theta \, d\theta d\phi$ assuming the horizontal gradient of the field radiance to be zero. The irradiance $E(z)$ defined by :

$$E(z) = \int_{4\pi} L(z,\theta,\phi)\cos\theta \, d\omega \tag{A.31}$$

is the net downward flux per unit horizontal surface at z, $E(z)$ having a downward ($E_d(z)$) and an upward ($E_u(z)$) component, where :

$$E_d(z) = \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} L(z,\theta,\phi)\cos\theta \, d\omega \tag{A.32}$$

and :

$$E_u(z) = \int_{\theta=\pi/2}^{\pi} \int_{\phi=0}^{2\pi} L(z,\theta,\phi)\,|\cos\theta|\, d\omega \quad . \tag{A.33}$$

The integral of the radiance distribution, at point z, over all directions about the point, is the scalar irradiance, $E_o$ :

$$E_o(z) = \int_{4\pi} L(z,\theta,\phi) \, d\omega \quad . \tag{A.34}$$

The downward ($E_{od}(z)$) and upward ($E_{ou}(z)$) components of scalar irradiance can be separately defined as :

$$E_{od}(z) = \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} L(z,\theta,\phi)\, d\omega \qquad (A.35)$$

and :

$$E_{ou}(z) = \int_{\theta=\pi/2}^{\pi} \int_{\phi=0}^{2\pi} L(z,\theta,\phi)\, d\omega \quad . \qquad (A.36)$$

Dividing the scalar irradiance by the velocity of light in water results in the radiant energy density - the available radiant energy per unit volume at a given point in space.

The second integral on the right hand side of equation (A.30) can be rewritten :

$$\int_{4\pi} L^*(z,\theta,\phi)\, d\omega = \int_{4\pi}\int_{4\pi} L(z,\theta,\phi)\beta(z,\theta,\phi;\theta',\phi')\, d\omega d\omega'$$

$$= \int_{4\pi} L(z,\theta,\phi)\, d\omega \int_{4\pi} \beta(z,\theta,\phi;\theta',\phi')\, d\omega' \qquad (A.37)$$

Because from equation (A.34) :

$$E_o(z) = \int_{4\pi} L(z,\theta,\phi)\, d\omega$$

and from equation (A.18), by deriving the total scattering coefficient at (z) :

$$b(z) = \int_{4\pi} \beta(z,\theta,\phi)(z,\theta,\phi;\theta',\phi')\, d\omega' \quad , \qquad (A.38)$$

it follows that :

$$\int_{4\pi} L^*(z,\theta,\phi)\, d\omega = E_o(z)b(z) \qquad (A.39)$$

From this equation (A.30) may be written :

$$\frac{dE(z)}{dz} = \frac{d}{dz}\,(E_d(z) - E_u(z)) = -c(z)E_o(z) + b(z)E_o(z)$$

or, because $c(z) = a(z) + b(z)$ :

$$\frac{d}{dx}\left[E_d(z) - E_u(z)\right] = -a(z)E_o(z) \tag{A.40}$$

and :

$$a(z) = \frac{1}{E_o(z)}\frac{d}{dz}\left[E_u(z) - E_d(z)\right]. \tag{A.41}$$

A.6.4. Inherent and Apparent optical properties.

An important distinction made by Preisendorfer (1961) concerns the inherent optical properties of water, which are independent of changes in the distribution of radiance, and the apparent properties, which depend on the inherent properties and the geometrical structure of the radiance field.

In the former category are listed the coefficients of absorption, total and volume scattering, and total attenuation. They represent the combined effects of the water itself and dissolved matter. In the latter category are the attenuation coefficients, defined in terms of radiance, irradiance, and their depth derivatives. The other important coefficients, listed by Nygård (1973), are all derived in the same manner. Although the apparent properties are functions of the radiance distribution at the surface, they display a striking regularity which enables a description of changing radiance with depth.

A.6.5. A solution to the radiative transfer equation.

Preisendorfer's solution to the equation of radiative transfer includes the following simplifying assumptions :

1) A known radiance distribution just below the surface, independent of time and horizontal position.

2) Optically homogeneous water.

3) A path function independent of time and horizontal position, attenuated in the z-direction with a constant attenuation coefficient K, so that an approximate form for the path function can be given from the two-flow Schuster equations for irradiance :

$$L^*(z,\theta,\phi) = L^*(0,\theta,\phi)e^{-K^*z} \qquad (A.42)$$

The analysis relates to a target point at a depth $z_t$, at a distance r from an observation point at depth z, with a path $(z_t,\theta,r)$ from $z_t$ to z along the direction $(\pi - \theta, \phi + \pi)$ (where $\phi$ is the angle between the nadir and the flux direction) so that $z - z_t = r \cos \theta$. To measure field radiance at z a radiance meter is pointed in the direction $(\theta,\phi)$.

If $L_o$ is the inherent target radiance, and $L_r$ the apparent radiance, integration of equation (A.26) along the path $(z_t,\theta,\phi,r)$ results in :

$$L_r(z,\theta,\phi) = L_o(z_t,\theta,\phi)e^{-cr} + \int_0^r L^*(z',\theta,\phi)e^{-c(r-r')}dr', \qquad (A.43)$$

where $z' = z_t + r' \cos \theta$. The apparent radiance is therefore the sum of a transmitted inherent radiance and a path radiance of flux scattered into the direction $(\pi- \theta, \phi + \pi)$ at each point of the path $(z_t,\theta,\phi,r)$ and then transmitted to the observation point.

Combining equations (A.26) and (A.43) results in :

$$L_r(z,\theta,\phi) = L_o(z_t,\theta,\phi)e^{-cr} + \frac{L^*(z,\theta,\phi)}{c-K^* \cos \theta} (1-e^{-(c-K^* \cos \theta)r}). \qquad (A.44)$$

At asymptote this reduces to :

$$L\theta = \frac{L^*(\theta)}{c-k \cos \theta} \qquad (A.45)$$

where k is the asymptotic value (that is, $\lim_{z \to \infty} K = k$).

As Jerlov (1976) has pointed out, it is a characteristic of this approach that no mathematical expression for the scattering function is introduced or tested. The whole path function is treated as a parameter with defined properties. Validation of the formulae, through the evaluation of L*, was undertaken by Tyler (1960), by determining L*(z) from experimental data at one depth and calculating L(z) for all other depths. The results compared well with observations.

Fig. A.1. Hypothetical values of some important hydrological optical parameters.

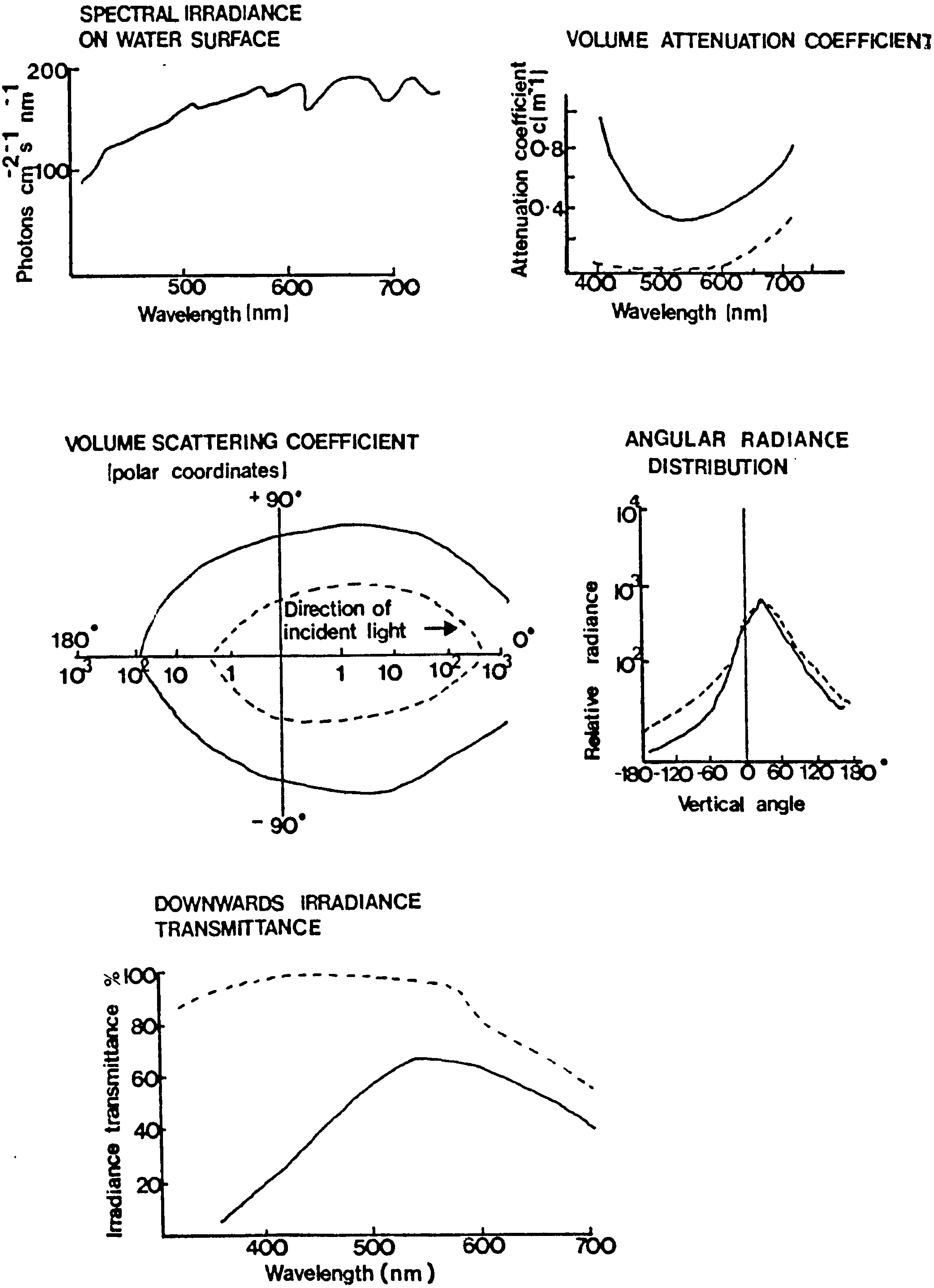


TABLE A.1. Fundamental concepts in underwater optics - definitions, symbols and units. (after Jerlov, 1968)

| CONCEPT | DEFINITION | UNITS | SYMBOL |
|---|---|---|---|
| Radiance | Radiant flux per unit solid angle per unit projected area of a surface. | $W/m^2 \omega$ | $L$ |
| Downward irradiance | The radiant flux on an infinitesimal element of the upper face of a horizontal surface containing the point being considered, divided by the area of that element. | $W/m^2$ | $E_d$ |
| Upward irradiance | The radiant flux incident on an infinitesimal element of the lower face of a horizontal surface containing the point being considered, divided by the area of that element. | $W/m^2$ | $E_u$ |
| Scalar irradiance | The integral of a radiance distribution at a point over all directions about the point. | $W/m^2$ | $E_o$ |

TABLE A.1. (Continued).

| CONCEPT | DEFINITION | UNITS | SYMBOL |
|---|---|---|---|
| Reflectance | The ratio of the reflected radiant flux to the incident radiant flux. | - | $\rho$ |
| Irradiance ratio | The ratio of the upward to the downward irradiance at a certain depth. | - | R |
| Transmittance | The ratio of the transmitted radiant flux to the incident radiant flux. | - | T |
| Absorptance | The ratio of the radiant flux lost from a beam by means of absorption, to the incident flux. | - | A |
| Scatterance | The ratio of the radiant flux scattered from a beam, to the incident flux. | - | B |
| Forward scatterance | The ratio of the radiant flux scattered through angles $0-90^{o}$ from a beam, to the incident flux. | - | $B_f$ |

TABLE A.1. (Continued).

| CONCEPT | DEFINITION | UNITS | SYMBOL |
|---|---|---|---|
| Backward scatterance | The ratio of the radiant flux scattered through angles 90-180$^o$ from a beam, to the incident flux. | - | $B_b$ |
| Attenuance | The ratio of the radiant flux lost from a beam by means of absorption and scattering, to the incident flux. | - | C |
| Absorption coefficient | The internal absorptance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness of the layer. | $m^{-1}$ | a |
| Volume scattering function | The radiant intensity (from a volume element in a given direction) per unit of irradiance on the volume and per unit volume. | $m^{-1}$ | $\beta(\theta)$ |
| Total scattering coefficient | The internal scatterance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness of the layer. | $m^{-1}$ | b |
| Forward scattering coefficient | The coefficient which relates to foward scatterance. | $m^{-1}$ | $b_f$ |

TABLE A.1. (Continued).

| CONCEPT | DEFINITION | UNITS | SYMBOL |
|---|---|---|---|
| Backward scattering coefficient | The coefficient which relates to backward scatterance. | $m^{-1}$ | $b_b$ |
| Total attenuation coefficient | The internal attenuance of an infinitesimally thin layer of the normal medium to the beam, divided by the thickness of the layer. | $m^{-1}$ | c |
| Refractive index | The phase velocity of radiant energy in free space divided by the phase velocity of the same energy in a specified medium. | - | n |
| Degree of polarization | The ratio of the polarized fraction to the total energy. | - | p |

APPENDIX B. Spectral reflectance and chromaticity coordinates of test tiles. The tiles were those used in Experiments 3a, 3b, 4b, 4c, 5a, 5b, 6a and 6b. The data were obtained on a Macbeth MS - 2000 spectrophotometer, with diffuse sphere illumination and 8° viewing geometry. Specular gloss is included. The chromaticity coordinates refer to Illuminant A.

| Wavelength (nm) | REFLECTANCE % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | TILE NUMBER | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 380 | 15.3 | 14.2 | 13.0 | 12.2 | 11.6 | 8.7 | 7.4 | 6.7 | 3.9 |
| 400 | 43.1 | 38.9 | 32.4 | 28.3 | 24.8 | 14.3 | 11.0 | 9.5 | 4.1 |
| 420 | 77.0 | 60.4 | 44.5 | 36.6 | 30.7 | 16.2 | 11.8 | 10.1 | 4.0 |
| 440 | 83.2 | 62.2 | 45.0 | 37.0 | 30.8 | 16.3 | 11.9 | 10.1 | 4.0 |
| 460 | 86.4 | 62.8 | 45.1 | 36.8 | 30.7 | 16.2 | 11.8 | 10.0 | 4.0 |
| 480 | 88.4 | 62.6 | 44.4 | 36.1 | 30.0 | 15.6 | 11.1 | 9.2 | 3.5 |
| 500 | 89.5 | 62.7 | 44.5 | 36.2 | 30.2 | 15.9 | 11.5 | 9.7 | 4.0 |
| 520 | 90.3 | 62.4 | 44.1 | 35.9 | 29.8 | 15.8 | 11.3 | 9.5 | 3.9 |
| 540 | 90.7 | 62.2 | 43.9 | 35.5 | 29.6 | 15.7 | 11.2 | 9.5 | 3.9 |
| 560 | 91.3 | 61.7 | 43.4 | 35.1 | 29.1 | 15.5 | 11.1 | 9.3 | 3.9 |
| 580 | 91.2 | 61.2 | 42.9 | 34.6 | 28.7 | 15.3 | 10.8 | 9.1 | 3.8 |
| 600 | 90.9 | 60.8 | 42.4 | 34.2 | 28.3 | 15.1 | 10.7 | 9.0 | 3.8 |
| 620 | 90.9 | 60.4 | 42.1 | 34.0 | 28.1 | 15.0 | 10.7 | 9.0 | 3.8 |
| 640 | 90.8 | 60.0 | 41.8 | 33.5 | 27.6 | 14.8 | 10.6 | 8.9 | 3.8 |
| 660 | 91.1 | 59.8 | 41.5 | 33.2 | 27.4 | 14.7 | 10.4 | 8.8 | 3.8 |
| 680 | 90.7 | 59.2 | 40.9 | 32.7 | 27.0 | 14.5 | 10.3 | 8.7 | 3.8 |
| 700 | 90.4 | 58.8 | 40.5 | 32.4 | 26.7 | 14.4 | 10.3 | 8.7 | 3.9 |
| x (A) | .451 | .444 | .442 | .441 | .440 | .442 | .440 | .440 | .446 |
| y (A) | .412 | .409 | .408 | .407 | .407 | .408 | .407 | .406 | .407 |
| Y (A) | 90.8 | 61.4 | 43.1 | 34.8 | 28.9 | 15.4 | 11.0 | 9.2 | 3.8 |

APPENDIX B (Continued).

| Wavelength (nm) | REFLECTANCE % | | | | | | |
|---|---|---|---|---|---|---|---|
| | TILE HUE NAME | | | | | | |
| | Blue | Green | Yellow | Red | Fluorescent Green | Fluorescent Yellow | Fluorescent Red |
| 380 | 9.5 | 5.9 | 7.4 | 6.1 | 3.6 | 4.5 | 5.1 |
| 400 | 23.9 | 7.2 | 9.3 | 7.0 | 3.4 | 3.9 | 5.4 |
| 420 | 37.6 | 7.2 | 9.1 | 6.8 | 3.0 | 3.1 | 5.6 |
| 440 | 48.1 | 7.2 | 8.9 | 6.6 | 3.0 | 3.1 | 6.2 |
| 460 | 54.3 | 7.8 | 9.5 | 6.7 | 4.5 | 4.1 | 7.8 |
| 480 | 52.5 | 18.2 | 21.3 | 8.0 | 20.9 | 18.7 | 9.1 |
| 500 | 47.3 | 40.7 | 31.2 | 9.0 | 68.4 | 72.6 | 7.8 |
| 520 | 35.4 | 48.5 | 32.4 | 7.9 | 94.8 | 115.3 | 5.1 |
| 540 | 24.9 | 42.9 | 32.1 | 7.7 | 84.8 | 113.4 | 4.8 |
| 560 | 15.6 | 31.3 | 54.3 | 8.0 | 80.7 | 129.6 | 9.0 |
| 580 | 11.4 | 20.8 | 72.5 | 18.3 | 50.4 | 107.2 | 40.1 |
| 600 | 9.8 | 12.8 | 75.8 | 44.2 | 25.7 | 85.8 | 90.8 |
| 620 | 9.1 | 10.1 | 76.4 | 53.8 | 17.3 | 79.9 | 92.3 |
| 640 | 8.8 | 9.5 | 75.8 | 54.6 | 14.7 | 76.1 | 78.5 |
| 660 | 9.1 | 9.5 | 75.6 | 55.5 | 14.5 | 73.8 | 67.3 |
| 680 | 9.1 | 10.9 | 75.2 | 55.0 | 17.3 | 72.3 | 58.8 |
| 700 | 8.5 | 12.4 | 74.6 | 52.9 | 20.1 | 71.3 | 54.0 |
| x (A) | .290 | .365 | .541 | .603 | .378 | .474 | .619 |
| y (A) | .359 | .533 | .421 | .358 | .563 | .497 | .357 |
| Y (A) | 17.9 | 26.2 | 57.8 | 23.6 | 55.6 | 101.6 | 39.5 |

## APPENDIX C. Mean horizontal visual ranges and standard deviations of the tiles in Experiment 3a (visual range study).

### CONDITION I

| OBSERVER | MEAN VISUAL RANGE (cm.) /S.D. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | TILE NUMBER | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 $\bar{X}$ | 53.6 | 47.4 | 44.9 | 40.4 | 36.0 | 33.9 | 34.6 | 36.2 | 32.1 |
| S.D | 0.52 | 0.75 | 0.84 | 0.47 | 0.41 | 0.32 | 0.70 | 0.63 | 1.20 |
| 2 $\bar{X}$ | 46.0 | 41.5 | 37.7 | 35.0 | 33.7 | 30.8 | 29.1 | 28.0 | 25.4 |
| S.D | 1.16 | 1.97 | 1.56 | 1.43 | 1.58 | 1.03 | 1.05 | 0.53 | 0.52 |
| 3 $\bar{X}$ | 46.2 | 41.3 | 39.1 | 32.7 | 29.8 | 25.2 | 23.8 | 23.3 | 21.8 |
| S.D | 1.27 | 1.03 | 1.52 | 1.38 | 1.59 | 1.56 | 1.32 | 1.36 | 1.48 |
| 4 $\bar{X}$ | 41.7 | 41.3 | 38.3 | 34.8 | 27.0 | 22.3 | 19.9 | 19.4 | 23.6 |
| S.D | 1.06 | 0.82 | 0.83 | 0.35 | 0.00 | 0.68 | 0.21 | 0.75 | 0.97 |
| 5 $\bar{X}$ | 40.5 | 37.6 | 33.5 | 31.2 | 29.2 | 27.0 | 26.5 | 23.9 | 22.6 |
| S.D | 0.94 | 0.84 | 0.71 | 0.42 | 0.79 | 0.60 | 0.58 | 0.24 | 0.83 |
| 6 $\bar{X}$ | 47.3 | 41.8 | 35.0 | 28.7 | 28.4 | 23.7 | 23.0 | 22.7 | 20.5 |
| S.D | 0.68 | 0.54 | 0.55 | 0.41 | 0.70 | 0.95 | 0.91 | 0.82 | 0.97 |
| 7 $\bar{X}$ | 49.1 | 40.5 | 41.2 | 39.0 | 36.3 | 26.6 | 26.6 | 23.1 | 21.3 |
| S.D | 1.45 | 1.83 | 1.99 | 0.96 | 1.25 | 1.64 | 0.32 | 0.99 | 0.95 |
| 8 $\bar{X}$ | 43.2 | 42.6 | 39.9 | 37.6 | 35.1 | 27.5 | 22.0 | 17.4 | 21.8 |
| S.D | 1.32 | 1.35 | 1.03 | 0.52 | 0.57 | 0.50 | 0.00 | 0.70 | 0.42 |
| 9 $\bar{X}$ | 38.7 | 32.5 | 28.2 | 26.2 | 25.3 | 18.8 | 17.4 | 18.2 | 17.7 |
| S.D | 1.27 | 1.67 | 0.92 | 0.88 | 0.68 | 0.43 | 0.70 | 0.63 | 1.25 |

APPENDIX C (Continued).

## CONDITION II

| OBSERVER | MEAN VISUAL RANGE (cm.) /S.D. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | TILE NUMBER | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 $\bar{X}$ | 24.2 | 24.4 | 23.9 | 23.2 | 21.9 | 21.5 | 22.1 | 22.6 | 23.7 |
| S.D | 0.63 | 0.70 | 0.97 | 0.34 | 0.77 | 0.97 | 0.57 | 0.57 | 0.42 |
| 2 $\bar{X}$ | 22.1 | 21.6 | 20.2 | 17.3 | 18.7 | 19.7 | 18.8 | 18.9 | 20.2 |
| S.D | 0.28 | 0.45 | 0.59 | 0.43 | 0.63 | 0.53 | 0.35 | 0.39 | 0.94 |
| 3 $\bar{X}$ | 22.5 | 20.5 | 18.5 | 18.3 | 16.7 | 17.0 | 17.9 | 19.1 | 22.8 |
| S.D | 0.94 | 0.47 | 0.96 | 0.59 | 0.35 | 0.33 | 0.57 | 0.52 | 0.49 |
| 4 $\bar{X}$ | 22.9 | 21.2 | 20.7 | 20.0 | 19.7 | 19.0 | 19.1 | 19.3 | 20.5 |
| S.D | 0.47 | 0.68 | 0.78 | 0.32 | 0.41 | 0.53 | 0.88 | 0.59 | 0.68 |
| 5 $\bar{X}$ | 23.4 | 21.4 | 20.6 | 19.8 | 18.6 | 19.9 | 19.3 | 20.6 | 21.7 |
| S.D | 0.74 | 0.39 | 0.76 | 0.63 | 0.46 | 0.34 | 0.79 | 0.60 | 0.48 |
| 6 $\bar{X}$ | 22.3 | 20.9 | 20.1 | 19.1 | 15.3 | 18.8 | 20.1 | 20.2 | 19.2 |
| S.D | 0.95 | 0.47 | 0.66 | 0.44 | 1.20 | 0.75 | 0.73 | 0.59 | 0.68 |
| 7 $\bar{X}$ | 22.4 | 22.3 | 19.4 | 18.3 | 17.7 | 19.9 | 20.5 | 21.5 | 22.1 |
| S.D | 0.78 | 0.59 | 0.47 | 0.68 | 0.63 | 0.66 | 0.85 | 0.62 | 0.81 |
| 8 $\bar{X}$ | 20.2 | 16.7 | 16.1 | 16.6 | 14.6 | 15.4 | 19.6 | 19.4 | 20.6 |
| S.D | 0.88 | 0.86 | 0.16 | 0.83 | 0.46 | 0.46 | 0.52 | 0.84 | 0.70 |
| 9 $\bar{X}$ | 21.0 | 19.7 | 18.1 | 18.0 | 17.8 | 17.9 | 18.2 | 19.2 | 19.7 |
| S.D | 0.37 | 0.35 | 0.16 | 0.16 | 0.54 | 0.62 | 0.35 | 0.26 | 0.34 |

APPENDIX C (Continued)

CONDITION III

| OBSERVER | MEAN VISUAL RANGE (cm.) /S.D. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | TILE NUMBER | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 $\bar{X}$ | 46.6 | 42.6 | 34.8 | 31.1 | 32.1 | 31.2 | 33.2 | 35.8 | 38.2 |
| S.D. | 0.37 | 0.69 | 1.06 | 1.85 | 1.37 | 0.59 | 1.23 | 0.26 | 0.53 |
| 2 $\bar{X}$ | 46.8 | 42.5 | 38.3 | 38.2 | 37.6 | 35.8 | 38.7 | 41.4 | 43.5 |
| S.D. | 0.79 | 0.64 | 0.42 | 0.47 | 0.21 | 0.26 | 0.54 | 1.31 | 1.12 |
| 3 $\bar{X}$ | 44.6 | 31.9 | 30.4 | 29.3 | 27.8 | 27.3 | 30.0 | 30.6 | 32.4 |
| S.D. | 1.85 | 1.11 | 0.84 | 1.70 | 1.36 | 0.42 | 0.91 | 0.52 | 1.51 |
| 4 $\bar{X}$ | 44.5 | 41.2 | 29.3 | 27.4 | 26.0 | 30.9 | 33.1 | 34.3 | 40.3 |
| S.D. | 0.33 | 1.09 | 0.86 | 0.75 | 1.11 | 0.47 | 0.55 | 0.63 | 1.49 |
| 5 $\bar{X}$ | 44.5 | 37.0 | 34.7 | 27.6 | 28.3 | 30.9 | 31.9 | 34.0 | 35.3 |
| S.D. | 0.69 | 0.78 | 0.42 | 0.44 | 1.03 | 0.39 | 0.63 | 0.28 | 0.63 |
| 6 $\bar{X}$ | 40.7 | 39.7 | 38.3 | 33.1 | 32.1 | 31.2 | 31.8 | 33.9 | 35.6 |
| S.D. | 0.86 | 1.87 | 0.26 | 2.04 | 0.66 | 0.98 | 0.35 | 0.78 | 0.39 |
| 7 $\bar{X}$ | 41.9 | 37.5 | 32.8 | 34.3 | 28.3 | 30.9 | 31.8 | 31.1 | 33.3 |
| S.D. | 2.12 | 0.44 | 1.38 | 0.92 | 1.25 | 0.66 | 0.48 | 0.52 | 0.54 |
| 8 $\bar{X}$ | 45.9 | 38.3 | 21.0 | 20.3 | 19.7 | 26.5 | 28.8 | 30.1 | 34.0 |
| S.D. | 1.27 | 0.42 | 1.04 | 0.92 | 0.26 | 0.93 | 0.35 | 0.84 | 0.94 |
| 9 $\bar{X}$ | 38.5 | 34.9 | 27.2 | 24.4 | 24.1 | 26.5 | 29.1 | 30.9 | 34.4 |
| S.D. | 0.50 | 0.57 | 0.26 | 0.67 | 0.64 | 0.55 | 0.55 | 0.94 | 1.05 |

## APPENDIX D. Repeated measures ANOVA summary tables for Experiments 3a and 3b (visual range studies).

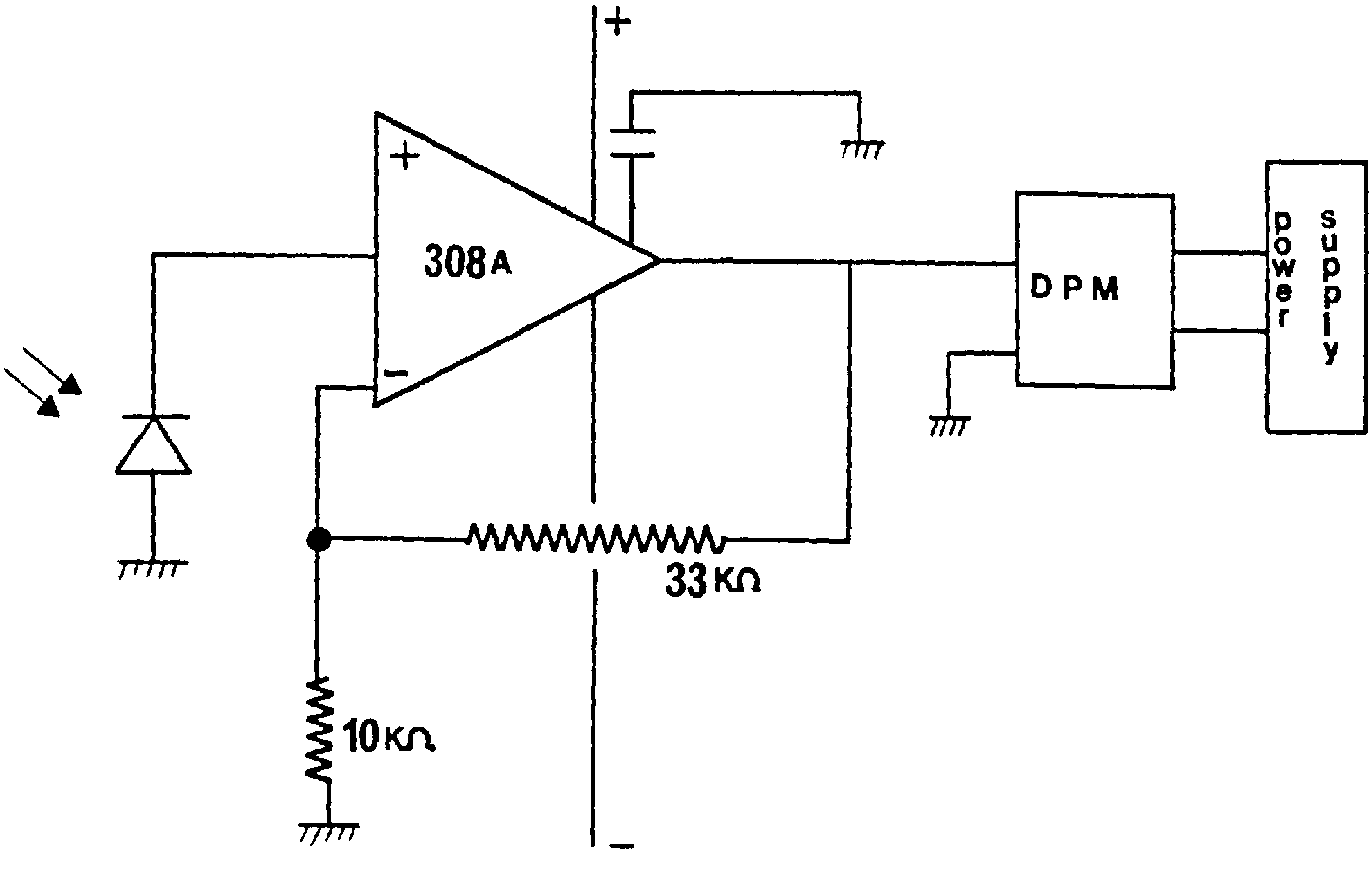
### EXPERIMENT 3a

| SOURCE | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Mean | 197433.76 | 1 | 197433.76 | 1138.43 | <.005 |
| Error | 1387.41 | 8 | 173.43 | | |
| Condition | 9079.87 | 2 | 4539.94 | 94.46 | <.005 |
| Error | 768.96 | 16 | 48.06 | | |
| Tile number | 3742.63 | 8 | 467.83 | 154.66 | <.005 |
| Error | 193.59 | 64 | 3.02 | | |
| Condition x tile number | 2838.63 | 16 | 177.41 | 35.11 | <.005 |
| Error | 646.77 | 128 | 5.05 | | |

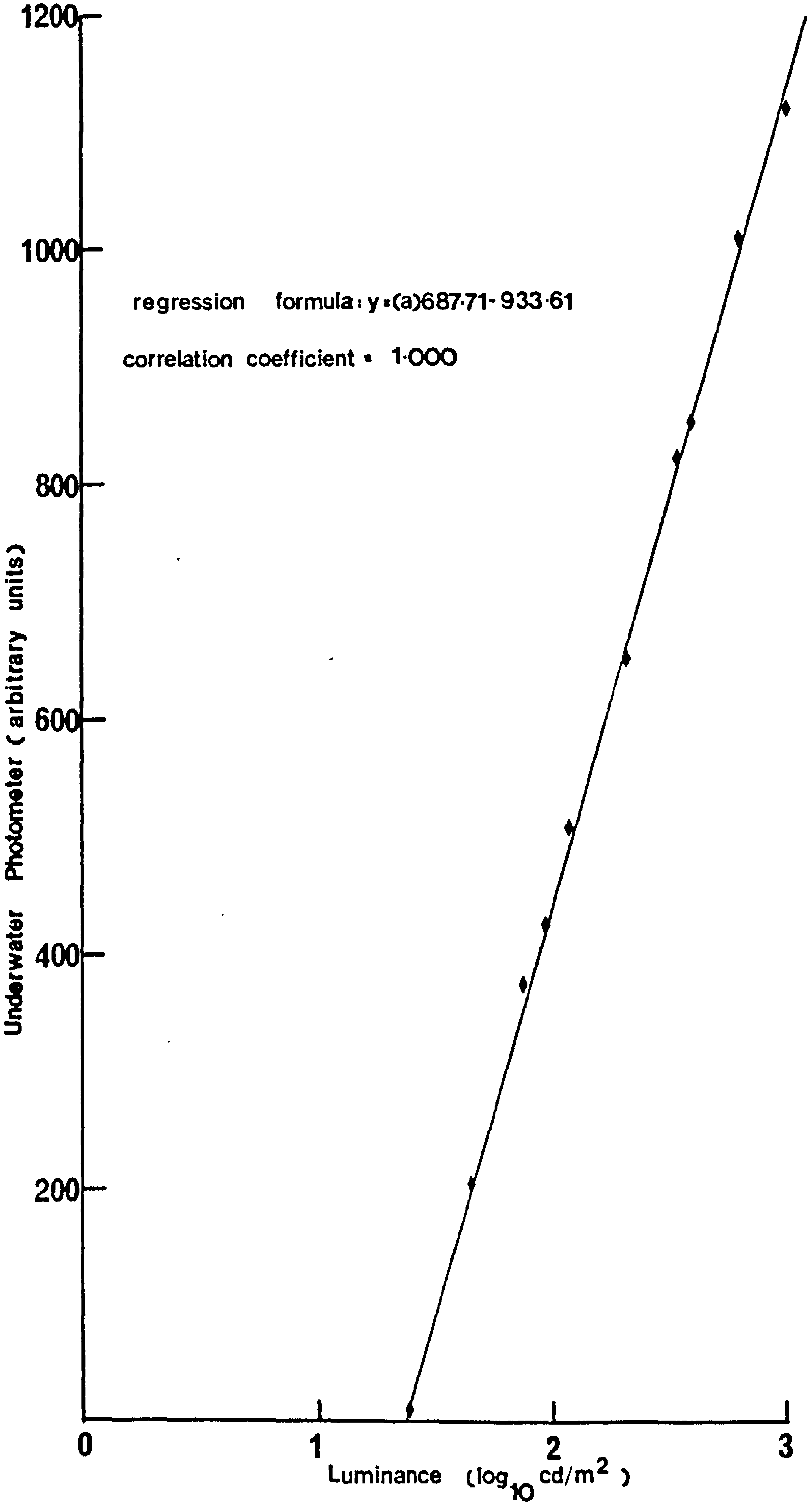
### EXPERIMENT 3b

| SOURCE | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Mean | 97831.02 | 1 | 97831.02 | 16248.75 | <.005 |
| Error | 6.02 | 1 | 6.02 | | |
| Water type | 1970.54 | 2 | 985.27 | 50.80 | <.025 |
| Error | 38.79 | 2 | 19.40 | | |
| Tile number | 2426.48 | 7 | 346.64 | 138.82 | <.005 |
| Error | 17.48 | 7 | 2.50 | | |
| Water type x tile number | 771.46 | 14 | 55.10 | 9.74 | <.005 |
| Error | 79.21 | 14 | 5.66 | | |

## APPENDIX E. Circuit diagram for the underwater photometer.

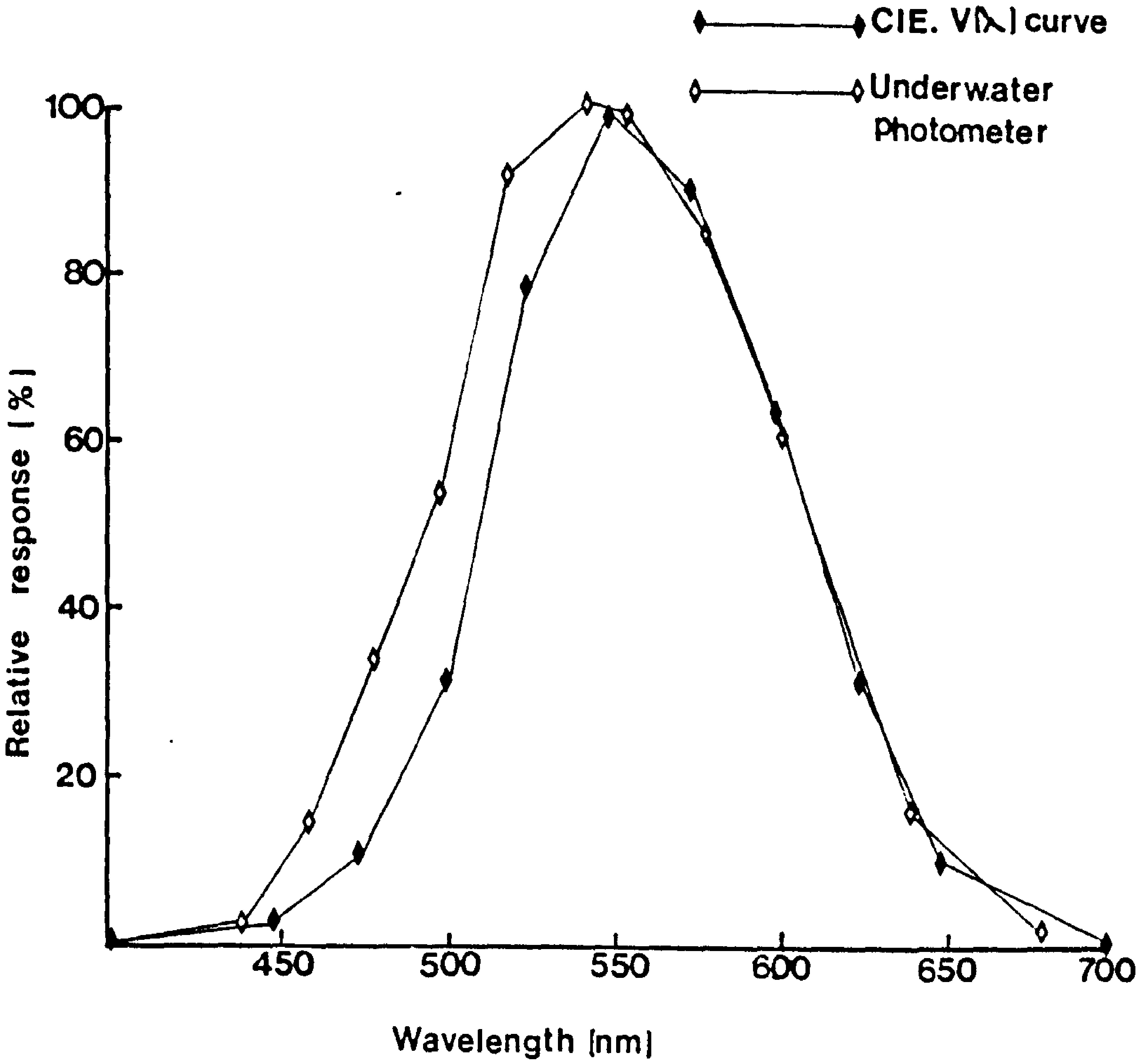


## APPENDIX F. Calibration curve for the underwater photometer.



## APPENDIX G. Spectral sensitivity of the underwater photometer.

The relative responses of the underwater photometer and the CIE Standard Observer have been plotted over the visual spectrum.



APPENDIX H. Mean horizontal visual ranges and standard deviations of the tiles in Experiment 3b (visual range study).

The blackbody distances for each observer at each location are also given.

| LOCATION | OBSERVER | VISUAL RANGE (m.) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TILE NUMBER | | | | | | | | | | | | | | | |
| | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | |
| Loch Turret 6-6-79 | G.M. | 7.0 | 7.3 | 6.2 | 6.6 | 5.8 | 6.1 | 5.5 | 6.0 | 4.5 | 4.9 | 4.0 | 4.6 | 3.4 | 4.2 | 4.0 | 4.5 |
| | R.D. | 7.2 | 7.6 | 6.2 | 6.2 | 5.7 | 6.1 | 5.8 | 5.1 | 4.8 | 5.6 | 3.6 | 4.2 | 3.6 | 3.9 | 3.9 | 4.3 |
| | L.R. | 7.7 | 7.4 | 6.3 | 6.3 | 5.9 | 5.9 | 5.9 | 5.4 | 4.4 | 5.4 | 4.3 | 4.2 | 4.2 | 3.9 | 4.1 | 4.0 |
| | W.W. | 7.4 | 7.9 | 6.8 | 6.0 | 6.2 | 6.1 | 5.9 | 5.9 | 4.5 | 5.0 | 4.3 | 4.7 | 4.0 | 4.2 | 4.4 | 4.2 |
| | $\overline{X}$ | 7.44 | | 6.33 | | 5.98 | | 5.69 | | 4.89 | | 4.24 | | 3.93 | | 4.18 | |
| | S.D. | 0.29 | | 0.26 | | 0.18 | | 0.32 | | 0.44 | | 0.34 | | 0.30 | | 0.21 | |
| Loch Turret 6-6-79 | G.M. | 7.9 | 7.1 | 6.3 | 6.5 | 5.6 | 6.5 | 5.6 | 5.6 | 4.6 | 4.8 | 4.5 | 4.4 | 3.9 | 4.1 | 4.1 | 4.3 |
| | R.D. | 7.3 | 7.0 | 6.1 | 6.4 | 6.3 | 5.8 | 6.0 | 5.9 | 4.9 | 4.9 | 4.1 | 4.0 | 4.1 | 4.1 | 4.1 | 4.1 |
| | L.R. | 6.8 | 7.2 | 6.3 | 6.6 | 6.2 | 5.7 | 5.4 | 5.5 | 4.7 | 4.3 | 4.6 | 4.3 | 3.3 | 3.8 | 3.8 | 4.2 |
| | W.W. | 7.8 | 7.5 | 6.7 | 6.3 | 6.6 | 6.4 | 5.3 | 5.5 | 4.6 | 5.0 | 4.7 | 4.1 | 3.4 | 3.5 | 4.3 | 4.0 |
| | $\overline{X}$ | 7.33 | | 6.40 | | 6.14 | | 5.60 | | 4.73 | | 4.34 | | 3.78 | | 4.11 | |
| | S.D. | 0.39 | | 0.19 | | 0.39 | | 0.24 | | 0.23 | | 0.26 | | 0.33 | | 0.16 | |
| Loch Airthrey 5-5-79 | G.M. | 4.0 | 5.0 | 4.1 | 4.3 | 4.0 | 4.3 | 3.4 | 3.2 | 2.8 | 2.6 | 3.4 | 2.9 | 3.1 | 3.5 | 4.0 | 4.3 |
| | R.D. | 4.6 | 4.4 | 4.0 | 4.0 | 3.8 | 3.7 | 3.7 | 3.5 | 2.4 | 2.5 | 3.9 | 3.4 | 3.7 | 3.3 | 4.0 | 4.2 |
| | J.M. | 5.0 | 4.4 | 4.0 | 4.3 | 3.8 | 3.8 | 2.8 | 3.0 | 1.8 | 2.2 | 3.3 | 3.0 | 3.9 | 3.9 | 4.6 | 4.0 |
| | J.M.M. | 5.2 | 4.9 | 4.0 | 5.1 | 3.9 | 3.9 | 3.4 | 3.1 | 2.6 | 2.4 | 3.6 | 3.4 | 3.7 | 3.6 | 4.5 | 4.0 |
| | $\overline{X}$ | 4.69 | | 4.23 | | 3.90 | | 3.26 | | 2.41 | | 3.36 | | 3.59 | | 4.20 | |
| | S.D. | 0.41 | | 0.38 | | 0.19 | | 0.29 | | 0.30 | | 0.32 | | 0.28 | | 0.24 | |
| Loch Airthrey 6-5-79 | G.M. | 4.2 | 5.1 | 4.2 | 4.2 | 4.1 | 4.1 | 3.6 | 3.4 | 3.0 | 3.1 | 3.4 | 3.6 | 3.8 | 3.9 | 4.1 | 3.9 |
| | R.D. | 4.9 | 4.5 | 4.1 | 4.7 | 3.9 | 3.7 | 3.4 | 3.2 | 3.1 | 2.7 | 3.5 | 3.0 | 3.1 | 3.6 | 4.2 | 3.6 |
| | J.M. | 5.1 | 4.6 | 3.9 | 4.2 | 4.1 | 3.7 | 3.7 | 3.1 | 2.9 | 3.3 | 3.1 | 3.8 | 3.5 | 3.6 | 4.1 | 4.1 |
| | J.M.M. | 4.1 | 4.3 | 4.0 | 3.6 | 3.8 | 3.9 | 3.2 | 3.5 | 2.6 | 2.9 | 3.7 | 3.7 | 3.4 | 3.9 | 4.3 | 3.9 |
| | $\overline{X}$ | 4.60 | | 4.11 | | 3.91 | | 3.39 | | 2.95 | | 3.48 | | 3.60 | | 4.03 | |
| | S.D. | 0.40 | | 0.31 | | 0.17 | | 0.21 | | 0.23 | | 0.29 | | 0.27 | | 0.22 | |

APPENDIX H. (Continued)

| LOCATION | OBSERVER | VISUAL RANGE (m.) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TILE NUMBER | | | | | | | | | | | | | | | |
| | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | |
| Atlantic Ocean 19-7-79 | G.M. | 4.8 | 5.2 | 4.1 | 4.7 | 4.7 | 4.3 | 4.4 | 4.1 | 4.6 | 3.8 | 3.9 | 3.5 | 3.8 | 3.1 | 4.9 | 4.5 |
| | R.D. | 5.6 | 5.0 | 5.3 | 5.3 | 4.6 | 5.8 | 4.6 | 5.2 | 3.3 | 3.8 | 3.7 | 3.3 | 4.2 | 4.0 | 4.0 | 4.6 |
| | J.M. | 4.8 | 4.5 | 4.4 | 4.0 | 3.9 | 4.1 | 3.8 | 4.2 | 3.2 | 3.6 | 2.7 | 2.9 | 3.6 | 3.4 | 3.9 | 3.8 |
| | J.J.M. | 4.6 | 4.8 | 4.8 | 4.3 | 4.4 | 4.1 | 4.1 | 3.9 | 3.2 | 3.0 | 2.7 | 2.9 | 3.3 | 3.3 | 3.8 | 3.5 |
| | $\bar{X}$ | 4.91 | | 4.61 | | 4.50 | | 4.30 | | 3.56 | | 3.20 | | 3.59 | | 4.13 | |
| | S.D. | 0.35 | | 0.50 | | 0.60 | | 0.45 | | 0.51 | | 0.47 | | 0.38 | | 0.48 | |
| Atlantic Ocean 20-7-79 | G.M. | 5.7 | 5.4 | 5.0 | 4.7 | 4.8 | 4.7 | 4.6 | 4.4 | 4.1 | 3.5 | 3.2 | 3.0 | 3.9 | 3.8 | 4.4 | 4.4 |
| | R.D. | 6.3 | 5.1 | 5.6 | 5.6 | 5.6 | 5.4 | 5.5 | 4.8 | 4.2 | 3.0 | 3.7 | 3.7 | 4.0 | 4.2 | 4.5 | 4.8 |
| | J.M. | 5.3 | 5.5 | 5.4 | 5.5 | 5.0 | 5.1 | 4.5 | 4.3 | 3.9 | 4.0 | 3.4 | 3.1 | 4.0 | 3.7 | 4.4 | 4.7 |
| | J.J.M. | 5.1 | 5.2 | 5.3 | 5.4 | 4.7 | 5.2 | 4.9 | 4.1 | 3.7 | 3.7 | 3.5 | 3.2 | 3.8 | 4.1 | 4.6 | 4.2 |
| | $\bar{X}$ | 5.45 | | 5.31 | | 5.06 | | 4.64 | | 3.76 | | 3.25 | | 3.94 | | 4.50 | |
| | S.D. | 0.40 | | 0.31 | | 0.33 | | 0.43 | | 0.39 | | 0.27 | | 0.17 | | 0.19 | |

| BLACKBODY DISTANCES (m.) | | | |
|---|---|---|---|
| LOCATION | BLACKBODY DISTANCE FOR EACH OBSERVER | $\bar{X}$ | S.D. |
| Loch Turret: 6-6-79 | 4,5,4.7,4.7,4.9 | 4.70 | 0.16 |
| Loch Airthrey: 5-5-79 | 5.0,4.9,4.8,4.7 | 4.85 | 0.13 |
| Loch Airthrey: 6-5-79 | 4.8,4.6,5.1,4.9 | 4.85 | 0.21 |
| Atlantic Ocean: 19-7-79 | 5.2,4.9,4.9,4.7 | 4.90 | 0.21 |
| Atlantic Ocean: 20-7-79 | 4.6,4.9,5.0,5.3 | 4.95 | 0.29 |

# APPENDIX I. Photometric contrast of tiles in Experiment 3b (visual range study).

The predicted contrast at zero viewing distance has been calculated from linear regression analysis.

| LOCATION | TILE | TARGET CONTRAST | | | | | Correlation Coefficient |
|---|---|---|---|---|---|---|---|
| | | MEASUREMENT DISTANCE (cm.) | | | | Predicted $C_o$ | |
| | | 40 | 30 | 20 | 10 | | |
| Loch Turret 6-6-79 | 1 | 1.765 | 1.938 | 2.051 | 2.136 | 2.279 | -0.987 |
| | 2 | 1.056 | 1.202 | 1.358 | 1.405 | 1.556 | -0.979 |
| | 3 | 0.856 | 0.829 | 0.977 | 1.076 | 1.137 | -0.913 |
| | 4 | 0.527 | 0.615 | 0.663 | 0.761 | 0.829 | -0.992 |
| | 5 | 0.342 | 0.422 | 0.471 | 0.521 | 0.586 | -0.992 |
| | 6 | 0.130 | 0.171 | 0.202 | 0.214 | 0.250 | -0.974 |
| | 7 | 0.430 | 0.053 | 0.074 | 0.093 | 0.109 | -0.990 |
| | 8 | -0.070 | -0.082 | -0.097 | -0.111 | -0.125 | 0.999 |
| Loch Airthrey 5-5-79 | 1 | 1.359 | 1.483 | 1.554 | 1.657 | 1.755 | -0.995 |
| | 2 | 0.745 | 0.862 | 0.947 | 1.007 | 1.108 | -0.989 |
| | 3 | 0.537 | 0.602 | 0.662 | 0.727 | 0.790 | -0.999 |
| | 4 | 0.320 | 0.411 | 0.486 | 0.542 | 0.625 | -0.994 |
| | 5 | 0.085 | 0.118 | 0.160 | 0.196 | 0.234 | -0.999 |
| | 6 | 0.000 | -0.020 | -0.038 | -0.055 | -0.074 | 0.999 |
| | 7 | -0.035 | -0.062 | -0.095 | -0.122 | -0.152 | 0.999 |
| | 8 | -0.161 | -0.186 | -0.196 | -0.218 | -0.236 | 0.988 |

APPENDIX I (Continued).

| LOCATION | TILE | TARGET CONTRAST | | | | | Correlation coefficient |
|---|---|---|---|---|---|---|---|
| | | MEASUREMENT DISTANCE (cm) | | | | Predicted $C_o$ | |
| | | 40 | 30 | 20 | 10 | | |
| Loch Airthrey 6-5-79 | 1 | 1.147 | 1.253 | 1.358 | 1.412 | 1.518 | -0.990 |
| | 2 | 0.588 | 0.687 | 0.813 | 0.916 | 1.029 | -0.999 |
| | 3 | 0.466 | 0.532 | 0.596 | 0.640 | 0.705 | -0.996 |
| | 4 | 0.181 | 0.282 | 0.358 | 0.426 | 0.515 | -0.996 |
| | 5 | 0.093 | 0.157 | 0.228 | 0.287 | 0.355 | -0.999 |
| | 6 | 0.004 | -0.021 | -0.067 | -0.138 | -0.174 | 0.977 |
| | 7 | -0.074 | -0.142 | -0.166 | -0.298 | -0.344 | 0.958 |
| | 8 | -0.146 | -0.236 | -0.279 | -0.312 | -0.379 | 0.971 |
| Atlantic Ocean 19-7-79 | 1 | 1.945 | 2.016 | 2.044 | 2.095 | 2.145 | -0.986 |
| | 2 | 1.473 | 1.497 | 1.552 | 1.629 | 1.669 | -0.975 |
| | 3 | 1.110 | 1.142 | 1.167 | 1.232 | 1.261 | -0.976 |
| | 4 | 0.570 | 0.667 | 0.742 | 0.805 | 0.891 | -0.995 |
| | 5 | 0.168 | 0.168 | 0.278 | 0.326 | 0.381 | -0.945 |
| | 6 | -0.108 | -0.122 | -0.131 | -0.129 | -0.141 | 0.893 |
| | 7 | -0.155 | -0.207 | -0.238 | -0.282 | -0.324 | 0.996 |
| | 8 | -0.299 | -0.303 | -0.326 | -0.340 | -0.354 | 0.971 |
| Atlantic Ocean 20-7-79 | 1 | 1.748 | 1.759 | 1.827 | 1.855 | 1.895 | -0.966 |
| | 2 | 1.171 | 1.309 | 1.400 | 1.531 | 1.646 | -0.997 |
| | 3 | 0.946 | 1.039 | 1.090 | 1.219 | 1.291 | -0.986 |
| | 4 | 0.383 | 0.491 | 0.674 | 0.692 | 0.838 | -0.962 |
| | 5 | 0.022 | 0.170 | 0.151 | 0.289 | 0.354 | -0.924 |
| | 6 | -0.194 | -0.252 | -0.274 | -0.319 | -0.359 | 0.987 |
| | 7 | -0.215 | -0.289 | -0.303 | -0.341 | -0.385 | 0.959 |
| | 8 | -0.284 | -0.314 | -0.347 | -0.430 | -0.462 | 0.965 |

# APPENDIX J. THEORETICAL ISSUES OF COLOUR VISION RELEVANT TO UNDERWATER STUDIES.

## J.1 Chromatic Adaptation.

An important consequence of the variance in background water colour is the variation in the adaptive state of the observer's visual system. Since the time of Maxwell and Helmholtz it had been appreciated that it might be possible to specify the appearance of any colour in terms of three values proportional to the absorption rates in the three photopigments thought to be present in the human eye. This was based on the fact that the actual absorption curves must be ultimately related to the data of colour matching experiments, because a colour match implies equal absorptions for each member of the metameric pair within the three types of cone pigment.

On the basis of data from dichromats lacking one of the normal cone pigments, progress has been made in reducing the range of possible absorption spectra (Smith and Pokorny, 1972, 1975; Pokorny and Smith, 1977). Furthermore, this general approach has recently been assisted by a substantial improvement in the agreement between psychophysical and direct measurements of the cone absorption spectra (Bowmaker, Dartnall, Lythgoe and Mollon, 1978; Bowmaker and Dartnall, 1980). Nonetheless, it has met with only limited success. It is one step to achieve a correlation between physiology and psychophysics under restricted experimental conditions, but quite another to assume a similar relationship when the cones are allowed to interact, as would be required by opponent-channel theories of colour vision. Fortunately, the transformation of the best available cone sensitivity curves into a suitable set of opponent curves promises the realisation of Maxwell's and Helmholtz's prediction in the near future.

Despite the importance of colour opponent models in specifying colour appearance, some adaptation must be assumed to take place before the cone signals are combined. It is possible to derive an estimate of cone response amplitude due to pupil dilation (Le Grand, 1968), photopigment bleaching (Rushton and Henry, 1968) and the nonlinearity of receptor processes (Boynton and Whitten, 1970). However, there are other mechanisms to be discovered that may complicate these estimates - for example Dowling and Ripps (1970) have indicated thatadaptation of receptor potentials occurs where the depletion effects due to bleaching are negligible.

Partly as a consequence of these problems, an alternative, more conservative approach has been suggested. According to this view (Stiles, 1939, 1949, 1953), the aim of the psychophysical experiments should be to measure the characteristics of unspecified cone 'mechanisms', whose exact nature cannot be deduced from psychophysics alone. Having defined the mechanisms operationally through the field sensitivity method developed by Stiles (Stiles, 1955), their characteristics may be compared with those of cone photopigment, cone action spectra or electrophysiological data.

The results obtained using the field sensitivity method are well known and have been recently summarised (Stiles, 1978). From these data, it is possible to gain insight into the mechanisms of chromatic adaptation. By plotting the curves relating the field radiance to the threshold test radiances for a variety of test and field wavelengths, Stiles was able to determine the spectral sensitivity of his $\pi$ mechansisms, on the assumption that the Principle of Univariance should produce threshold versus intensity (TVI) curves of fixed shape. It is the shape of these curves, as well as the resulting sensitivities of the mechanisms that are partially defined by them, that underline chromatic adaptation.

Despite, or perhaps because of the simplicity of the method, there is some disagreement about the interpretation of some of the curves. For example, whereas Ingling and Tsou (1977) have proposed that $\pi_4$ and $\pi_5$ receive input from both red cones and a signal from the red-green channel, Bowmaker, Dartnall, Lythgoe and Mollon (1978) have suggested that the $\pi_5$ and the red cone absorption spectra are identical.

An early, direct approach to the quantification of the effects of chromatic adaptation was taken by Von Kries (1905, cited in Judd and Wyszecki, 1975). He proposed that the tristimulus values of a stimulus for one adaptive state of the eye, expressed in terms of the fundamental primaries of the Young-Helmholtz theory, bear fixed relationships to the corresponding tristimulus values of the visually equivalent stimulus observed in an alternative adaptive state. This linear hypothesis implies that a metameric colour match is unaffected by the adaptive state of the eye. Only an approximate agreement can be found between empirical data and values using Von Kries coefficients. As indicate above, however, the fundamental primaries have yet to be accurately specified. In addition, the possibility of adaptation 'downstream' of the receptors, coupled with a lack of adequate experimental control of adaptation (Judd and Wyszecki, 1975, p. 362) could also contribute to errors using this method. A variety of other transformation equations have therefore been proposed (for example, Bartleson, 1979).

## J.2 Chromatic discrimination.

In addition to the effects of adaptation, a theoretical explanation of colour recognition underwater must include the concept of colour discrimination. Two main classes of theory are distinguishable. The first assumes that threshold differences are determined through direct access of the brain to the outputs of each class of cone separately (the view of Helmholtz) or by the receptors themselves (the view of Stiles). Within this type of explanation, it is possible to hypothesise many forms for the interaction between the changing cone outputs. Wyszecki and Stiles (1967, p. 511) provide an account of the geometrical representation of such interactions.

In the simplest form of such a model, threshold is given by the distance between the representation of the response loci of the three signals in three dimensional space. Variations in the particular formula used reflect differences in the nature of the geometrical space needed to represent colour differences. Although this approach has found strong experimental support (Wyszecki and Fielder, 1971), an alternative view is also possible. This regards the discrimination process as being based on the colour channels defined by the opponent theory of colour vision. Similarly, the model has several forms. Guth, Donley and Marrocco (1969) and De Valois and De Valois (1975) have proposed inputs to the yellow-blue channel as comprising red minus blue signals, whereas Walraven (1962), Ingling and Tsou (1977) and Boynton (1979) have suggested a red plus green minus blue signal. Vos and Walraven (1972, a and b) have outlined the development of a line element equation based on an opponent model.

There is further disagreement over the nature of spatial interactions between regions of the visual field. In the limiting case of a uniform visual field (the Ganzfeld), this does not apply - colours appear desaturated and sometimes disappear totally (Avant, 1965). Where a contour exists, account must be taken of lateral neural inhibitory networks which govern (in the case of red and green cones) both spatial and chromatic vision (Kelly, 1975). Two major classes of response have been recorded. In some studies, incorporating three simultaneously visible fields (test, inducing and matching), the inducing field produced in a neutral test stimulus the appearance of an approximately complementary colour (Kinney, 1962; Valberg, 1974). Hasegawa (1977), on the other hand, found that the appearance of a test stimulus shifted slightly away from the strict complementary of the inducing stimulus. Similar results were obtained using only test and inducing stimuli (Akita et al., 1964; Oyama and Hsia, 1966; Wooten, 1970; Eichengreen, 1976; Ware and Cowan, 1982).

At the present time, insufficient is known about the underlying physiology to be specific about such effects. Ware and Cowan (1982) distinguished six models of chromatic discrimination, of which four (the additive receptor, the multiplicative receptor, the additive linear opponent and the multiplicative linear opponent) were refuted by their adaptation data. Two further models, the multiplicative receptor additive linear, and the multiplicative receptor multiplicative linear opponent model were described as providing a "rough and ready framework, and little more." (p. 1360). In no case was a fit obtained between data and model that would locate a colour within one standard deviation of its predicted position. As a general consequence of this type of uncertainty, heated exchanges have taken place as to the relative merits of the various models (see, for example, that between Walraven 1976; 1979; 1981; and Shevell 1978; 1980).

## APPENDIX K. Repeated measures ANOVA summary tables for Experiments 4a, b and c (detection and recognition threshold studies).

| EXPERIMENT | SOURCE | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| 4a Recognition threshold | Targets (T) | 9121.0 | 3 | 3040.0 | 5.40 | <.005 |
| | Subjects (S) | 1516.0 | 9 | 168.4 | 0.30 | >.05 |
| | T X S | 15199.0 | 27 | 562.9 | | |
| 4a Detection threshold | Targets (T) | 2495.0 | 3 | 831.7 | 47.00 | <.005 |
| | Subjects (S) | 94.0 | 5 | 18.8 | 1.06 | >.05 |
| | T X S | 265.0 | 15 | 17.7 | | |
| 4b Atlantic Ocean 17-7-79 | Targets (T) | 6.374 | 6 | 1.062 | 2.75 | <.05 |
| | Subjects (S) | 2.905 | 3 | 0.968 | 2.51 | >.05 |
| | T X S | 6.948 | 18 | 0.386 | | |
| 4b Atlantic Ocean 24-7-79 | Targets (T) | 10.854 | 6 | 1.809 | 2.95 | <.05 |
| | Subjects (S) | 1.086 | 3 | 0.362 | 0.59 | >.05 |
| | T X S | 11.060 | 18 | 0.614 | | |
| 4b Loch Airthrey 7-5-79 | Targets (T) | 9.987 | 6 | 1.664 | 6.30 | <.005 |
| | Subjects (S) | 2.107 | 3 | 0.702 | 2.66 | >.005 |
| | T X S | 4.760 | 18 | 0.264 | | |

## APPENDIX K (Continued).

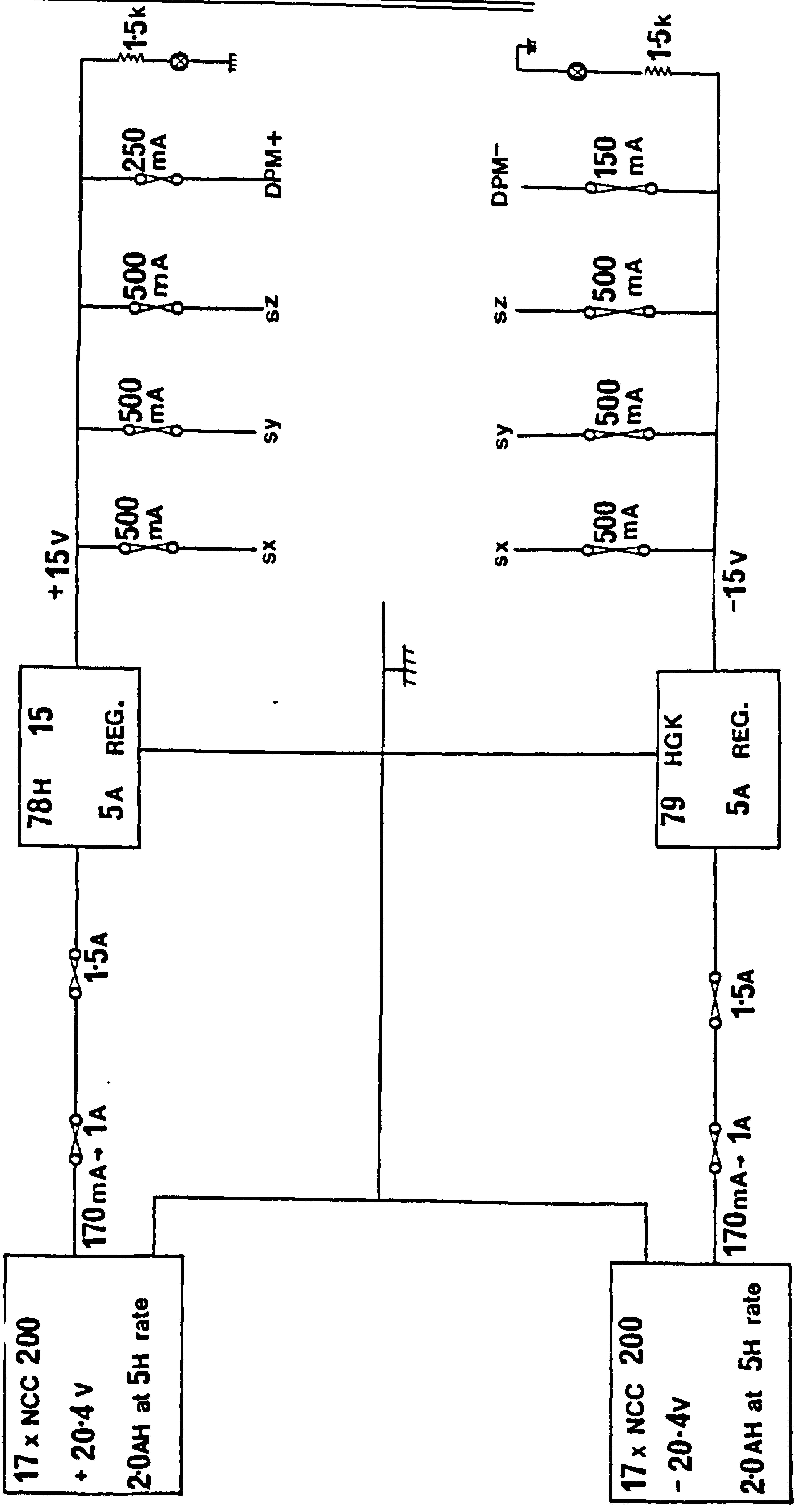
| EXPERIMENT | SOURCE | SS | df | MS | F | p |
|---|---|---|---|---|---|---|
| 4b Loch Airthrey 8-5-79 | Targets (T) | 19.562 | 6 | 3.26 | 10.06 | <.005 |
| | Subjects (S) | 3.859 | 3 | 1.29 | 3.97 | <.05 |
| | T X S | 5.837 | 18 | 0.32 | | |
| 4b Rainbow Springs 12-5-80 | Targets (T) | 1653.0 | 9 | 183.60 | 31.10 | <.005 |
| | Subjects (S) | 51.0 | 3 | 17.10 | 2.90 | >.05 |
| | T X S | 159.0 | 27 | 5.89 | | |
| 4c Off-white background | Targets (T) | 15543.0 | 9 | 1727.0 | 9.90 | <.005 |
| | Subjects (S) | 429.5 | 7 | 61.40 | 0.35 | >.05 |
| | T X S | 10988.6 | 63 | 174.40 | | |
| 4c Green back-ground | Targets (T) | 1369.7 | 9 | 152.19 | 634.13 | <.005 |
| | Subjects (S) | 141.8 | 7 | 20.26 | 84.42 | <.005 |
| | T X S | 15.4 | 63 | 0.24 | | |
| 4c Blue background | Targets (T) | 48426.7 | 9 | 5380.70 | 53.70 | <.005 |
| | Subjects (S) | 10058.5 | 7 | 1436.90 | 14.33 | <.005 |
| | T X S | 6312.0 | 63 | 100.20 | | |

APPENDIX L. Spectroradiometer circuit diagram.

APPENDIX M. Circuit diagrams for the underwater colourimeter.

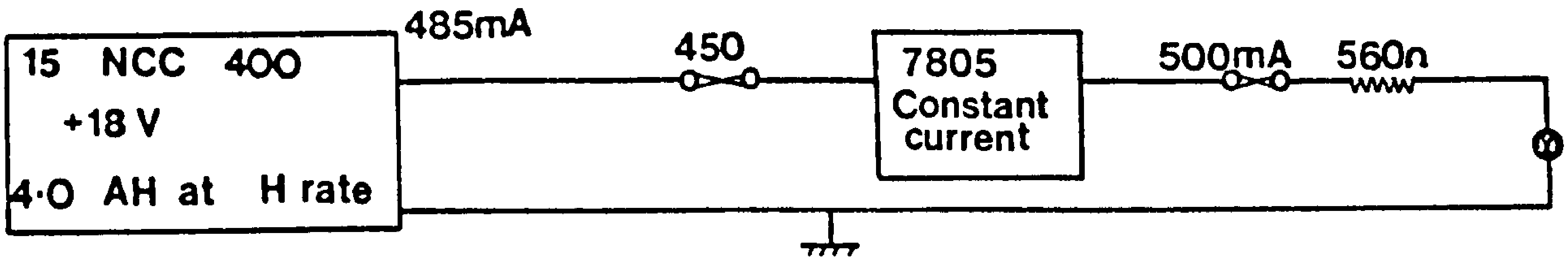
APPENDIX M (continued).

## POWER SUPPLY SERVO & DPM

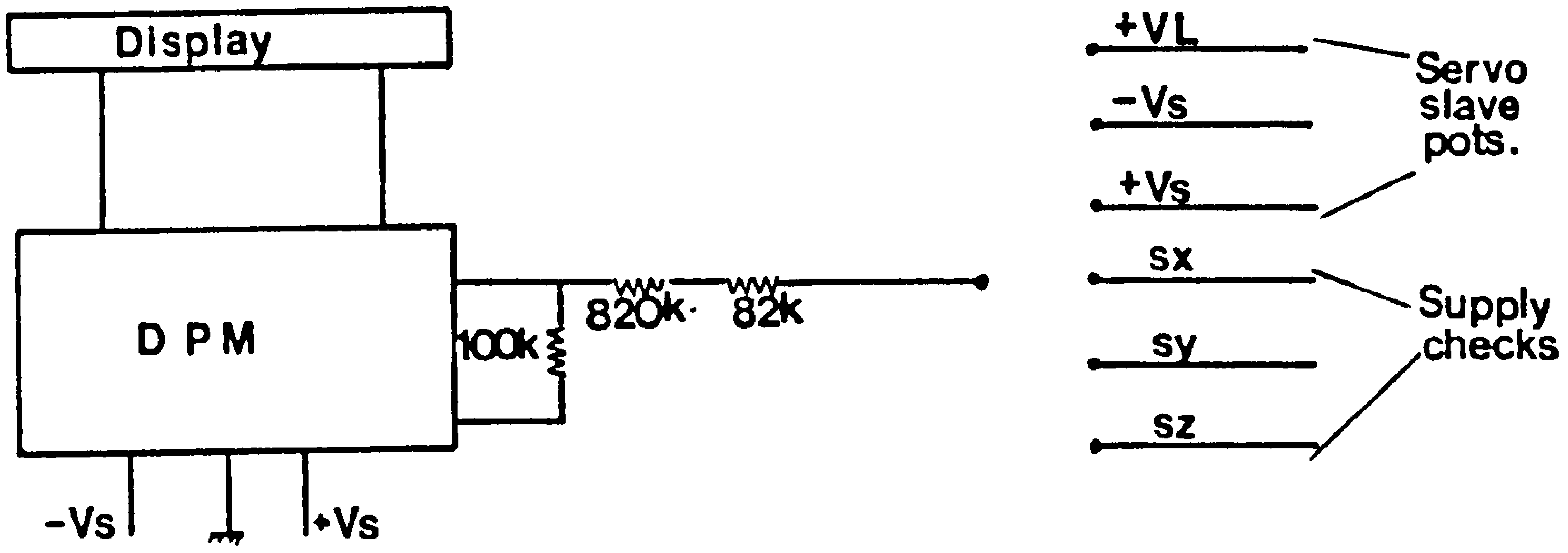


APPENDIX M (continued).

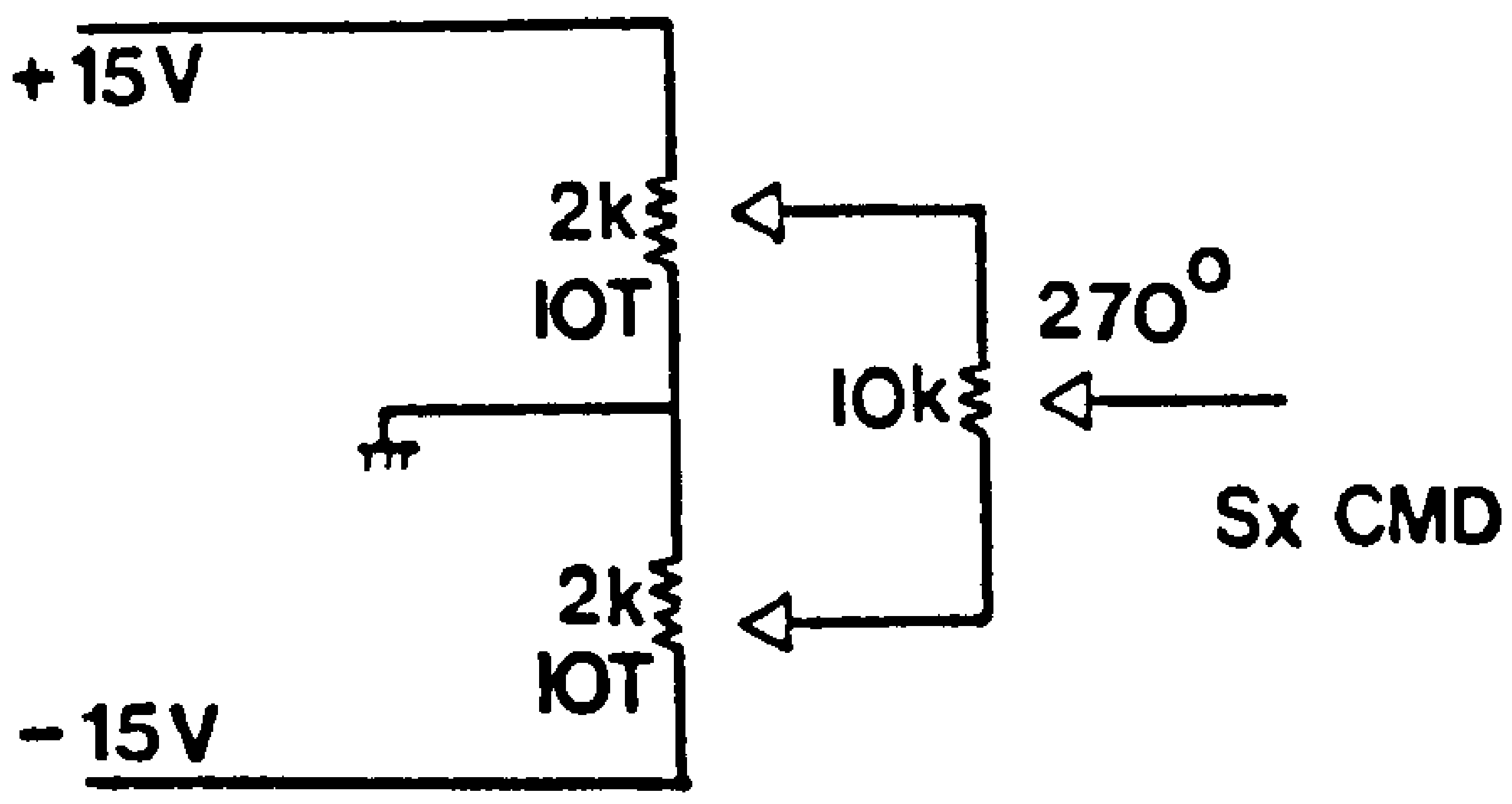
## POWER SUPPLY – STIMULUS LAMP

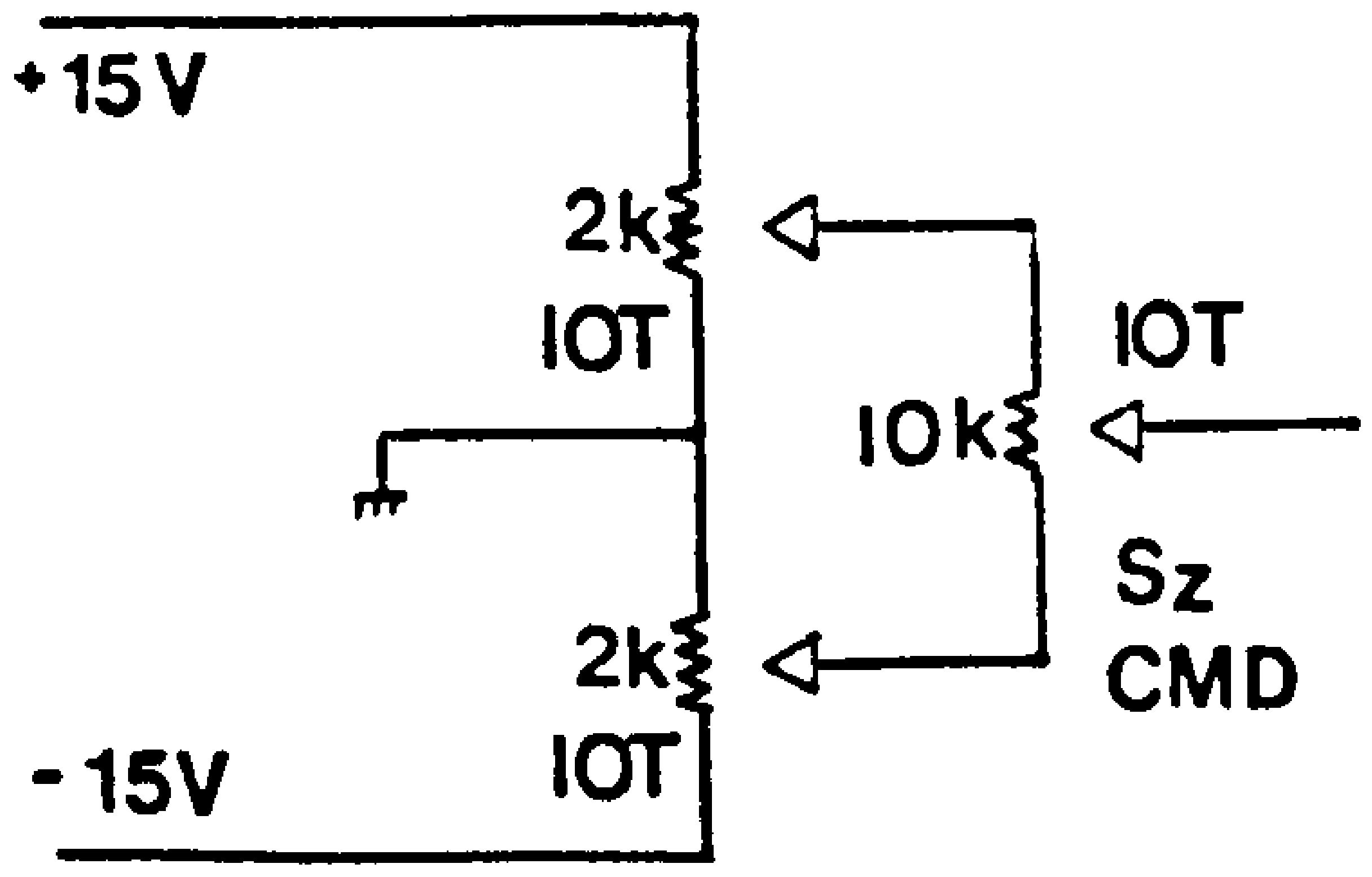


## DPM & SELECTOR SWITCH



## SUBJECT CONTROLS

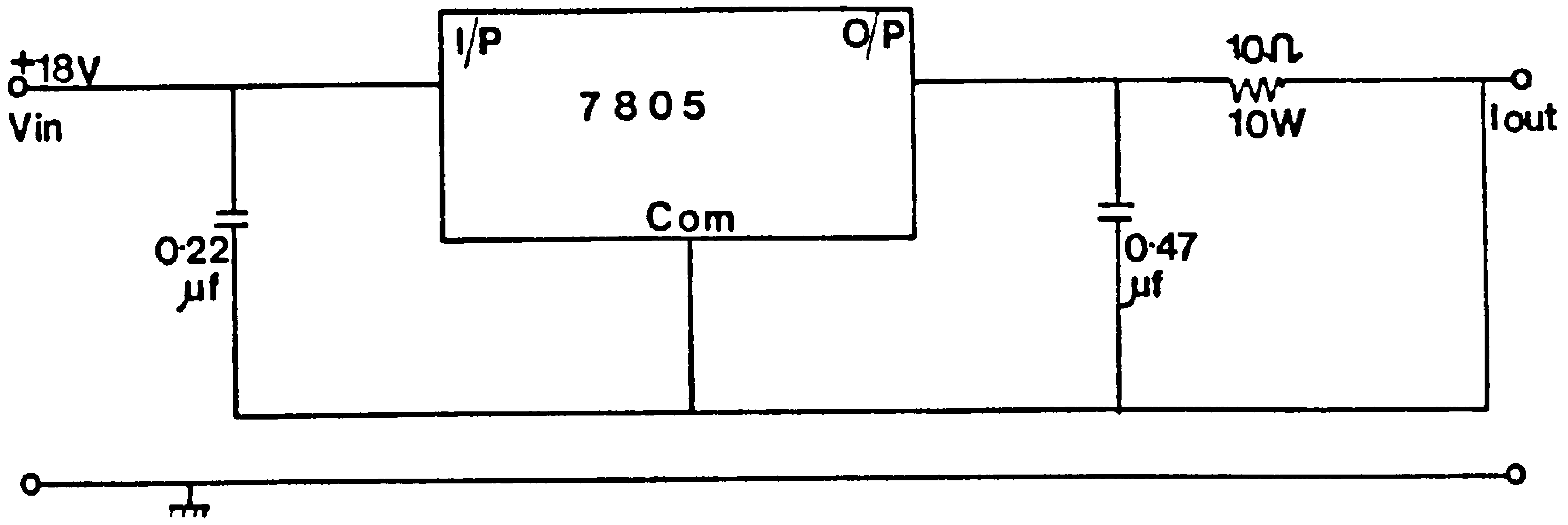




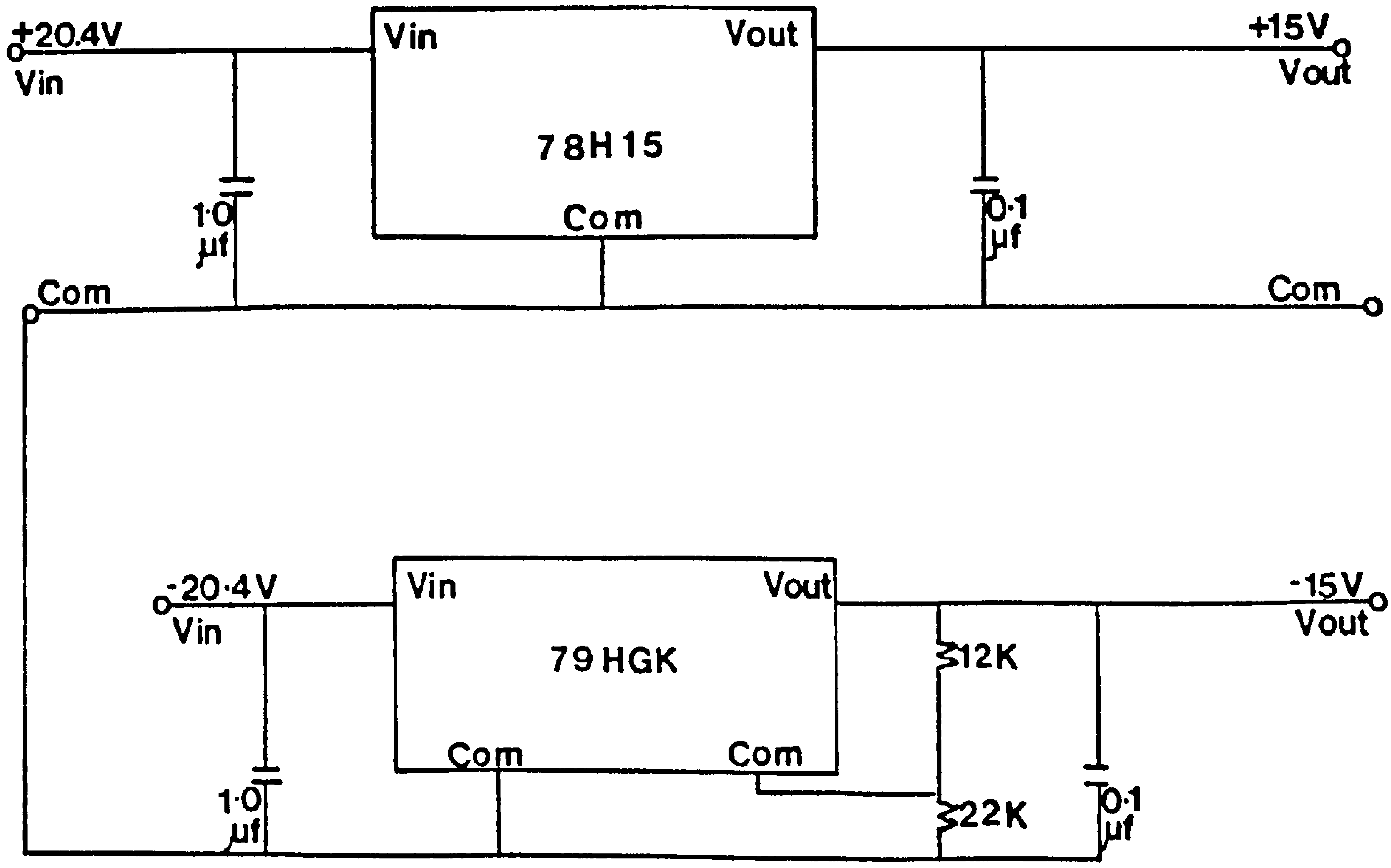
Sy Control identical

APPENDIX M (continued).

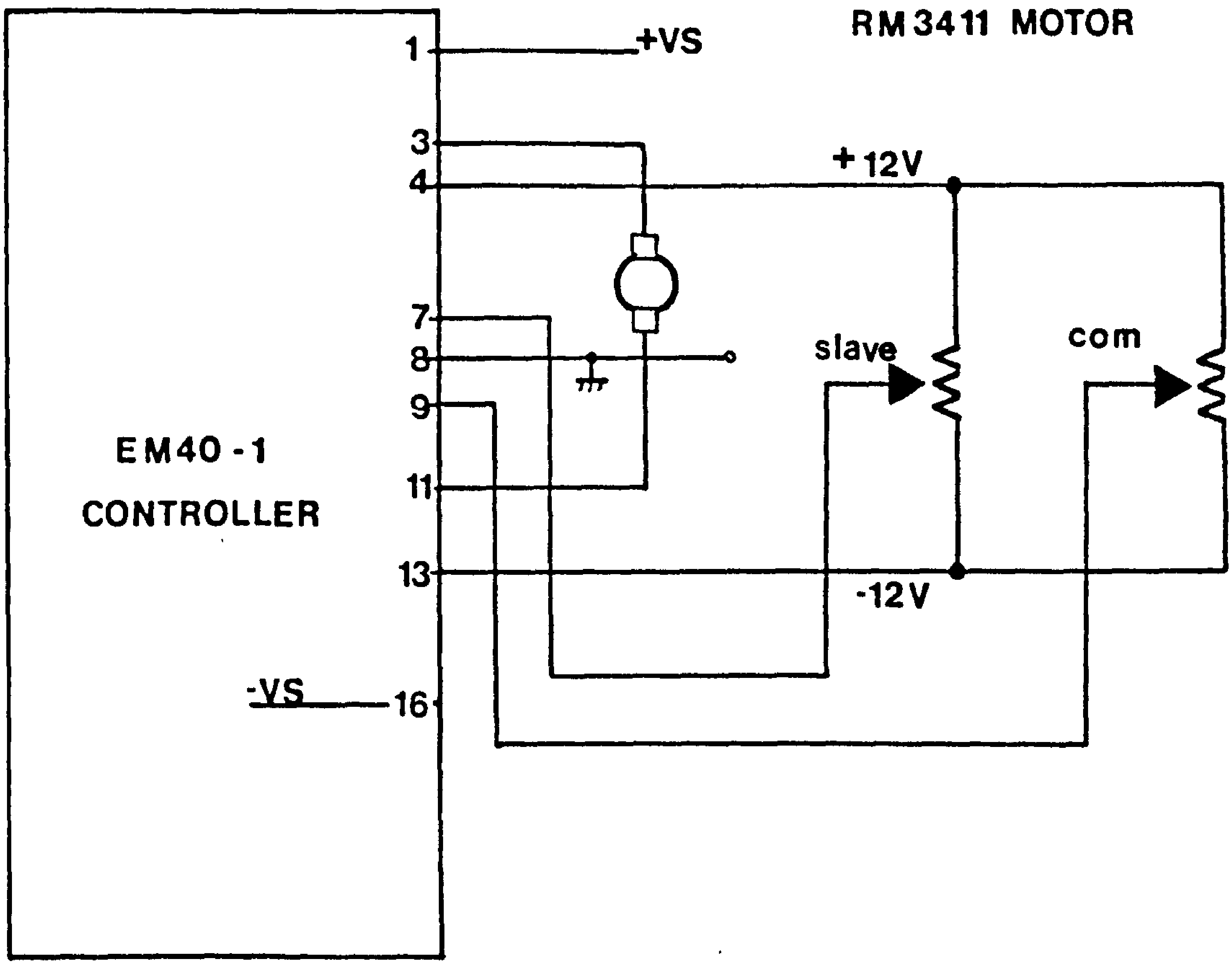
## CONSTANT CURRENT REGULATOR (Lamp supply)



## VOLTAGE REGULATORS



APPENDIX M (continued).



SERVO MOTOR SYSTEM

# APPENDIX N. Visual and instrumental colour matches (Experiments 5a and 5b).

Comparison of the mean colour matches of four observers for various targets under different experimental instructions in two laboratory and two field studies with spectroradiometric measurements of the same targets. The matches of the water backgrounds in the horizontal plane assessed visually and measured spectroradiometrically have also been given. The data are represented as CIELUV chromaticity coordinates u',v' and lightnesses L*.

Notes. [1] Experimental conditions :

1. PAC : Plaques, apparent colour
2. PRC : Plaques, real colour
3. PRCC : Plaques, real colour with cues
4. OAC : Objects, apparent colour
5. ORC : Objects, real colour

[2] Target dominant hues (in air) :
W = white, B = blue, G = green, Y = yellow, R = red.

[3] Matches were :
A = Visual (binocular viewing), P = Instrumental.

[4] Viewing distances 1,2 and 3 refer to 5, 25 and 50 cm for the laboratory studies, and to the distances given in Table 5.4 for the field studies.

| EXPERIMENTAL CONDITION[1] | TARGET DOMINANT HUE[2] | COLOUR MATCH[3] | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER[4] | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Rainbow Springs 10-5-80 and 14-5-80 | W | A | .249 | .529 | 96.7 | .187 | .478 | 94.6 | .161 | .162 | 65.9 | .147 | .446 | 55.8 |
| | | P | .256 | .526 | 96.3 | .156 | .451 | 94.3 | .135 | .415 | 58.7 | .136 | .397 | 42.4 |
| | B | A | .174 | .480 | 51.9 | .150 | .462 | 53.2 | .140 | .442 | 45.4 | .136 | .431 | 40.9 |
| | | P | .172 | .480 | 49.4 | .130 | .462 | 53.8 | .131 | .430 | 44.0 | .134 | .413 | 39.6 |
| | G | A | .166 | .553 | 57.3 | .139 | .529 | 63.0 | .138 | .493 | 47.0 | .135 | .458 | 41.1 |
| | | P | .168 | .554 | 58.2 | .127 | .519 | 60.2 | .131 | .455 | 46.0 | .137 | .414 | 39.9 |
| | Y | A | .312 | .546 | 76.0 | .245 | .528 | 77.0 | .180 | .502 | 55.8 | .163 | .480 | 44.6 |
| | | P | .311 | .544 | 80.7 | .233 | .513 | 74.9 | .146 | .469 | 52.7 | .135 | .421 | 41.8 |
| | R | A | .402 | .527 | 47.9 | .289 | .501 | 43.8 | .240 | .467 | 42.2 | .203 | .437 | 36.9 |
| | | P | .397 | .529 | 55.7 | .296 | .455 | 12.6 | .142 | .397 | 33.4 | .140 | .406 | 37.0 |
| Water back-ground | | A | .164 | .445 | 43.0 | | | | | | | | | |
| | | P | .138 | .406 | 37.8 | | | | | | | | | |
| Rainbow Springs 16-5-80 | W | A | | | | .238 | .516 | 94.6 | .228 | .509 | 91.4 | .236 | .501 | 81.8 |
| | | P | | | | .153 | .467 | 94.2 | .125 | .435 | 56.7 | .133 | .415 | 41.5 |
| | B | A | | | | .145 | .428 | 59.7 | .162 | .444 | 67.7 | .166 | .489 | 68.3 |
| | | P | | | | .131 | .459 | 54.4 | .131 | .433 | 42.7 | .135 | .419 | 39.0 |
| | G | A | | | | .140 | .546 | 61.7 | .136 | .541 | 60.6 | .147 | .497 | 59.3 |
| | | P | | | | .120 | .529 | 60.1 | .128 | .460 | 46.5 | .135 | .426 | 40.4 |
| | Y | A | | | | .227 | .547 | 79.8 | .229 | .552 | 78.0 | .219 | .538 | 71.0 |
| | | P | | | | .231 | .515 | 72.3 | .138 | .482 | 53.7 | .129 | .444 | 42.6 |
| | R | A | | | | .327 | .526 | 51.8 | .336 | .526 | 50.9 | .274 | .527 | 59.2 |
| | | P | | | | .244 | .486 | 14.2 | .138 | .412 | 36.5 | .137 | .412 | 38.1 |
| Water back-ground | | A | .157 | .430 | 43.8 | | | | | | | | | |
| | | P | .137 | .412 | 38.2 | | | | | | | | | |

APPENDIX N (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | $u'$ | $v'$ | L* | $u'$ | $v'$ | L* | $u'$ | $v'$ | L* | $u'$ | $v'$ | L* |
| Oban 6-10-79 and 9-10-79 | W | A | .249 | .529 | 95.6 | .191 | .527 | 86.1 | .173 | .535 | 77.0 | .169 | .536 | 68.5 |
| | | P | .256 | .526 | 96.3 | .166 | .533 | 88.9 | .134 | .545 | 70.8 | .129 | .546 | 66.3 |
| | B | A | .175 | .484 | 48.7 | .157 | .483 | 50.3 | .152 | .500 | 52.9 | .149 | .515 | 58.6 |
| | | P | .172 | .480 | 49.4 | .137 | .488 | 55.3 | .128 | .538 | 63.5 | .128 | .543 | 64.4 |
| | G | A | .169 | .556 | 58.6 | .136 | .554 | 61.5 | .132 | .549 | 60.1 | .130 | .547 | 57.3 |
| | | P | .168 | .554 | 58.2 | .115 | .549 | 68.0 | .124 | .547 | 65.7 | .126 | .547 | 65.1 |
| | Y | A | .310 | .544 | 81.6 | .246 | .544 | 75.1 | .221 | .544 | 70.6 | .214 | .545 | 65.9 |
| | | P | .311 | .544 | 80.7 | .186 | .547 | 74.4 | .140 | .547 | 66.6 | .132 | .547 | 65.3 |
| | R | A | .395 | .527 | 52.8 | .329 | .542 | 54.2 | .310 | .547 | 57.1 | .301 | .550 | 54.0 |
| | | P | .397 | .529 | 55.7 | .227 | .529 | 55.0 | .139 | .545 | 63.7 | .131 | .546 | 64.5 |
| Water back-ground | | A | .158 | .535 | 63.0 | | | | | | | | | |
| | | P | .126 | .547 | 65.0 | | | | | | | | | |
| Oban 10-10-79 | W | A | | | | .241 | .524 | 91.3 | .226 | .526 | 84.2 | .216 | .526 | 80.7 |
| | | P | | | | .168 | .533 | 89.9 | .134 | .544 | 72.7 | .129 | .546 | 68.0 |
| | B | A | | | | .172 | .498 | 55.8 | .176 | .500 | 50.9 | .164 | .505 | 51.6 |
| | | P | | | | .132 | .495 | 54.8 | .130 | .533 | 63.1 | .127 | .543 | 64.5 |
| | G | A | | | | .168 | .542 | 60.1 | .161 | .533 | 61.5 | .165 | .537 | 63.0 |
| | | P | | | | .115 | .549 | 68.2 | .124 | .548 | 65.9 | .127 | .547 | 65.4 |
| | Y | A | | | | .288 | .547 | 77.9 | .282 | .547 | 77.0 | .272 | .536 | 70.6 |
| | | P | | | | .198 | .543 | 74.8 | .147 | .546 | 67.3 | .133 | .547 | 65.8 |
| | R | A | | | | .379 | .529 | 50.2 | .370 | .510 | 42.3 | .303 | .469 | 43.0 |
| | | P | | | | .235 | .527 | 54.7 | .147 | .543 | 63.4 | .131 | .546 | 64.6 |
| Water back-ground | | A | .160 | .531 | 52.9 | | | | | | | | | |
| | | P | .127 | .547 | 65.1 | | | | | | | | | |

APPENDIX N (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Oban 11-10-79 | W | A | | | | .240 | .525 | 92.5 | .228 | .525 | 90.3 | .232 | .523 | 89.1 |
| | | P | | | | .168 | .532 | 90.6 | .142 | .540 | 74.1 | .134 | .544 | 68.7 |
| | B | A | | | | .168 | .478 | 52.1 | .164 | .473 | 50.3 | .165 | .474 | 50.0 |
| | | P | | | | .141 | .480 | 53.5 | .132 | .530 | 61.6 | .122 | .540 | 63.3 |
| | G | A | | | | .167 | .556 | 60.1 | .169 | .550 | 58.6 | .169 | .557 | 58.8 |
| | | P | | | | .115 | .548 | 68.2 | .125 | .547 | 65.5 | .126 | .546 | 64.8 |
| | Y | A | | | | .287 | .543 | 78.0 | .294 | .544 | 80.7 | .301 | .543 | 77.9 |
| | | P | | | | .200 | .542 | 74.2 | .153 | .545 | 67.1 | .140 | .544 | 65.4 |
| | R | A | | | | .378 | .530 | 54.4 | .368 | .531 | 56.0 | .355 | .529 | 56.0 |
| | | P | | | | .246 | .524 | 52.7 | .161 | .538 | 62.1 | .138 | .544 | 63.6 |
| Water back-ground | | A | .160 | .531 | 63.0 | | | | | | | | | |
| | | P | .127 | .546 | 64.3 | | | | | | | | | |
| Oban 23-20-79 and 25-10-79 | B | A | .163 | .478 | 51.9 | .145 | .481 | 54.2 | .132 | .528 | 58.8 | .127 | .538 | 61.7 |
| | | P | .163 | .479 | 52.0 | .137 | .486 | 53.8 | .127 | .536 | 62.3 | .126 | .543 | 63.8 |
| | G | A | .102 | .548 | 61.5 | .105 | .549 | 72.4 | .111 | .548 | 67.3 | .120 | .545 | 60.1 |
| | | P | .100 | .549 | 64.6 | .114 | .549 | 73.4 | .122 | .547 | 68.1 | .124 | .547 | 66.4 |
| | Y | A | .302 | .545 | 87.0 | .242 | .541 | 89.2 | .223 | .543 | 78.8 | .203 | .544 | 69.1 |
| | | P | .299 | .545 | 87.0 | .188 | .550 | 91.7 | .143 | .548 | 72.1 | .131 | .547 | 67.3 |
| | R | A | .344 | .535 | 51.9 | .317 | .546 | 51.9 | .307 | .545 | 58.6 | .298 | .543 | 64.4 |
| | | P | .344 | .531 | 53.6 | .263 | .527 | 54.7 | .158 | .542 | 63.1 | .135 | .545 | 64.2 |
| Water back-ground | | A | .158 | .532 | 64.4 | | | | | | | | | |
| | | P | .126 | .546 | 64.7 | | | | | | | | | |

## APPENDIX N (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Oban 24-10-79 | B | A | | | | .155 | .477 | 53.1 | .152 | .477 | 52.9 | .154 | .485 | 52.9 |
| | | P | | | | .136 | .487 | 56.1 | .131 | .530 | 63.0 | .133 | .538 | 64.3 |
| | G | A | | | | .107 | .544 | 63.0 | .112 | .542 | 63.0 | .105 | .541 | 61.5 |
| | | P | | | | .119 | .546 | 74.0 | .129 | .544 | 67.8 | .130 | .544 | 66.2 |
| | Y | A | | | | .267 | .542 | 87.2 | .263 | .541 | 87.2 | .264 | .541 | 84.5 |
| | | P | | | | .202 | .546 | 74.8 | .153 | .545 | 67.0 | .138 | .544 | 65.6 |
| | R | A | | | | .340 | .541 | 54.5 | .334 | .539 | 57.1 | .340 | .541 | 58.6 |
| | | P | | | | .274 | .524 | 55.2 | .165 | .538 | 63.4 | .142 | .541 | 64.6 |
| Water back-ground | | A | .163 | .531 | 60.1 | | | | | | | | | |
| | | P | .131 | .544 | 65.0 | | | | | | | | | |
| Laboratory green background PAC | W | A | .245 | .529 | 90.3 | .226 | .524 | 92.5 | .184 | .521 | 79.7 | .162 | .525 | 67.7 |
| | | P | .256 | .526 | 96.3 | .195 | .516 | 91.7 | .133 | .524 | 70.3 | .106 | .522 | 63.7 |
| | B | A | .174 | .480 | 47.9 | .159 | .475 | 54.5 | .136 | .496 | 52.9 | .120 | .510 | 58.6 |
| | | P | .172 | .480 | 49.4 | .139 | .483 | 53.2 | .109 | .513 | 59.7 | .104 | .524 | 60.9 |
| | G | A | .165 | .552 | 62.4 | .149 | .553 | 67.3 | .142 | .552 | 61.2 | .133 | .545 | 67.9 |
| | | P | .168 | .554 | 58.2 | .150 | .546 | 65.7 | .123 | .535 | 63.1 | .103 | .526 | 62.2 |
| | Y | A | .312 | .548 | 75.7 | .225 | .539 | 77.4 | .202 | .532 | 70.6 | .192 | .523 | 64.4 |
| | | P | .311 | .544 | 80.7 | .187 | .528 | 73.3 | .143 | .524 | 64.2 | .104 | .526 | 61.9 |
| | R | A | .399 | .530 | 45.7 | .313 | .519 | 47.9 | .265 | .504 | 52.9 | .236 | .522 | 58.6 |
| | | P | .397 | .529 | 55.7 | .270 | .514 | 54.6 | .155 | .522 | 59.9 | .105 | .526 | 61.0 |
| Water back-ground | | A | .136 | .528 | 60.0 | | | | | | | | | |
| | | P | .101 | .527 | 61.3 | | | | | | | | | |

APPENDIX N (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Laboratory green background PRC | W | A | | | | .249 | .529 | 93.4 | .249 | .529 | 84.4 | .249 | .529 | 77.0 |
| | B | A | | | | .162 | .479 | 52.7 | .160 | .457 | 48.7 | .160 | .477 | 45.4 |
| | G | A | | | | .150 | .555 | 72.9 | .146 | .542 | 63.0 | .155 | .535 | 51.3 |
| | Y | A | | | | .285 | .551 | 79.3 | .285 | .537 | 73.7 | .284 | .553 | 79.2 |
| | R | A | | | | .352 | .511 | 43.4 | .339 | .519 | 48.4 | .307 | .511 | 40.2 |
| Laboratory green background PRC+cues | W | A | | | | .249 | .529 | 96.7 | .249 | .529 | 91.3 | .249 | .529 | 91.3 |
| | B | A | | | | .149 | .472 | 57.3 | .160 | .470 | 58.8 | .157 | .477 | 51.9 |
| | G | A | | | | .159 | .549 | 55.7 | .160 | .546 | 57.3 | .153 | .541 | 51.3 |
| | Y | A | | | | .304 | .550 | 85.5 | .305 | .535 | 82.6 | .289 | .540 | 82.4 |
| | R | A | | | | .361 | .501 | 57.3 | .350 | .512 | 54.4 | .350 | .502 | 56.0 |
| Laboratory green background OAC | W | A | .249 | .529 | 96.7 | .249 | .529 | 89.2 | .234 | .521 | 80.7 | .234 | .521 | 71.0 |
| | | P | .249 | .529 | 97.7 | .197 | .517 | 91.5 | .133 | .525 | 69.5 | .107 | .521 | 63.4 |
| | B | A | .194 | .358 | 17.6 | .167 | .429 | 18.1 | .166 | .467 | 44.4 | .165 | .485 | 52.9 |
| | | P | .200 | .362 | 18.6 | .156 | .440 | 17.2 | .120 | .497 | 53.7 | .104 | .522 | 60.8 |
| | G | A | .187 | .509 | 53.2 | .173 | .530 | 53.1 | .149 | .533 | 57.1 | .137 | .530 | 60.1 |
| | | P | .185 | .505 | 51.9 | .164 | .504 | 64.8 | .128 | .532 | 61.8 | .104 | .527 | 61.4 |
| | Y | A | .263 | .548 | 78.0 | .230 | .556 | 74.6 | .199 | .553 | 74.3 | .179 | .546 | 69.7 |
| | | P | .263 | .554 | 75.5 | .246 | .557 | 70.4 | .152 | .535 | 64.0 | .106 | .526 | 61.3 |
| | R | A | .408 | .520 | 51.9 | .348 | .519 | 51.6 | .280 | .516 | 55.8 | .260 | .529 | 61.5 |
| | | P | .408 | .518 | 51.6 | .289 | .505 | 53.6 | .184 | .522 | 59.2 | .103 | .523 | 60.9 |

APPENDIX N (Continued)

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Air | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Laboratory green background ORC | W | A | | | | .249 | .529 | 95.7 | .249 | .529 | 95.6 | .249 | .529 | 94.6 |
| | B | A | | | | .159 | .374 | 21.6 | .161 | .374 | 22.3 | .159 | .373 | 23.5 |
| | G | A | | | | .149 | .527 | 58.8 | .147 | .532 | 58.7 | .146 | .526 | 58.8 |
| | Y | A | | | | .236 | .553 | 77.0 | .239 | .550 | 77.0 | .240 | .544 | 75.1 |
| | R | A | | | | .396 | .511 | 51.6 | .383 | .511 | 51.6 | .385 | .512 | 51.6 |
| Laboratory blue background PAC | W | A | | | | .237 | .516 | 94.6 | .191 | .497 | 58.6 | .180 | .483 | 47.9 |
| | | P | | | | .187 | .496 | 93.9 | .141 | .471 | 59.5 | .128 | .451 | 45.4 |
| | B | A | | | | .164 | .473 | 53.2 | .147 | .460 | 46.2 | .140 | .455 | 45.4 |
| | | P | | | | .155 | .473 | 52.7 | .132 | .458 | 43.2 | .123 | .450 | 40.6 |
| | G | A | | | | .152 | .532 | 58.6 | .145 | .509 | 44.6 | .139 | .492 | 40.1 |
| | | P | | | | .140 | .513 | 53.5 | .132 | .477 | 43.6 | .125 | .452 | 40.8 |
| | Y | A | | | | .270 | .529 | 77.9 | .236 | .512 | 53.1 | .218 | .501 | 45.2 |
| | | P | | | | .218 | .518 | 61.0 | .154 | .486 | 46.4 | .129 | .455 | 41.3 |
| | R | A | | | | .301 | .520 | 28.7 | .254 | .519 | 36.0 | .243 | .508 | 41.9 |
| | | P | | | | .265 | .506 | 27.9 | .140 | .462 | 38.6 | .125 | .449 | 39.7 |
| Water back-ground | | A | .159 | .447 | 46.7 | | | | | | | | | |
| | | P | .123 | .447 | 39.9 | | | | | | | | | |
| Laboratory blue background PRC | W | A | | | | .249 | .529 | 96.7 | .230 | .517 | 91.5 | .202 | .492 | 82.4 |
| | B | A | | | | .165 | .473 | 58.6 | .145 | .423 | 56.5 | .146 | .405 | 59.8 |
| | G | A | | | | .148 | .551 | 60.2 | .147 | .548 | 63.1 | .144 | .545 | 62.9 |
| | Y | A | | | | .246 | .549 | 75.1 | .248 | .540 | 68.8 | .238 | .535 | 74.5 |
| | R | A | | | | .338 | .517 | 46.4 | .327 | .517 | 43.5 | .312 | .509 | 33.6 |

APPENDIX N (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | COLOUR MATCH | CHROMATICITY COORDINATES AND LIGHTNESS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VIEWING DISTANCE UNDER WATER | | | | | | | | |
| | | | 1 | | | 2 | | | 3 | | |
| | | | u' | v' | L* | u' | v' | L* | u' | v' | L* |
| Laboratory blue background PRC plus cues | W | A | .249 | .329 | 97.8 | .239 | .521 | 95.7 | .234 | .521 | 93.3 |
| | B | A | .168 | .472 | 57.3 | .159 | .465 | 55.8 | .153 | .461 | 57.3 |
| | G | A | .144 | .534 | 58.8 | .138 | .531 | 58.7 | .138 | .525 | 57.1 |
| | Y | A | .299 | .534 | 76.1 | .286 | .542 | 80.7 | .283 | .503 | 75.1 |
| | R | A | .343 | .521 | 47.6 | .334 | .515 | 47.0 | .332 | .509 | 44.6 |
| Laboratory blue background OAC | W | A | .249 | .529 | 95.7 | .231 | .518 | 73.3 | .224 | .509 | 60.3 |
| | | P | .199 | .492 | 93.8 | .142 | .466 | 59.3 | .127 | .450 | 44.6 |
| | B | A | .175 | .396 | 14.2 | .158 | .407 | 23.1 | .152 | .411 | 27.7 |
| | | P | .159 | .396 | 20.5 | .134 | .428 | 36.7 | .124 | .445 | 39.3 |
| | G | A | .169 | .488 | 61.5 | .151 | .471 | 53.2 | .140 | .460 | 45.4 |
| | | P | .158 | .494 | 53.5 | .133 | .469 | 45.3 | .124 | .450 | 45.3 |
| | Y | A | .244 | .546 | 61.5 | .215 | .527 | 51.6 | .196 | .511 | 46.2 |
| | | P | .211 | .520 | 59.1 | .143 | .481 | 44.1 | .128 | .453 | 40.2 |
| | R | A | .314 | .541 | 26.9 | .275 | .518 | 31.3 | .253 | .491 | 31.0 |
| | | P | .278 | .500 | 26.7 | .146 | .463 | 37.9 | .127 | .447 | 39.8 |
| Laboratory blue background ORC | W | A | .249 | .529 | 93.5 | .249 | .529 | 94.6 | .249 | .529 | 93.5 |
| | B | A | .174 | .555 | 17.3 | .174 | .352 | 19.4 | .174 | .356 | 21.3 |
| | G | A | .157 | .520 | 53.6 | .154 | .520 | 69.9 | .153 | .515 | 53.6 |
| | Y | A | .266 | .548 | 80.6 | .264 | .549 | 77.9 | .265 | .554 | 76.1 |
| | R | A | .379 | .554 | 51.9 | .371 | .547 | 51.9 | .376 | .546 | 51.9 |

## APPENDIX O. Constancy ratios for the colour matches of four observers (Experiments 5a and 5b).

The mean degree of colour constancy (N=4) has been expressed as 100 - (perceived colour change/physical colour change) for the various targets presented in Experiments 5a and 5b (binocular viewing) over three changes of viewing distance. 100 represents perfect constancy, 0 indicates that perceived and physical colour changed by the same amount, and a negative value that the perceived colour change was greater than the physical colour change.
The colours were (in air) :
W =white, B = blue, G = green, Y = yellow, R = red.
The experimental conditions were :

1. PAC : Plaques, apparent colour
2. PRC : Plaques, real colour
3. PRCC : Plaques, real colour with cues
4. OAC : Objects, apparent colour
5. ORC : Objects, real colour

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | CONSTANCY RATIO | | |
|---|---|---|---|---|
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air to 5 cm in water | 5 - 25 cm in water | 5 - 50 cm in water |
| Laboratory blue water background PAC | W | 20.8 | - 31.7 | - 13.3 |
| | B | 3.9 | 0.2 | 2.6 |
| | G | 36.4 | - 3.7 | 4.2 |
| | Y | 51.1 | - 4.7 | - 18.3 |
| | R | 29.8 | 70.5 | 62.5 |
| Laboratory blue water background PRC | W | 79.9 | 26.4 | - 35.8 |
| | B | -42.4 | -306.5 | -366.0 |
| | G | 35.5 | 54.9 | 61.3 |
| | Y | 26.6 | 56.9 | 34.1 |
| | R | 50.4 | 81.9 | 61.4 |
| Laboratory blue water background PRCC | W | 76.4 | 54.6 | 51.0 |
| | B | -23.3 | 23.8 | - 39.9 |
| | G | 5.2 | 58.9 | 73.5 |
| | Y | 77.9 | 60.0 | 59.9 |
| | R | 62.7 | 80.7 | 79.0 |
| Laboratory blue water background OAC | W | 95.4 | 21.1 | 9.5 |
| | B | 63.0 | 45.0 | 31.2 |
| | G | 48.8 | 16.5 | 14.4 |
| | Y | 45.3 | 30.3 | 18.1 |
| | R | 77.7 | 73.1 | 64.5 |

APPENDIX O (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | CONSTANCY RATIO | | |
|---|---|---|---|---|
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air to 5 cm in water | 5 - 25 cm in water | 5 - 50 cm in water |
| Laboratory blue background ORC | W | 95.3 | 97.5 | 95.8 |
| | B | 33.7 | 85.2 | 78.6 |
| | G | 58.2 | 55.2 | 63.8 |
| | Y | 41.6 | 97.5 | 79.4 |
| | R | 30.5 | 85.8 | 90.2 |
| Laboratory green background PAC | W | 58.1 | 8.3 | 8.2 |
| | B | 23.0 | 41.5 | 10.6 |
| | G | -13.3 | 35.3 | 50.9 |
| | Y | 53.3 | 44.2 | 43.0 |
| | R | 45.6 | 63.3 | 59.5 |
| Laboratory green background PRC | W | 92.8 | 79.7 | 71.8 |
| | B | 23.4 | 15.2 | 37.6 |
| | G | -50.7 | - 2.2 | -22.8 |
| | Y | 76.8 | 9.4 | 66.3 |
| | R | 64.3 | 79.2 | 76.7 |
| Laboratory green background PRCC | W | 91.4 | 88.1 | 90.8 |
| | B | -19.7 | 70.6 | 59.1 |
| | G | 38.3 | 41.4 | 56.5 |
| | Y | 82.8 | 21.7 | 46.3 |
| | R | 63.9 | 75.0 | 89.3 |

APPENDIX O (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | CONSTANCY RATIO | | |
|---|---|---|---|---|
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air - 5 cm in water | 5 - 25 cm in water | 5 - 50 cm in water |
| Laboratory green background OAC | W | 84.3 | 45.4 | 47.5 |
| | B | 38.7 | 62.5 | 48.6 |
| | G | 71.6 | 31.6 | 21.0 |
| | Y | -25.9 | 59.1 | 57.8 |
| | R | - 5.9 | 43.5 | 58.5 |
| Laboratory green background ORC | W | 98.4 | 97.7 | 98.2 |
| | B | 46.8 | 91.9 | 90.0 |
| | G | 41.5 | 63.8 | 72.8 |
| | Y | - 4.9 | 87.8 | 89.0 |
| | R | 68.7 | 88.1 | 93.8 |
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air - 0.5 m in water | 0.5 m in water - 13.5 m in water | 0.5 m in water - 29 m in water |
| Rainbow Springs 14-5-80 | W | 35.2 | 33.4 | 47.4 |
| | B | 40.8 | 44.7 | 45.2 |
| | G | 19.2 | 22.0 | 16.3 |
| | Y | 19.2 | 15.2 | 14.6 |
| | R | 19.0 | 69.0 | 39.8 |
| Rainbow Springs 16-5-80 | W | 84.7 | 62.8 | 75.8 |
| | B | -53.5 | 20.0 | -102.3 |
| | G | 36.4 | 87.8 | 44.1 |
| | Y | 1.5 | 77.7 | 42.5 |
| | R | 52.0 | 80.8 | 27.8 |

APPENDIX O (Continued)

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | CONSTANCY RATIO | | |
|---|---|---|---|---|
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air - 0.5 m in water | 0.5 m in water - 2.8 m in water | 0.5 m in water 4 m in water |
| Oban 9-10-79 | W | 38.3 | 23.6 | - 0.4 |
| | B | 49.4 | 63.2 | 42.7 |
| | G | 49.1 | 46.8 | 5.5 |
| | Y | 45.8 | 31.9 | 27.6 |
| | R | 54.1 | 81.4 | 71.8 |
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air - 0.5 m in water | 0.5 m in water - 2.8 m in water | 0.5 m in water - 4.5 m in water |
| Oban 10-10-79 | W | 75.7 | 5.0 | -22.8 |
| | B | 46.6 | 38.4 | 63.4 |
| | G | 78.9 | -29.5 | -79.9 |
| | Y | 75.8 | 72.3 | 25.5 |
| | R | 81.7 | 65.6 | 11.5 |
| Oban 11-10-79 | W | 85.4 | 4.0 | 36.9 |
| | B | 38.2 | 85.7 | 83.0 |
| | G | 88.2 | 16.1 | 23.6 |
| | Y | 75.5 | 61.6 | 72.8 |
| | R | 69.4 | 86.6 | 78.4 |
| Oban 23-10-79 | B | 13.3 | 10.1 | - 0.1 |
| | G | -115.6 | 9.1 | -64.1 |
| | Y | 47.4 | 34.7 | - 2.7 |
| | R | 63.4 | 90.8 | 86.6 |

APPENDIX O (Continued).

| EXPERIMENTAL CONDITION | TARGET DOMINANT HUE | CONSTANCY RATIO | | |
|---|---|---|---|---|
| | | CHANGE IN VIEWING DISTANCE | | |
| | | 0.5 m in air - 0.5 m in water | 0.5 m in water 2.8 m in water | 0.5 m in water -4.5 m in water |
| Oban 24-10-79 | B | 82.3 | 92.3 | 93.5 |
| | G | 53.8 | 100.0 | 82.6 |
| | Y | 98.0 | 100.0 | 94.5 |
| | R | 94.7 | 97.1 | 96.3 |