Journal of the

Colour Group

Number 16 1972

The period covered by this second issue of the Journal in its annual form is that of the group's activities up to the middle of 1971.

Typewriter setting has again been adopted, but publication has been much delayed by the necessary dependence on "voluntary labour" in the typing stage, and on the goodwill of the companies by whom the personnel involved are employed. To them, and to the long-suffering patience of the typist, who must remain anonymous to nearly everyone of us, the Colour Group owes a great debt.

It is our earnest hope that these delays in publication will become less as we become more accustomed to this method of production; the alternatives are increased subscriptions or no Journal.

What Use is Colorimetry?

G J Chamberlin

In 1962 I was a member of the committee which inaugurated the Newton Lectures and never did it occur to me that I should be asked to stand here myself. I sat in respectful admiration of my predecessors, and now the present committee has moved rather unexpectedly from the academic world to industry and I feel highly honoured but apprehensive. I am no scientist and have done little original research: what I know of colour I have learnt from my fellow members of The Colour Group and from the practical experience of 35 years in colorimetric work.

My favourite bedside book is still Professor Wright's collection of discourses under the title "The rays are. not coloured" (Ref 1) which title was taken from his inaugural Newton Lecture, which set a very high standard. I am continually delighted by his easy style and learn something fresh each time I read the book.

I suppose that ultimately all of us here are beneficiaries of Sir Isaac Newton's work, and I recently found a tribute to him which 1 want to quote. It is from a book on Colour Vision by Edmund. . Hunt published in Glasgow in 1892 (Ref 2) and shows the attitude to him at the end of the last century:-

> *No other science can be said to belong so peculiarly to one man as that of Colour does to Newton. His diagram of colour was a marvellous invention, and remarkable as much for the extremely little there was to suggest it as for its complete and admirable appropriateness.*
>
> *Long after Newton's time, theories of colours prevailed which did not agree with his diagram, but such theories, although appearing at the present day in some cheap would-be text books, are now discarded by scientists, and his diagram is held to accord perfectly with facts.*

I wonder whether the author is referring to Thomas Young and Clerk Maxwell. However, although we certainly strayed from Newton's corpuscular thesis, the quantum theory nearly brought us back into the fold again later.

Another quotation on the subject, this time from the book *Newton and the origin of colours* (Ref 3) by Roberts and Thomas published in London in 1934.

Newton's discoveries consisted in finding terms and methods which best express the results of experiments and measurements which other people had made before he entered the field.

He would undoubtedly be pleased with the great upsurge of interest in colour science which has taken place this century, and especially since 1931, when the Commission International de l'Eclairage included colorimetry within its scope.

There is a world fellowship of people, cutting across many different disciplines, who have a common interest in colour science, and it has been my priviledge to meet a fair cross-section of them. I have lectured on colour in 18 different countries and discussed colour in as many more, and found the people I met enthusiastic and friendly and very willing to talk about their work. How right we were when we decided that The Colour Group should become an independent body, so that we could bring into membership all those interested, whether scientists, artists or industrialists. Some of you may remember that it was during my term of office as Chairman of the Group that we made the decision to separate from the newly amalgamated Institute of Physics and Physical Society. Before bringing the matter to the whole membership, 1 took the unusual step of consulting every available Past Chairman, and all but one were in favour; elder statesmen can be wise sometimes. Mention of elder statesmen reminds me of the reference in a Japanese scientific journal last year to Professor Wright and myself as "reverend fore runners of color science" I'm not sure what is meant, unless it infers that it is time we were gathered to our ancestors!

Going back in memory over past meetings, I realise how wide a range we have covered under the general title of Colour, and how fortunate we are in having such enthusiasts to talk to us. Surely Colour Science,and its handmaiden Colorimetry, must be useful if such experts have devoted their lives to it. Quite apart from our many lectures and discussions on the mathematics and mechanics of colour measurement (which I suppose is the bread and butter of our common interests), I recall papers on Colour Vision, on the Philosophy of Colour, on the Psychology of Colour, on Art, on Colour in Stagecraft, on Design and Architecture, on Illumination, on Television, on Photography, Glassmaking, Paints and Dye-stuffs, Food and Colour, Education.

I could continue in this strain for a long while but I hope that I have made the point that our subject is as wide as man's activities.

At many of our meetings I have been puzzled and confused by high-powered mathematics and instrumentation, and have gone away to hide my head in shame, wondering where I stand in regard to the remark in one of Luckiesh's books (Ref 4) that *Only the wholly ignorant know everything*. On such occasions I have sometimes been comforted by the quiet remark of a fellow member, whose judgement I respect, that *The more we know, the more we doubt ourselves and our measurements*. Again quoting from Luckiesh, *It is possible that complete knowledge would reduce the subject of colour to simplicity*. Who of us will be the first to dare to claim complete knowledge?

To me, colour is what I see, and I try to keep the subject down to "eye level" in my thinking; for example, I can understand uniform chromaticity triangles much better when I break the theory down into a cartoon strip! Colour is not a series of figures from a computer, although the subject may be easier for some people to handle that way. The real thing is much more complicated, and in the end we have to be content with averages and approximations. We have to take into account the human factor, adaption, contrast, fatigue, state of health, skill and so on before we can really talk about what a colour looks like. Wright, among others, constantly reiterates this point of view, but it keeps getting lost sight of by instrumental enthusiasts. I was quite shocked when at a recent meeting of ours a speaker, after describing instrumental match predictions commented in parenthesis "and we finally look at the result." Why did everyone laugh? That's our trouble. We don't use those supreme instruments, our eyes, nearly enough. I read with enthusiam the report of one of our overseas members, Miss Ruth Johnston, to the Inter Society Colour Council on "Color Measuring Instruments" at their 1969 meeting (Ref 5) and I quote rather extensively:-

> *The title is somewhat misleading in its implication that instruments 'measure' color - in ordinary usage we speak of color measurement, but in reality, we do not "measure" colour with an instrument. Instead we "describe" color in idealized standardized terms, "Colour is what we see". It is seldom that the idealized conditions used for color description exist exactly in the real world of visual color evaluation and it is important to remember this. In general, color measurement is used to provide numbers which can be correlated with visual evaluations, and the degree to which this can be accomplished depends on both measurement and visual evaluation conditions. We do not wish to imply that "color measurement" is not a very powerful tool. It is indeed, when properly used. So we will continue to use the term "color measurement" because of its general acceptance, keeping in mind that we actually mean a subjective description based on an objective physical measurement.*

I also like the remark by Professor Fred Billmeyer in the *Optical Spectra* for February last - "Remember that nobody accepts or rejects a colour because of figures from an instrument; it's the way it looks that counts."

search widened into a general consideration of the best illumination in an operating theatre, so that the anaesthetist could most easily detect changes in the flesh colour of his patient and take the appropriate action. This enquiry led to a most interesting series of colorimetric readings of flesh colours under every possible type of light source, with especial emphasis on sources which showed colour differentials while maintaining high general illumination.

Also in the medical field, Doctor B. Jolles, radiologist at the Northampton General Hospital, has published a considerable amount of colorimetric data on changes in skin colour due to erythema under short-wave bombardment, and we designed a special portable apparatus for him, lie is working on cancer research, and the information is important in controlling dosage. An allied field is in plastic surgery, where consecutive colorimetric skin readings have been used to forecast whether rejection is likely to occur in a skin graft.

From medicine to cosmetics, and work on screening-lotions to avoid or speed sun-tan, A great amount of coloriroetry of the skin has gone into this, both here and abroad, and this has had considerable television publicity including a lot of bally hoo with pictures of bathing beauties. In one interview I was closely questioned about this, from which we got on to the interesting subject of beauty queens, and by the most wonderful of "non-sequiturs" we found ourselves finally discussing the ideal colour for French-fried potatoes.

This brings me to food research. As long ago as 1953 I took part in a Symposium on the subject in Chicago, when colour change in food during storage was discussed, and colorimetric readings were used to illustrate the oxidation and polymerisation of colourless constituents into coloured, thus producing coloured signs of deterioration. Since then, much more has been published, as I mentioned here some while ago in reviewing the book on *Colour of Foods* by Mackinney and Little (Ref 6).

It is a small step from food to agriculture. Professor Wallace of Bristol University wrote a most interesting book entitled *The Diagnosis of Mineral Deficiences in Plants* (Ref 7) in which he established a system of diagnosis of these deficiences from the observation of colour changes in the leaves. The colour of flowers can sometimes be used as an indication of qualities other than appearance. The agricultural research people at Cambridge showed that a particular shade in red clover was a clue to the best strains for use as breeding stocks for producing prolific yields for cattle feed, and I helped in laying down standards for the most desirable colour for these purposes. I was also associated with a research programme on the ripening of fruits under various growing conditions, when colorimetric readings played an essential part. Here again a portable colorimeter was used, so that the fruit could be measured while still on the tree;. Another example comes from the aerial spraying of crops. The problem was to obtain an idea of the density of spray material per unit area when operating from different heights, and the answer came from spraying with a coloured material on to large white areas, and then assessing the various densities colorimetrically.

I mentioned earlier that colour is what we see, and 1 know that some people regard me as an anachronism because I still believe in visual colorimetry, but an example of how this can be used arose when the CIE. Committee was obtaining data about daylight for the new illuminant now designated the Illuminant D series. I carried out daily visual measurements on the colour of north daylight over a period of a year, and the results were presented to you in 1962 and subsequently published in *Light and Lighting* (Ref 8). I was the only one of the many contributors to this exercise who actually looked at the daylight and measured what he saw; and the results tied in well with the spectrophotometric data presented by others. In fact, Judd included them in his final analysis on which the recommendations were made. I found that the largest number of results fell within the range of correlated colour temperatures 6700K to 8000K , but extended almost to infinity, and that the points were scattered close to the locus of a Planckian radiator, with a small bias to the green side. In addition, I reported the comments of colour graders on the light conditions in which they found grading easy or difficult; for example that the diffused light of an overcast sky was much preferred to a clear one, and that they were completely thrown off balance when the ground was snow covered and the light was reflected upwards.

I suggest this illustrates the point that useful colorimetric work can be done by means of quite simple methods.

Turning now to examples from industry, commerce and day to day experiences, there are the obvious ones which do not need elaboration. I refer to the colour-using industries, plastics, paints, textiles, inks, paper, etc., where records, standards, specifications and tolerances are the business of colorimetry, and now the new science of "mix predictions" for dyes and paints is proving a boon. Coloured lights for signaling in the field of transport and communications have all been brought firmly into the area of colorimetry today, and it is unnecessary for me to discuss this here. It is interesting to note, however, that the Americans have produced specifications to define areas in the colour triangle which are prohibited to illuminated advertising signs, so as to prevent confusion with traffic lights. Deane B. Judd did much of this work for the police authorities, and he brought me into it to provide the physical standards.

The use of colorimetry is well illustrated in the world of oils and fats, where colour and quality usually go hand in hand. Most countries now have standard colour specifications for every conceivable grade of mineral, vegetable and animal oil, and sometimes a great deal of money may depend on a colorimetric reading. I recall a case where a tanker had docked with thousands of tons of whale oil aboard, and a dispute arose as to the cash value, which hinged on colour. I was asked to adjudicate, and a fortune depended on which side of a line I placed the colour. In the U.S.A., Canada and Australia there are a number of provincial and state laws concerning the colour of oleomargarine. In this case, a maximum colour is specified which will prevent confusion with butter, and any increase in colour is penalised by the levying of a duty, expressed on a sliding scale which increases with colour.

Hardy, in his book *Handbook of Colorimetry* published in 1936 (Ref 9), was I believe the first to~ refer to the shape of log density curves as being the property of the medium alone, independent of thickness or concentration, but 40 years before that J.W. Lovibond had hit on a similar idea, and I found in his Lab. Book for 1896 what he called the Law of Specific Colour Development which says "Every definite substance has its own specific rate of colour development for increasing densities," by which he meant liquids viewed in increasing depths. This idea was developed in his book *An introduction to the study of colour phenomena* published in 1905 (Ref 10).

I used this method some 30 years ago as a means of identifying a number of shellac solutions, and their rates of colour development were strikingly dissimilar. Later work on oils showed that the method could separate different oils which matched in some given depth, say 1 inch, and were quite different in greater depths. This led me to consider whether the visual colour measurement approach had any advantages to offer over the log density curve, and I think that in some cases it has. I have recently been interested in tests on tea liquors, and this seems a case in point. The sample is produced in the time honoured way - one tea-spoonful of tea, a cupful of boiling water, infuse 3 minutes and decant: measure immediately, before it clouds.

In a spectrophotometer, the curve is smooth and unexciting and there is little separation to distinguish one brew from another.

When you look at the samples together, however, it is clear that they do behave differently in different depths, and I felt that this should be followed up.

I measured a number of different teas such as Assam, Orange Pekoe, China, and so on, visually in terms of Lovibond units in varying deptlis and found that if I plotted Red values against Yellow these ratios gave quite exciting differences, and a definite pattern emerged.

This led me to be more ambitious, and 1 obtained four Ceylon teas grown on different estates at different heights but in the same region.

The log density curves were not very dissimilar but distinctive visual patterns were found which I was able to reproduce repeatedly. They show a family resemblance, unlike other types of tea. There is little distinction in depths up to 25mm but measurements at 40, 75,100 and 150mm show increasing divergence. I had to stop there, as the liquid was opaque beyond that depth.

The next step was to try blends, and much to my joy the method worked. It does seem that here is a useful method of identification which could be developed and some day I hope to continue the work on other materials as well. This is yet another example of the application of that useful tool colorimetry.

In the field of horticulture, botany and zoology there are innumerable colour charts and atlases, and as many of these have tied their standards to colorimetric records we come back to our subject again. 1 was involved with one of the well-known bird observatories and the colorimetric readings taken of the plumage of birds captured and ringed has brought out the information that there are subtle geographical colour variations in the same species, so that it is often possible to pinpoint the area from which a bird comes by reference to chart showing these variations.

The National Gallery gave us an example of colorimetry in the Art world, when the late Ian Rawlins published colorimetric data on the progress of the cleaning of old paintings. He showed that the dingy colours associated with so many old paintings were due entirely to the yellowing of the varnish applied as a preservative by later generations, and the careful removal of the varnish by suitable solvents revealed the startlingly brilliant pigments of the original. By repeated colorimetric readings as the cleaning slowly progressed, he was able to know when he had got down to the original pigment and had removed all the varnish, and this in a non-destructive manner which would have been impossible if he had used chemical methods.

In the field of forensic science there are of course many uses for colorimetry, but one side of this which has always interested me is the detection of forgeries by minute colour differences in written characters. Not only can different inks be identified, but words written at different dates with the same ink will show up, because of chemical changes caused by atmospheric oxidation (Refs 11, 12).

Turning to geology and soil colours, it was his work for the International Society of Soil Science which brought the late Doctor R.K. Schofield (Chairman of the Colour Group in 1946) into the field of colorimetry. In a paper he wrote in 1938 (Ref 13) he hailed the coming of the CLE. system as a landmark in the classification of soil colours, because previously there had been a lack of uniformity in the reports reaching him from different countries. I suppose that today the best known system of classifying soil colours is due to Munsell, but that is itself ultimately tied to the CIE System.

In connection with foodstuffs there are many colour standards to ensure that products maintain "sales appeal", and in some countries there are enforceable standards which insist that the good name of the country shall not be prejudiced by the export of bad-coloured products. There are such standards, for example, for Malaysian pineapple and Californian peaches, for citrus juices from Chile, and Australian honey.

Some buying authorities go to great length on this subject. I was involved in a colour specification by the U.S. Army concerning canned meat issued to their troops. I can understand this, as colour and condition are closely related. But when they specified the colour of shortening to be used in the manufacture of cookies (biscuits) I was lost in wonder.

The Japanese fishery research people are working on the idea that the colour appearance of the sea can give them some guidance as to the distribution of good and bad feeding grounds, and on the strength of a small news paragraph in the newspapers I was approached by a big-game fisherman to see if he could get a portable colorimeter which would lead him infallibly to where the big fish are to be found. This is, 1 fear, carrying wishful thinking on the benefits of colorimetry too far.

The U.S.A. authorities are using colorimetric measurements of aerial survey photographs to assess healthy and diseased areas of vegetation, especially in forest areas, and similar surveys in Libya have indicated, through colorimetric assessment, certain desert areas which have since been shown to be able to produce crops.

This technique has been applied to colour photographs from space, to assist in hydrological and mineralogical surveys and oceanographic studies, (Ref 14) and in studies of coastal pollution by oil and sewage.

The testing and measurement of colour vision abnormalities is a facinating sub-section of our subject pursued by many of our Group and 1 mention it only to observe that I recently saw a bank applicant's medical report form on which was printed "The only colour discrimination requirement is to be able to distinguish black from red."

Turning to another use of colorimetry, namely in chemical analysis, I find this a truly fascinating field of work which has unlimited applications. A book I wrote on analytical chemistry received a review I've never forgotten. The book, I admit, contained a good many references to apparatus manufactured by my firm (but, after all, that was why I wrote the book) and the reviewer said "This is a most useful book, but it reminds me of a taxi driver I knew, who when asked the best way to anywhere invariably replied 'In my taxi'.'[1] At one end of the scale there are the fully automated laboratories such as one finds in the large hospitals, where production-line working is in operation, and thousands of standardised analysis are carried out daily, and at the other end of the scale are the occasional field tests carried out by the farmer or veterinary surgeon.

The most frequently performed colorimetric tests are in connection with water, such as public supplies, swimming pools, effluents or boiler water. The prize for the simplest non-colorimetric swimming pool test I know was contained in a recent letter from Africa "If the dogs drink the water, there isn't enough chlorine." These water tests are closely followed, in the sense of the number of tests performed regularly, by public health tests, such as the control of foods, air pollution and medical tests. The procedure consists of three steps.

1. The isolation from interfering materials of the chemical substance to be determined.
2. The development of a colour by the action of a suitable chemical reagent.
3. The measurement of the colours so produced, and from that result the calculation of the concentration of the chemical under investigation.

The measurement of the colour may be done in a variety of ways, from comparison against prepared standard solutions, through the gamut of printed charts, plastic or glass filters to photo-electric devices using appropriate filters, sometimes with automatic recording.

All this is everyday stuff to the chemist. I want to talk about some of the less commonplace work in this sphere which has come my way.

In the last few years I have worked with the U.S. Public Health Authorities on the smog problem in Los Angeles and other air pollution problems there connected with the internal combustion engine, and with the

Factory Inspectorate in England on industrial atmospheric pollution. The series of booklets published by H.M. Stantionary Office entitled "Methods for the detection of toxic substances in air" all make use of colorimetric methods.

Water pollution testing and research is also a very important field for colorimetric methods, and I believe that our branch of science has a great contribution to make in this direction, in connection with World Pollution Year.

The World Health Organisation has produced some interesting problems. One was in connection with aerial crop-spraying; the materials used can be very toxic to the operators, both in the air and on the ground, and a colorimetric field test for the people involved was devised for safeguarding their health by checking the level of the chemical in their blood. Another job was in Africa, where there is a big drive to control and reduce the incidence of the dreaded disease bilharzia. The approach is to kill the aquatic snails, which are the carriers, by dosing the rivers, streams and canals with a suitable chemical. The dosage must be controlled and a simple colorimetric field test has been developed. My third example is in connection with opium smuggling. A colorimetric test is employed to identify the geographical region of origin of seized consignments, and this is a big help to the enforcement officers. It uses the identification of certain contaminants which are peculiar to the soil of the various places of origin.

Mention of soil tests brings me to a very important field for colorimetric work in assessing mineral deficiencies, and I want to mention one interesting piece of detective work done by the late Doctor R. K. Schofield, whom I have already mentioned. While working at Rothampstead he was consulted about repeated lack of success in re-afforesting a particular area. His routine analysis revealed nothing to account for the trouble, but he tried the effect of various fertilisers, and after a time he noticed that one area, which had been treated with a mulch containing some spent hops from a brewery, was producing results. Careful analysis of this mulch by colorimetric methods showed nothing unusual, except about one part of copper in 50 million which he traced back to the copper vats in which the hops were boiled. Apparently the soil in that place was completely devoid of copper and the particular trees they were trying to grow needed that minute stimulus; with that information they were able to make a success of the undertaking.

The art and mystery of tea-tasting would seem to be the acme of a subjective test, but work has been published on colorimetric tests for theaflavin and therubigin in tea. If this work fulfills the hope of certain chemists, tea grading may be possible on the basis of the proportions of these constituents (Ref 15).

From tea to milk is not a far step, and some of you may not know that there is a colorimetric chemical test, with legal force, which sorts out pasteurised milk from unpasteurised (Ref 16), although organoleptic tests of taste and smell and appearance will not help. The presence of mastitis in cows can also be detected by colorimetric tests on the milk (Ref 17). Imported liquid eggs must be pasteurised to prevent *Salmonella* infection being brought into the country, and here again a colorimetric test is the legally authorised check (Ref 18).

One large baker I know was in trouble over the old "half a beetle found in a slice of your cake" blackmail trick, but a perfectly simple colorimetric test proved that the beetle had never been cooked and therefore could not have been inside the cake as sold.

Turning to medical work, two extremely simple "on the spot" colorimetric tests allow the anaesthetist to check the carbon dioxide and water vapour content of his patient's breath while under the anaesthetic,thus giving valuable information.

I recall moments of acute apprehension during the last war, when explosive experts brought captured enemy shells and bombs to my laboratory for colorimetric analysis, to see if **they** had something **we** hadn't got. The nonchalent way that they dismembered the wretched things filled me with alarm.

Another wartime commitment was an involvement through the Minstry of Agriculture in the encouragement of a study of hydroponics or growing vegetables without soil. The seedlings are planted in sand or clinker and fed with chemical nutrient solution, which needs constant analytical checking to keep it up to strength. This check is done colorimetrically and that is how I was involved. The idea was to produce extra crops where soil or weather conditions were unfavourable, especially on remote islands used as refuelling stations. It was successful but expensive, and we produced some first-rate tomatoes and cauliflowers as a contribution to the war effort. There has recently been a renewal of interest in this work, and a bulletin was issued by the Food and Agriculture Organisation of the United Nations in 1966 entitled *Soilless cultivation and its application,to Commercial Crop Production* (Ref 19).

A recurring problem for engineers dealing with underground ducts for cables is the presence of water. Is it just surface water and harmless, or is it sewage seeping in from a broken pipe? Colorimetric chemical methods have produced a simple test for the presence of organic acids which gives an immediate indication of the source. In a very different field, printers sometimes meet trouble with smudged work because the ink does not dry quickly enough. This is caused by incompatibility in pH of the ink and the paper. The Printing Industries Research Association have produced a simple colorimetric test which will diagnose this.

All that I have said is admittedly discursive and superficial; you have heard nothing very original, and most of you could add something to some part of it. I hope, however, that 1 have indicated the fascination and wide-ranging uses of colorimetry, and that you will agree with me that it is a worth-while study to pursue and to encourage.

The formation of many National Colour Groups and of the International Colour Association shows that colorimetry is recognised as an important subject in its own right, and the size and enthusiasm of our many international conferences shows that colorimetry is not only useful but a way of life for many of us.

This brings me back full circle to my opening remarks, and I can now say with conviction *Floreat Newton*. I wish he could attend some of our meetings.

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Some Historical Aspects of Vision Research in Scotland

At the second Scottish Symposium on colour (Edinburgh 1968) Professor R.W. Pickford gave a paper on this subject. This has subsequently been published under the title *Colour Vision research in Scotland in the first part of the 20th Century*.

It traces the history of colour vision research from its beginnings in Glasgow and follows its movements to and from Edinburgh and its eventual spread to Aberdeen and Ayr, transcending all the time the barriers of university disciplines.

It was from this paper that the inspiration came to invite Dr. R. Thouless to recall his research work on colour vision at a special meeting and dinner of the Scottish Group in April 1970.

At this meeting and afterwards at the Dinner, Dr. Mary Collins, Dr. R.A. Houstoun and Professor Pickford, who have all played leading parts in Scottish Vision Research, were guests of honour. The dinner was concluded with a toast to the guests by Dr. W.O.G. Taylor to which Professor Pickford replied.

Dr. Thouless' recollections have been published in this journal, and in order that they may be seen in the context of Colour Vision Research at that time,part,of Professor Pickford's paper is also reproduced.

During discussion after Dr. Thouless had presented his paper it was noted how frequently his experiments had touched on problems which are still relevant today.

Extracts from a paper by R W Pickford

THE WORK OF DREVER AND COLLINS

James Drever (1st) who was Professor of Psychology in Edinburgh, always took a keen interest in colour vision and its varieties and defects, and in theories of colour vision. He derived the Drever-Hilger spectrometer, and introduced Mary Collins to the study of colour vision. One of his most interesting writings on colour vision was his well-know introduction to her book *Colour Blindness* (1925). After explaining her intentions, and the purpose of her experiments, he gave some general facts about the subject of defective colour vision and its history from Dalton (1766-18434) onwards, which Collins followed up much more fully in her own introductory chapter.

An interesting paper was published by Drever in 1931. He discussed the question, "in what sense can we speak of primary colours?" He set out to contrast and criticise the artist's conception of primary colours (red, yellow and blue) with the physicist's (red, green and blue) from mixtures of which all other hues can be imitated, and to consider whether there is a really scientific and ultimate basis for the classification of colours into the primaries of the physicist. The artist's classification, of course, depends on the fact that it is satisfactory for him to use a yellow and a blue which, when mixed, transmit and/or reflect a large amount of green between them, whereas neither freely transmits and/or reflects the apparent colour of the other, but cuts it out. Drever, however, concludes that, if anything, the psychologist's classification of primary colours into red, yellow, green, and blue, which are psychologically (or phenomenologically) simple and stable, is the best, and that the physicists classification does not supersede that of the psychologist. This has much interest in view of what Houstoun and others said almost at the same time and later.

Drever and Collins started the systematic testing of printing apprentices in Edinburgh, which was still carried out regularly and had fallen into the hands of Lakowski and his colleagues. Drever and Collins also produced a group test of colour vision defects for use in schools (Collins and Drever, 1932 and 1935).

In 1925 Mary Collins, Lecturer and subsequently Header in Psychology in the University of Edinburgh, published her book on *Colour Blindness*, of which the writer bought a copy in Cambridge in 1929, a year before he first met her. She carried out tests on ten colour vision defective subjects, A to J. She was one of the first to make a systematic comparison of different tests, but she opened her book with a very interesting chapter on the history of studies of defective colour vision onwards from the case of Harris, reported in 1777 by Huddart. She dealt with yellow-blue defects and total colour blindness as well as with acquired and red-green defects. In her next chapter she discussed theories of colour vision with special reference to its defects. In this she gave an account of the theories of Young and Helmholtz, McDougall, Hering, MUller, Ladd-Franklin, Schenck and Edridge-Green, and these two chapters have formed a valuable introduction to the whole subject for many students since the book was published.

The remainder of the book is concerned with the detailed results of the tests she used on the ten subjects, and the conclusions she drew. The tests she used were:-

> Stilling's Pseudo-isochromatic Tables, Holmgren's, Wool Test, Colour Naming of the colours in these two tests, Colour Mixing with the Bradley coloured papers on the colour wheel, the Rayleigh Equation with rotating disks. Analysis of the Spectrum, a Test using the Bradley Coloured Papers, Contrast Experiments, the Nagel Card Test, the Edridge-Green Lantern, Roaf's Painting Test and a Test of Colour Preferences.

In her concluding remarks she suggests that the Hering, Young-Helmholtz and Ladd-Franklin theories all fit the facts of red-green colour vision defects when the condition is extreme, but seem to fail to take account of cases in which there is a less marked disability. She also mentions the inheritance of colour vision defects and their frequency in various populations.

Three papers on colour vision were also published by Collins. One of these was about the use of the Rayleigh Equation with rotating disks (1929), and another (1932) was about a study of immediate colour memory, concerning four spectral colours, red (670nm) yellow (588nm), green (535nm) and blue (460.9nm), with the Drever-Hilger Spectrometer, on six subjects. The third was a comparative study of tests in common use for the diagnosis of colour vision defects (1937) in which she also mentions the frequencies of these defects in various racial groups.

THE WORK OF HOUSTOUN, THOULESS AND PICKFORD

R.A. Houstoun, who was Lecturer in Natural Philosophy (Physics) in the University of Glasgow, became interested in the Rayleigh Equation, and built a spectral anomaloscope of his own design. He was also interested in other colour vision tests, such as the Edridge-Green Beads Test, and the writer remembers being tested by Houstoun with it in 1942. Houstoun presented him with his copy of the test twenty years later. Houstoun designed an instrument called the **Colour Patch Apparatus** for mixing colours produced with colour filters, and used it for a detailed study of colour vision defective subjects.

With his anomaloscope Houstoun tested 423 men and 104 women and showed how the normal curve of the distribution of the Rayleigh equations of those who were not defective compared with the scattered positions of the defectives. He recommended the use of the logarithm of the ratio of red to green, which was adopted by Collins in her paper on the Rayleigh Equation (1929). Houstoun's first paper on the Rayleigh Equation was published in 1922. In 1932 he published a book about *Vision and Colour Vision* in which he republished this research and others with it.

As a result of his experiments on colour vision Houstoun became a supporter of a modified form of the Hering theory. His arguments in its favour and his objections to the Young-Helmholtz Theory are published in his book (1932, chapter XIV). He drew attention to the distinction between "colour weakness" and "colour difference" in major defectives and those with ordinary or normal variations of colour sensitivity. Colour vision defect he thought, was due to an irregularity in the working of synapses. Those whom he called "colour different" have good colour discrimination, but the region of change-over of the nerve responses from one state (red) to the other (green) is displaced towards the green or the red, giving green anomaly or red anomaly, accordingly. In those he called the "colour weak" the region of change-over of the responses of many neurons is much wider than in the normal, but may or may not be displaced to one side or the other (1932, p.23l). These ideas would not be likely to be accepted today without change but they seemed to the writer to be such a clear interpretation of colour vision variations and defects that he started a long series of observations to test the hypotheses, using an apparatus which used yellow and blue, and other colour pairs, as well as the red and green of the Rayleigh Equation.

Houstoun's suggestion of opposite pairs of physiological responses, along the lines of the Hering theory as far as colour rather than brightness is concerned, has found support in recent work by a number of experimenters (see Pickford 1968c), but not at the receptor level, where the presence of only red, green and blue absorptive pigments is most likely. The distinction between colour difference and colour weakness has also proved important, as will be seen later.

Houstoun also dealt in his book (1932) with the Visibility of the spectrum, the laws of colour mixing hue discrimination data, recurrent vision, fatigue, after sensations and simultaneous contrast, Thus more than half of his book is directly related to problems of colour vision and its defects, experimental work on these problems, and theories of colour vision.

In a later paper (lG35) Houstoun developed some of his ideas further, and showed that a parabola can be a near fit to the CLE. Chromaticity diagram. In this paper he seems to favour a form of the Young-Helmholtz Theory.

R.H. Thouless, who was Lecturer in Psychology in the University of Glasgow, showed that there is a phenomenal difference between "whiteness" and "brightness", by his experiments on phenomenal regression (1932). He summarises his findings by saying, "For most subjects (but not all) the immediate experience of brightness is different from the immediate experience of whiteness, and when there is this difference, a subject's probable point of balance for equal apparent brightness of two papers of different reflectivity differently illuminated shows little relationship with his phenomenal regression for size and shape" (pp. 216-241).

He was also interested in phenomenal regression for colour, as in the experiment in which a white or grey disk is seen illuminated by light of a given colour, say red, and a disk of the same colour as the red light is illuminated by white light. The "real" colours of the disks may be compared if they are viewed side by side through a reduction screen which cuts out the appearances of the different sources of illumination. Their "apparent" colours may be compared when the reduction screen is removed, and the coloured illumination of the white or grey disk is seen in comparison with the white illumination of the coloured disk.

R.W. Pickford, subsequently Professor of Psychology in the University of Glasgow, became interested in the construction of a test for minor or normal differences in colour sensitivity which could also be applied to major defectives. He was introduced to the Rayleigh Equation by Collins and set up a series of experiments, at first with rotating disks, using Hering's coloured papers and Marbe Rotators, and later changing to an anomaloscope using Ilford Spectral Colour Filters. The experiments were aimed in the first place at testing Houstoun's hypotheses, mentioned above, and two colour equations were used at first, namely red-green and yellow-blue. In a later series five pairs were used, red-green, orange-bluegreen, yellow-blue, yellowgreen-purple and green-magenta. Altogether more than 1000 subjects, mostly adults, were tested. An interest was taken in: (a) the distribution of variations of mid-matching point and matching range among normal subjects; (b) the same variations among colour defectives; (c) the dimensions of colour vision variations as shown by factor analysis; (d) the frequencies of variations and defects in the Vest of Scotland and among other peoples; (e) the inheritance of colour vision defects; (f) the construction of a portable filter anomaloscope; and (g) theories of colour vision.

Many of the results of these experiments were reported in a book about individual differences in colour vision (1951),and the author's publications on colour vision and defective colour vision include about sixty papers and articles. Among these it will be sufficient to mention a book on the inheritance of colour vision defects, with R. Kherumian (1959), a chapter on the inheritance of these defects in the C1BA book on colour vision (1965b), a paper on the Pickford-Nicolson Anomaloscope (now manufactured by Rayner and Keeler, London), jointly with Dr. R. Lakowski (1960), and a paper on anomaloscope tests and colour vision theories (1967b).

Pickford found that his results were in line with and supported the claims of Houstoun, especially in the significance of opponent colour functions and the distinction between colour difference and colour weakness. Colour difference is seen in all deviations of mid-matching point in the Rayleigh and other colour equations, both among normal subjects and in the protanomalous and deuternomalous. Colour weakness is seen in enlargements of the matching range in normal subjects as well as in the anomalous and dichromats, where it reaches extreme proportions. The data on heredity supported the sex-linked nature of major red-green defects together with the dominance order for protan and deutan alleles and the two-locus theory of their inheritance, and showed evidence for heterozygous manifestation (1959), and variability of manifestation of deuteranomaly (1967). The study of racial differences led to the support of the hypothesis of relaxation of natural selection against defective colour vision with increasing civilization (1963). The study of individual variations in relation to occupation led to the discovery of colour vision defective artists and students of art, about whom the writer is now compiling a book, but references to this section of his work may be found in the writer's papers on colour defective artists (1964, 1965a, 1972, 1969).

Pickford received much encouragement and support from WJ.B. Riddell, Professor of Ophthalmology in the University of Glasgow, who was keenly interested in the genetics of colour vision defects, and the practical aspects of the study of individual differences in colour vision in art and industry (Riddell, 1949).

An important outcome of the whole research was the construction of a portable anamaloscope which could be used with several voltages, and on 12 volt car batteries if necessary, and which would give bright enough spots of light to be visible in a not very brightly lighted room, in such a way that the spots being compared by the subject were seen by him without an optical eyepiece and could be viewed by the experimenter at the same time. Such an instrument would be a valuable aid in research on colour vision differences under various conditions and in different populations, and the construction of the provisional model was sponsored by the late W.B. Nicolson, and later by the *International Biological Program*, Section HA, *Human Adaptability*, and supported by the Medical Research Council. The writer hopes that it will be more understood that the proper use of the anomaloscope depends on the distinction between matching range and deviation, representing, as they do, colour weakness and colour difference. Early use of the anomaloscope was at a disadvantage because only deviation was considered. If both are properly taken into account, together with the darkening of the red in protans, then the anomaloscope will be found to be better than any other test for normal variations and for major defects of colour vision.

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My Researches into Colour Vison

R.H.Thouless

I have always been interested in the problems of colour, and this interest was stimulated further when, after an address given in Glasgow, an optician presented to me a colour mixing instrument (for the laboratory). This instrument produced spectra by a diffraction grating which has now I understand been cleaned off by a too conscientious lab steward. It was not a precision instrument, since it had no wavelength calibration and there was no second colour patch with which the mixed colours could be matched. Nevertheless it was an interesting instrument to play about with but not, I think, particularly useful for the solution of any research problem.

When I went to Cambridge in 1938, I found a much more satisfactory instrument for research in colour vision. This was Nagel's anomaloscope, an instrument designed to apply Rayleigh's test for anomalous trichromacy by mixing spectral red and green lights to match a spectral yellow light. The relative brightnesses of the red and Jihe green could be adjusted until an exact match was obtained, the-idea being that the proportions of red and green required to make the: match were different for the anomalous trichromat. This difference was either in the direction of requiring more red or more green, giving the two classes of anomalous trichromats, protanomalous and deuteranomalous. The effect of trying the anomaloscope test on a true dichromat is interesting although perhaps predictable; he will accept any ptuportion of red and green light as a match for the yellow, requiring only a suitable adjustment of the total brightness of the mixture to make a perfect match.

The Cambridge Psychological Laboratory had other attractions for research in colour vision as well as its posession of an anomaloscope - it was very fortunate in the number of the members of the laboratory who had a colour defect. Two of its quite small teaching staff were anomalous trichromats with marked green weakness, and one of its two laboratory stewards was a dichromat (protonope). My note books show that these members of the laboratory were generous in the time they gave up to being experimented on by me; I am grateful to all of them. Amongst the students, there also turned up two dichromats (a protonope and a deuteronope) and an anomalous trichromat with weakness in the red. I have often had the impression that defects in colour vision are more common among psychologists than in the general population, but this must have been an unusual richness even in a psychological community.

My thoughts on colour problems have always been much influenced by the views of Hering and Ostwald. It was during these early years that I formed the opinion that colour theory can start better from the phenomenological facts of the colour solid than from Newton's observations on the spectrum. The basic fact of the colour solid is that for a person of normal colour vision, all colours of any single 'mode of appearance' can be represented three-dimensionally on a sphere or on some equivalent figure. Such a figure will have saturated hues round its equator, the colours without hue from white to black along its axis and the full range of unsaturated hues in intermediate positions on the surface or in the interior of the solid. The metrical characters of the colour solid will depend on what convention is adopted as to positions of these intermediate colours. Thus two metrically different but topologically equivalent colour solids will result either from the conventions (l) that the position half-way between any two colours is occupied by the colour produced from a mixture of equal parts of those two colours, and (2) that the half-way point is occupied by the colour which is an equal sensory inter¥al from the two colours it lies between. These conventions give two metrically different colour solids, both valid as representations of the phenomenological facts of colour relations.

The phenomenological facts of colour vision are not, to my mind, properly described by saying that all colours can be represented as elements on a single three-dimentional solid; one must add the limitation that this applies to all colours of a single mode of appearance. The modes of appearance of colours are the differences, discussed by Katz in *The World of Colour* (1935), between 'surface colours', 'film colours', 'glossy colours' etc. A film colour, such as the yellow seen in a spectroscope, has no place in the colour solid of surface colours since, although it may be matched for hue somewhere in the hue ring of this colour solid, it can not with any certainty be matched for brightness. As a further example, the greys and browns of the surface colour-solid do not appear to be represented as greys or browns in the solid of film colours although this contains the full range of possible brightness of white and of orange. One must therefore think of a number of colour-solids corresponding to these different modes of appearance of colours, solids that have certain correspondences although they are not identical.

One somewhat unfruitful line of experimental enquiry in which I became involved was started by a report from Dr. Gibson of Glasgow that, by wearing tinted glasses, he was led to make matches identical with those of a dichromat. I tried looking through variously hued films at test objects, and also I tried the effect of wearing coloured goggles for a long time in order to induce hue fatigue. It was possible by both methods to reduce the apperance of the hue ring to the condition in which two complementary hues were seen at opposite points of the ring with unsaturated hues lying between, but by neither method could I produce any tendency to make dichromatic responses to the Ishihara colour test. There remained differences in brightness which made the test numbers stand out clearly when they would have disappeared for the person with dichromatic vision. I concluded that it was not possible to simulate dichromacy in the person of normal colour vision either by the use of vision through films or by producing fatigue for certain bands of wavelengths. At the same time it must be admitted that I did not explore the possibilities very thoroughly. Someone else may now have produced artificial dichromacy by such methods.

There is one observation that I made while experimenting on colour vision which is more or less predictable but which, so far as I know, has not been reported. This is the effect of giving instructions to colour blind persons that would lead a normally sighted person to construct the hue ring. If a normal person is given a patch of surface colour of a saturated yellow and the remaining 23 colours of Ostwald's hue ring and is instructed to arrange them so that any two neighbouring patches have the least possible hue difference, he will either produce a figure which is the normally accepted hue ring or else a straight line with minimal hue difference between the two ends.

A dichromat gives a startlingly different result. A deuteronope on whom I tried the experiment gave the order (using Ostwald's hue numbers): 2,1,3,24,14,13,12,16, 11,15,17,10,18,19,20,9,21,8,22,23, 4,7,5,6. Asked where were the points of maximum and of minimum hue saturation, the subject pointed to the range from 2 to 3, to the 13, and to the 6 as points of maximum hue, whereas the minimum was at 21 where the colour was reported to be grey.

A protonope gave a somewhat different arrangement: 1,2,24,23,3, 22,21,4,5,6,7,8,9,10,11,13,12,14,15,16,17,18,19,20. He reported maximum hue saturation over the regions 1,2 and 11,13, while minimum hue saturation (a grey colour) was found at 21 and over the region 20,19,18.

In words,the deuteronope's arrangement of the saturated hues started as orange-yellow, lemon-yellow, orange, yellow-green, cobalt blue, ultramarine, violet, ... , while that of the protonope started as lemon-yellow, orange-yellow, yellow-green, orange, middle green, ... Both are very different from the arrangement acceptable to the normally sighted person. This is quite a striking way of displaying colour defect; I did not pursue the matter far enough to find out whether it is of any diagnostic value. One would have to try this experiment with a much larger number of dichromatic subjects to know whether the differences in the arrangements by my protonope and my deuteronope were really diagnostic of the differences between their colour defects or whether they were merely idiosyncracies of these two subjects.

It must have been a few years after 1 went to Cambridge that 1 began to speculate as to how differences in colour vision might be represented as differences in the geometrical characters of the colour-solids of different individuals. 1 did not take for granted that there were discrete differences between dichromats, anomalous trichromats, and those with normal colour vision; it seemed likely that there might be a continuous gradation between them. Whether or not they were separable conditions, I wanted to devise a method of specifying them as differences in the character of the colour solid and to find ways of measuring this difference experimentally. The colour vision of any individual could then be specified in terms of the metrical properties of his colour solid. I made two attempts at the solution of this problem; both were failures. As failures they have not been published, but I am glad of this opportunity of giving a brief account of what I was attempting. If there is anything in the idea I was trying to develop (of which I have not much hope) someone else may succeed in making it usable.

The hypothesis I had in mind started from the fact that, if the iphenomenology of normal colour vision could be represented by the colour solid, that of dichromatic colour vision could be represented by a two-dimensional figure which I is an axial cross section of the colour solid. It is, in fact, a circle with two contrasting hues at opposite ends of one diameter and the various degrees of desaturation of those hues through a neutral grey along that diameter, while the series of unhued colours from white to black lies on a diameter at right angles to this. The colour situation of a particular dichromat could, in principle, be described by specifying the angular distance round the hue circle from some arbitrarily chosen starting point at which this axial section is made. It would be convenient to follow Ostwald's convention of treating yellow as the starting point and measuring the angles round the circle from this position. I had one protonope and one deuteronope on whom I could make the necessary observations; neither then nor at any other time have I been fortunate enough to find a tritanope.

To estimate the angle of section of the dichromat, one can either determine the positions on the hue circle at which he sees a neutral grey or those at which he reports maximum hue. Using a circle of surface colours one finds that both protonope and deuteronope report a neutral grey at about 300° (middle green); maximum hue falling at 180° (ultramarine blue) and also at about 0° (pure yellow). The only apparent difference was that the protonope showed a much wider neutral band extending to 255° (turquoise). This would suggest, for both protonopes and deuteronopes, an angle of section at about 0° on this scale.

These quantitative results are not, of course, to be taken as more than preliminary findings. They were based on only two cases and should have been checked by experiments with spectral colours. Their indications give some encouragement to the idea that dichromacy may be specified as a particular kind of cross-section of the colour-solid. They obviously give little encouragement to the idea that the kind of dichromacy can be specified by the angle that this section makes on the hue circle.

That the angle of section of the colour solid might provide a new way of specifying the kind of dichromacy was not, however, my principal concern which was rather with the possibility of using the metrical properties of the colour solid to specify the type and degree of a colour anomaly. The main point of the hypothesis that I then had in mind was that,just as dichromacy might be considered as a collapse of the colour solid to a two-dimentional figure which was one of its axial sections, so anomalous tri-chroraacy might be regarded as partial collapse of the colour solid, its equatorial section (the hue circle) becoming elliptical. Thus, for the anomalous trichromat, the full range of hue variation might be present along the long axis of this hue ellipse (let us say, blue-yellow) while there was a restricted range of variation of hue saturation along the axis at right angles to this (turquoise-red). The measurements required would be those of the number of steps of just noticeable differences of saturation in various directions from the centre of the hue ellipse. If these measurements could be successfully carriec out, it was my hope that they would give the experimenter, for any particular experimental subject, a measure of the angle of the long axis of his hue-ellipse and a measure of its degree of ellipticity (the ratio of the short to the long axis). These two measurements would specify the kind and degree of colour abnormality of any particular subject in a purely phenomenological manner without reference to any colour theory. They would also enable one to determine whether classes of colour defect distinguished by such tests as the Stilling and Ishihara were separate classes or whether there was continuous variation between them.

I still think that all degrees and kinds of colour defect might have been specified by these measurements, and that many of the puzzles of colour defect might have been resolved by them, but I have to admit that I did not succeed in making the proposed measurements although I gave much time and trouble to preparing tests for this purpose.

My first idea was to use the anomaloscope for the purpose of making the required measurements. The construction of this instrument does not limit one to the Rayleigh equation; one can adjust it to other pairs of wavelengths than the red and green. It would not, of course, enable one to explore the whole hue circle, since part of this is not matched by any spectral light, but one could explore about three quarters of it. I was, however, deterred from its use for this purpose by finding an unexpected difficulty in using the anomaloscope as an instrument of precision. I noticed first that, in making the Rayleigh match of yellow light with mixed red and green, the same individual gave significantly different proportions for his matches on different days. I eliminated lamp colour variations by using a battery but still found day-to-day variation in the readings and finally decided that this was probably due to differences in the state of colour adaptation of the subject's eyes through difference in the colour of the daylight under different weather conditions. This seemed an interesting possibility but it was not my concern at that time. I gave up the attempt to use the anomaloscope for this purpose and decided instead to use surface colours as my experimental material.

For this purpose, I prepared a number of squares painted with gouache to match various degrees of saturation of hues in seven directions from the centre of the hue circle. A similar set of squares in the direction terminating in ultramarine blue was used as standard. The experimental subjects were required to match for saturation each of the variable squares with the appropriate saturation of ultramarine. The instruction was to say which of the standard ultramarine squares had "as much colour (or hue) in it" as the given square which showed some degree of saturation of some other hue.

I hoped that this task would be carried out by subjects in such a way that I could see at once to which hues they showed diminished sensitivity. I found in fact that I could not get sufficiently consistent answers to draw any conclusions whatever. The task of making judgement of hue saturation seems to be beyond any subject who is without a considerable degree of psychological sophistication and it is not easy for those with psychological training. A particular difficulty is that an unsaturated orange may be seen to have a lot of 'colour' or 'hue' in it, but this colour is brown not orange. In general the task could not be carried out by the subjects in any way that gave an answer to my question. It seems, from my notes, to have been about 1942 that I gave up the problem. I was not convinced that it was insoluble, only that it was not to be solved by me. Perhaps some time someone else will revive the elliptical hue hypotheses and find out how to make the measurements that 1 did not succeed in making.

Finally, I should like to give a brief account of the one research on a problem in colour vision which I carried to a successful conclusion and published (B.J.P. XXII, p.l ff.). This was an experiment carried out before I left Glasgow and before I started my unsuccessful attempt to solve the problems of colour defect. It was published a long time ago (in 1931) and I think it is safe to assume that it has been forgotten so I may be excused for reviving it.

The problem that worried me was as to why, although we can demonstrate the phenomena of simultaneous induction of complementary colours under the special conditions of the psychological laboratory, we do not generally see them in the perceptual field of everyday life. There is laboratory evidence that the shadowed part of a red object will set into action the retinal process that should produce a sensation of the complementary green; Most of us do not however see such shadows as green. When the impressionists paint green shadows on human faces, the average man might be persuaded to accept this as a physiologically correct statement, but still insist that this was not how face shadows looked to him, however red the face might be. That at least is what most people are inclined to say on the matter and it is what I should say myself. Some others report that they do see complementary colours in shadows, and it may well have been the case that the leaders of the impressionist school of painters were amongst those for whom complementary colours in shadows are a perceptual reality.

It seemed to me that both the normal non-perception of coloured shadows and the individual differences in whether they were percieved or not might be explained if this tendency to perceptual nonappearance of colours in shadows were regarded as an example of the general tendency of objects to be perceived as more like reality than would be predicted from their stimulus conditions. I had earlier studied this tendency in the perception of shapes at different inclinations, of sizes at different distances, and of brightnesses under different illuminations and called it 'phenomenal regression.' (B.J.P. XXI, 339 ff.).

I arranged an experiment to test this hypothesis in the following way. A circular disc of green paper (Zimmermann's L) was mounted on cardboard. In this disc, an aperture was cut in the shape of a cross, immediately behind which a Marbe colour wheel was rotated- On the colour wheel were mounted a paper of the same hue as the disc itself together with a grey paper of the same brightness. The aperture could therefore be filled with any of the series of colours ranging from neutral grey to a green which was the same in hue and saturation as the background. The object was to discover at what point of saturation the cross began to be seen as green, and at what point the retinal process began to be of the green-sensation kind rather than of the red-sensation kind. The first question was anwered simply by the report of the subject as to whether the cross 'looked to him' to be reddish, grey, or greenish. The answer to the second question was obtained by instructing the subject to fixate one of the inner corners of the cross for 30 seconds and then to look at a screen of neutral grey and report the colour of the after-sensation of the cross.

When the cross was physically of a pure grey, all four subjects involved saw it as a reddish hue since conditions were favourable to colour contrast. As green was added on the colour-wheel, this reddish appearance diminished and finally disappeared; the cross was seen as a neutral grey although it still gave a green after-sensation, showing that the red process had in physiological fact predominated on this part of the retina. Only when the green constituent on the colour wheel was still further increased, did the greenness of the after-sensation disappear altogether showing that the red-process no longer predominated on the retina.

This is exactly parallel to the kind of thing that happens in phenomenal regression. The apparent shapes of inclined objects and the apparent sizes of objects at different distances are not those predicted from the conditions of peripheral stimulation but are a compromise between this and the 'real' shapes and sizes of the objects. In the present experiment too, there is a point of balance at which the retinal stimulus is (as a result of colour contrast) such that it would by itself produce a red sensation; the object is however, in physical fact of a greenish hue, and the apparent grey colour of the cross is a compromise between the reddish stimulation and the greenish reality. Below this point of balance, there is a region in which the real colour is only slightly green and the reddish contrast stimulation predominates sufficiently to make the apparent hue a reddish one although this is a more unsaturated red than would be produced if the conditions of peripheral stimulation were uninfluenced by the real colour. Here top, as also in the region above the balance point where the apparent colour becomes greenish in hue, the law of phenomenal regression is found to hold, the apparent colour being a compromise between the stimulus colour and the 'real' or physical colour of the object.

These experiments seemed to me to indicate strongly that the law of phenomenal regression explained why colour contrast effects are much less common as perceived phenomena than they are as facts of retinal physiology. If this were the explanation, one would expect to find considerable individual differences in the extent to which contrast colours are seen, since there are considerable individual differences in other aspects of phenomenal regression. One would expect also that the non-appearance of contrast colours would be correlated with phenomenal regression as measured in other perceptual situations.

The expectation that the effect would show wide individual differences was, in fact, fulfilled. The proportion of the peripheral retinal process that appeared to have been eliminated by phenomenal regression ranged from 17.5% for the subject R.P. to 83% for the subject K.F. I do not seem to have recorded the index of phenomenal regression in other perceptual situations for all the subjects, but I did note that the subject R.P., who showed least elimination of the contrast colour, had also shown low phenomenal regression in other experiments. This, of course, is in line with what my theory would lead me to expect. He also reported that, in everday life, he did commonly see contrast colours in shadows. Unless my memory is at fault, the subject K.F. was one who showed high phenomenal regression in other experiments, as would also be expected from the theory.

A further expectation from the theory would be that the appearance of colour contrast would be heightened by any perceptual factor that reduced phenomenal regression. An easily controllable factor affecting the amount of phenomenal regression is the degree to which the possible area of contrast colour is seen as an object segregated from its background. This separation is enhanced by the sharpness of the outline and, as is well known, this also determines the intensity of contrast colour, which is increased if the outline is confused.

A quantitative determination of the extent to which this takes place was made with the subject K.F. when the outline of the cross was confused with tissue paper, the reddish coloration persisted until a much larger quantity of green had been introduced into the figure. It appeared, in fact, that whereas 83% of the contrast effect was eliminated by phenomenal regression when the cross was observed in the ordinary way, only 25% of it was eliminated when the cross was seen through tissue paper. This also agreed with the expectations roused by the view that elimination of contrast colours is an effect of phenomenal regression.

So far as I can remember, this investigation of the relationship of colour induction to phenomenal regression is my only published contribution to research on colour. My notebooks show that I was still doing experiments with my own laboriously prepared colour material for fifteen years after that, but nothing was sufficiently matured for publication. It may seem that this was a very small mouse to come out of such a mountain of effort. Perhaps it was, but I have no particular regrets in the matter. The effort itself was great fun, and it taught me a lot about colour vision although it may not have contributed appreciably to the knowledge of other people.

Physics Exhibition - 1971

Comment by C I Boltz (Physics Bulletin 22, 204, Aptil 1971)

"There is a lot of interest in displays. Naturally the sort of display we are all familiar with is our natural environment and in this connection the Colour Group has broken away from preoccupation with measurement and is showing 'perceived' colour investigating how to relate this to the known specification systems that are so unconvincing to people who are not colour scientists."

Some Other Turbid Medium Theories

S.E. Orchard

A paper given at the March 1970 meeting of the Colour Group

INTRODUCTION

Turbid medium theories are nowadays widely used in the paints, plastics, and textile industries for colour match prediction, that is, finding the colorant mixture that will match a given sample for colour. Whether the match is spectrophotometric (non- metameric) or colorimetric (possibly metameric) is irrelevant here, since all theories deal with only one wavelength at a time.

In this short account, the discussion is limited to the diffuse reflection of light by fully opaque mixtures of colorants. The reflectance of the colorant mixture at any particular wavelength is **not** simply related to the reflectances of the component colorants, but colour match predictions always assume that reflectance is determined by certain constants that **are** additive. Such constants must surely be determined by the average probabilities that a photon will be absorbed, or scattered through a particular angle, in a typical small volume in which only single scatter takes place.

In industry, the theory of Kubelka and Munk (here abbreviated to KM) is almost the only one known for deriving additive 'constants' from reflectance data. For simplicity, the KM theory considers only the (scalar) flux and not the (vector) intensities, so that there are only two parameters, one for absorption (K) and one for backscatter (S). It is usual to derive the formulae by setting up differential equations for the backward and forward fluxes, integrating, and fitting the boundary conditions. A simpler derivation using more physics and less mathematics is given in ref. 1, where the limitations of KM theory were also noted. Such a theory, which does not say anything about the angular distribution of the reflected light, does not lead to a very satisfactory allowance for the internal surface reflection, which is important with gloss paints and plastics. It appears that the errors in using the usual simple allowance are at least as large as the errors in predicting the flux in the absence of surface reflection (ref. 2).

In the present discussion, other approaches and results are indicated briefly, and it is hoped that these will stimulate thought and thus help towards better-based and more accurate algebraic formulae for routine use. Predictions from such formulae can be checked against exact radiative transfer theory (refs. 3 and 4) without obfuscation by random experimental errors. For -simplicity, only **isotropic** scattering is considered.

All results are presented finally in terms of the true constants of single scatter rather than in terms of the 'adjustable parameters' K and S. Thus:

α = absorption per unit length)

σ = scatter per unit length)

both above for parallel light.

$$\omega = \frac{\alpha}{\alpha + \sigma}$$

where ω is the probability of photon survival in an encounter (dimensionless)

$$\tau = (\alpha + \sigma)x$$

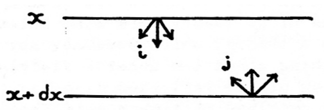
where τ is optical depth (dimensionless) and R is total diffuse reflectance.

{Note: ω may be thought of as the concentration of white in a mixture of a perfect unit white, ($\alpha = 0, \sigma = 1$) with a perfect unit black ($\alpha = 1, \sigma = 0$)}

DESCRIPTION OF THEORIES

a) KM 2-Flux Theory

Consider the balance of energy across a typical thin slice of the mixture:



On the assumption that the intensity distribution is of constant form, we have:

$$\frac{di}{dx} = -(S + K)i + Sj$$

$$\frac{dj}{dx} = +(S + K) - Si$$

whence $$\frac{d^2i}{dx^2} = K(K + 2S)\, i$$

For isotropic scattering, S = ½σ; K = α; so that $\frac{d^2i}{d\tau^2} - (1 - \omega)\ i = 0$

The solution for an opaque layer with incidence and collection in the same angular form as assumed is:

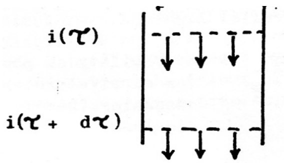
$$R = \frac{1 - \sqrt{1 - \omega}}{1 + \sqrt{1 - \omega 1}} \quad (1)$$

or

$$\frac{\omega}{2 - \omega + 2\sqrt{1 - \omega}}$$

b) Diffusion Theory : One Dimension

By considering a different physical picture the same result can be obtained as with the KM 2-Flux Theory.



Let n = number of photons per unit volume

i = photon current density

For simplicity, let photon velocity = 1. Then

$$i = \frac{-dn}{d\tau} \quad \text{(Law of Diffraction)}$$

$$\frac{di}{d\tau} = 0 - (1 - \omega)n$$

(Photon balance for isotropic scattering)

$$\text{Therefore } \frac{d^2 i}{d\tau^2} - (1 - \omega)\, i = 0$$

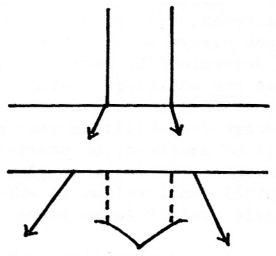
The appropriate solution is identical with the KM result:

$$R = \frac{1 - \sqrt{1 - \omega}}{1 + \sqrt{1 - \omega}} \quad (2)$$

Diffuse incidence **plus** diffuse collection are never used in practice, and three-dimensional situation is more realistic.

c) Diffusion Theory : 3

Assume a beam of directed photons at normal incidence which generates diffuse photons in a slab at a rate $\omega e^{-\tau}$



Then

$$i = -\tfrac{1}{3}\,\text{grad}\; n \quad \text{(Law of Diffraction)}$$

$$\text{div}\; i = \omega e^{-\tau} - (1 - \omega)n$$

(Photon balance for isotropic scattering)

Therefore $$\frac{d^2 i}{d\tau^2} + \omega e^{-\tau} - 3(1 - \omega) \quad i = 0$$

The appropriate solution is:

$$R = \frac{3\omega}{[1 + \sqrt{3(1 - \omega)}][(3 + 2\sqrt{3(1 - \omega)}]}$$

or

$$\frac{\omega}{3 - 2\omega + 5\sqrt{(1 - \omega)/3}} \qquad (3)$$

which is approximately

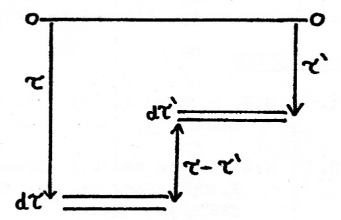
$$\frac{1 - \sqrt{1 - \omega}}{1 + 2\sqrt{1 - \omega}}$$

For anisotropic scattering, equation (3) is modified to include the mean cosine of the angle of single scatter (Ref 5).

d) <u>Photon Exit : 1 Dimension</u>

This is the one dimensional version of a very powerful method (Ref 6) and brings out the probabilistic nature of the phenomenon.

Consider the probability $p(\tau)$ of exit from the medium of an incident photon intercepted at an arbitrary depth, and then sum all such probabilities.



For an incident photon intercepted in a layer dτ , the probability of sirvival = ω ; some survivors exit directly with a probability of ½$e^{-\tau}$,and the other survivors are intercepted in a higher or lower layer such as dτ' with a probability of $e^{-i\tau - \tau' i}$ dτ'

The total probability of exit $p(\tau)$ must now satisfy the **integral** equation (which includes the boundary conditions):

$$p(\tau) = \frac{\omega}{2} e^{-\tau} + \frac{\omega}{2} \int_0^{inf} e^{-i\tau - \tau' i} p(\tau') d\tau'$$

The solution is $p(\tau) = (1 - k)e^{-k\tau}$ where $k = \sqrt{1 - \omega}$

This one-dimensional treatment naturally gives the same answer as KM theory.

$$R = \int_0^{inf} e^{-\tau} p(\tau) \qquad d\tau = \frac{1 - \sqrt{1-\omega}}{1 + \sqrt{1-\omega}} \qquad (4)$$

e) Photon Exit : 3 Dimensional Single Scatter

The treatments discussed so far show clearly that the square root term arises from diffusion, and it might be expected that this would disappear with dark colours ($\omega \ll 1$) where the probability of multiple scatter becomes very small. The total reflectance for normal incidence for isotropic single scattering can be obtained conveniently by the method of photon exit in three dimension.

For an incident photon intercepted in layer dτ , the porbability of survival and rebound in unit solid angle around an angle θ with normal is ω/4π . For $\omega \ll 1$, we have only to consider the subsequent probability of direct exit = $e^{-\tau \sec \theta}$.

Then $$p(\tau, \theta) = \frac{\omega}{4.\pi} e^{-\tau \sec \theta}$$

Total probability of exit in direction θ is :

$$\int_0^{inf} e^{-\tau}\ p(\tau\,,\theta) \qquad d\tau \ = \ \frac{\omega}{4\pi} \,.\, \frac{1}{1\ +\ sec\,\theta}$$

The total reflectance R is then :

$$R\ =\ \frac{\omega}{2}\int_0^{\pi/2} \frac{sin\,\theta\ d\theta}{1\ +\ sec\,\theta}$$

$$=\ \frac{\omega}{2}\ (1\ -\ ln\,2)\ \ =\ 0.153\ \omega \qquad (5)$$

REMARKS

The method of photon exit in three dimensions yields all the results of exact radiative transfer theory; furthermore, it also enables physical significance to be attached to functions that arise in the theory.

A number of other treatments are possible, but most of these are clumsy and do not help one's understanding- For instance, the four constant theory of Ryde leads again to equation (l) on the assumption of diffuse incidence **and** collection, while for parallel incident light it leads to a cumbersome expression of doubtful value or significance.

COMPARATIVE RESULTS

In Table 1, this asymptotic formula (5) is compared with the results of exact radiative transfer theory, and also with an asymptotic formula for ω-> 1 (Ref. 7). It is clear that there is a large gap between the two formulae, and that the multiple scattering formula covers a much wider **reflectance** range (although a similar range in ω).

Table 2 indicates the relative merits of the KM and diffusion theories for predicting the reflectances of a range of simulated pigment mixtures. These mixtures comprise an isotropically scattering 'unit white' ($\alpha = 0$, $\sigma = l$) and a 'unit black' ($\alpha = 1$, $\sigma = 0$). For this case, the concentration of white is identical with ω , and exact total reflectances have been tabulated (e.g. ref. 5). These reflectances were treated as experimental results at known concentrations, and for each theory, the **absorption co-efficient of the black** pigment was allowed to change from an initial value of 1 until a best-fit (in the least-squares sense) was obtained between the 'experimental' and the theoretical reflectances. The best-fit value of the absorption co-efficient of the black was 1.85 for KM theory and 1.07 for diffusion theory, which indicates the greater physical truth of the latter. Table 2 shows that diffusion theory also gives more accurate reflectance predictions (maximum error -0.3%) than does KM theory (maximum error +0.9%) in the case of **isotropic** scattering. However, both theories show a systematic lack of fit, although in opposite senses (compare with Fig. 1 of Ref. 2); this indicates that neither model is really adequate. No doubt the fit would be much better if the darker shades were excluded, which involve mainly single scatter. For the strongly anisotropic scattering; that usually occurs in practice, it may also be desirable to include a parameter to allow for this, as is done in the Eddington theory (see e.g. Ref. 5), although this by itself will not enable dark shades to be dealt with very satisfactorily.

SURFACE REFLECTION

Finally, in the case of gloss paints and plastics, the importance of an adequate allowance for internal surface reflection should not be forgotten. The simple formula commonly used (usually attributed to Saunderson) is not good enough for accurate predictions over a wide range of reflectances, or in other words, the internal reflectance 'constant[1] is not constant. There is not space here to discuss this further, and a valuable treatment has already been published (Ref. 8). A convenient but apparently little used method for determining this internal reflectance 'constant[1] has also been described in the literature (Ref. 9).

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TABLE 1

Total Reflectance (R) of Isotropic Diffuser for Normal Incidence; Asymptotic Formulae

Table 1 is on the next page.

Notes for Table 1:

$$* R \rightarrow \frac{1 - 1.176\sqrt{1-\omega}}{1 + \sqrt{3(1-\omega)}} \quad \text{for } \omega \rightarrow 1$$

$$** R \rightarrow ½\psi\omega(1 - ln\, 2) \quad \text{for } \omega \rightarrow 0$$

TABLE 1

Single-Scatter albedo (W)	True R (Rad. Transfer)	Asymptotic R	
		Multiple Scatter*	Single Scattert
.999	.913	.913	.153
.995	.817	.817	.153
.99	.753	.752	.152
.975	.641	.639	.150
.95	.536	.531	.146
.925	.467	.460	.142
.90	.415	.406	.138
.85	.340	.326	.130
.80	.285	.267	.123
.70	.209	.183	.107
.60	.156	.122	.092
.50	.115	.076	.077
.40	.083	.038	.061
.30	.057	.007	.046
.20	.035	-.020	.031
.10	.016	-.044	.015

TABLE 2

Total Reflectance (R) of Black/White (Isotropic) Mixture For Normal Incidence; Best-Fit Predictions

Cone, of White (C)	True R	Predicted R	
		KM (eqn 1) $\alpha = 1.85$	Diffusion (eqn 3) $\alpha = 1.07$
.999	.913	.918	.911
.995	.817	.825	.814
.99	.753	.762*	.750*
.975	.641	.649	.638
.95	.536	.511	.534
.925	.467	.470	.466
.9	.415	.416	.415
.85	.340	.337	.341
.8	.285	.280	.287
.7	.209	.201	.211
.6	.156	.148	.158
.5	.115	.108	.118
.4	.083	.077	.085
.3	.057	.052	.059
.2	.035	.032	.036
.1	.016	.015	.017

*Worst predictions.

Colour in Therapy

M.H.Wilson

A Paper given at February 1971 meeting

INTRODIUCTION

This paper does not put forward a theory of colour therapy but describes some experiences which have been collected over a number of years in a privately run home-school for mentally subnormal children.

PAINTING THERAPY

At our most advanced level we have a class for disciplined painting with children aged 11-16 who have already learnt to paint crude action-and-mood pictures on wet paper. Many of these children are severely subnormal and none of them are capable of understanding the laws of proportion or perspective. Here they learn to stretch their paper on boards and then to lay successive washes of colour on the dry paper, allowing each wash to dry before applying the next. Through copying the teacher stage by stage they learn to build up a simple picture in terms of flat washes. They discover what happens when successive washes of the same colour are applied and what happens when washes of different colours are superimposed. They also learn the significance of an empty space left by a surrounding wash. In one exercise a lunar landscape is built up in which the light of a crescent moon is pale yellow while the surrounding darkness is in terms of blue, green and brown for sky and earth. Through repeating this exercise the child learns not only the discipline of clean painting, but learns to feel the working of the yellow as a source of light, and the enclosing and darkening activity of the surrounding blue and green. Another exercise is the study of a candle flame, in washes of warm colours. Such work stimulates them to observe their surroundings and also helps to co-ordinate hand and eye. The devotion with which they learn to handle their materials is impressive to watch, and is itself a therapy. The process is a long and slow one, but the results are highly prized.

Action-and-mood painting is done by a whole class with their class-teacher. Ket paper, large brushes and liquid colours are put before them. They may illustrate the action of a story that is told to them, or perhaps the moods of nature in the different seasons of the year. The results are crude, but are completed in the course of a single lesson, and the children are enabled to live in the expressive power of the different colours.

At this level a child will sometimes reveal its particular pathology without knowing. Whereas it may think it is painting a house or a forest or a man or a boat, the actual forms which appear may be an unconscious representation of its own inner condition. If such a child is allowed to choose his colours and to cover the paper just as he will, he may provide important diagnostic material. We have seen children paint unmistakable forms of erupting teeth while they were teething, or of semi-circular canals during an ear infection, of an obstructed colon prior to appendicitis, or of a rash of red blobs while sickening for measles. An epileptic child would signal the approach of an attack by painting a picture with a blue-black sky; when the attack has passed he would paint in light clear colours once In these cases the children were quite incapable of understanding what they were actually painting. It is therefore clear to us that the same formative forces which are at work in the physiological processes are expressing themselves in the painting activity. The less the intellect interferes, the more strongly does this expressive force show itself.

COLOUR - PROJECTION ROOM

For children at a still lower mental level and who cannot manage to use a brush at all we have designed a small colour-projection room where the child merely sits in front of a projection screen and watches what happens. No other activity is asked of it.

A long narrow room is divided by a translucent back-projection screen, and slide projectors with remote-control three-colour wedges, neutral and diffusing wedges and a slide-changing mechanism are installed in the space behind the screen. The apparatus is controlled from a console operated by the therapist who sits close to the child and watches all its reactions. Specially drawn designs are projected, usually in two colours roughly corresponding to figure and ground, so that these can be faded in and out and the colours varied over an infinite range according to the reactions of the particular child. The designs are non-representational though mostly organic and dynamic in character; occasionally geometrical designs are used. The form of the designs, together with the choice of colours and the seciuence of the colour cycles, are worked out for a particular child. The purpose is to give the child a visual experience, if possible unrelated to anything in its memory, which will help to stimulate, co-ordinate and balance its visual and emotional faculties.

During a typical session the child comes in and sits down on a small chair in front of the screen. The room-light slowly dims to deep blue, and then perhaps to complete darkness. As it gets dark, a luminous cloud, nondescript, slowly appears on the screen. There is a moment when one cannot tell whether the screen is reflecting or transmitting. This change of illumination holds the child's attention. Slowly out of the luminous cloud a form crystallises. This might be a curved organic form, or perhaps a simple radiant star. The child's attention is rivetted on the screen until the form is sharp and strongly coloured. The colours may change through a whole cycle until they reach their climax. Then the whole appearance fades out, the screen becomes dark and the room-lights go up once more. During the whole cycle the child will concentrate in a way that it cannot do at any other time during the day. The whole cycle may be repeated once or twice during the 15-20 minute session.

For a child who is over-tense and is continually obsessed with small details in its surroundings, the reverse cycle is used. Out of the darkness a sharply contrasted form appears in strong and bright colours, and then gradually diffuses and fades out until nothing is left but a faint luminous cloud. What happens? If the child relaxes and yawns then a great deal has been achieved. In this way a spastic child may achieve conscious and complete relaxation such as otherwise happens only in sleep.

For another child a different kind of cycle has been of value. This child was a small-headed and restless boy of 7 who always appeared to be living in what went on around him and never came to any repose in himself. At the same time he had weak lungs and tended to suffer from bronchitis and pneumonia. For him we designed a symmetrical form slightly reminiscent of lungs or the lobes of the brain. To begin with the figure is projected in a cold blue colour against a red background. Both colours then become dim and the blue figure slowly changes to a purple and then to red while the background changes from red to blue. The boy has watched this change some hundreds of times but each time he sees the cold blue figure begin to glow with warmth he gets quite excited. It is a special moment for him. Even with several 15-minute sessions in the week he has never got tired of it. He looks forward to it as to a good meal. He is always impatient for the next session, and if he sees the therapist at any time during the day he will take her by the hand and try to lead her to the colour-room.

There is no doubt that this treatment has not only improved his poise and behaviour but also his general health. It is as if the change of the active red colour from the outside to the inside produces a corresponding organic activity within him.

Occasionally it happens that a child begins to rationalise and to ask questions about what it sees. This is a sure sign that it is out growing the therapy and needs to attend school.

Another child, a healthy-looking girl of 8, had encephalitis at the age of 4 months with no development of speech since that time. She had the typical symptoms of this kind of brain damage: she resented any change of routine, played with toys in a repetitive mechanical way, and would lie on the floor if she did not want to do what was asked of her. It was difficult to engage her attention at all, and in the colour room nothing had any effect until the whole room and screen were flooded with strong green. To most of us this would be highly unpleasant, but to her it was the only sensation that gave her any satisfaction. A further variation was to have some red light in the room behind her, so that when she played with her fingers in front of her eyes, they appeared strong red against the strong green background of the screen. This suggests that her comprehension of colours is limited and that a violent contrast is required to produce any significant sensation.

An 8-year old boy had brain damage so severe that his behaviour was rather like that of a tough little animal. We designed a form to exhibit the maximum impact of red and blue, and found that the adjustment and balance of these two colours had to be quite exact before the boy would become quiet. Again it seemed that this child was so insensitive that very crude effects were necessary in order to get his attention at all.

We have a 9-year old epileptic girl who chatters incessantly in order to call attention to herself. What seems to help most in her case is a static star-like form projected in a near-white tone against a background that slowly alternates between red and green: Here it is a kind of breathing rhythm that gives her satisfaction.

THE ILLUMINATSD POOL

A rather different use of coloured lighting is in a small therapeutic pool we have constructed. This is a covered and heated pool 14 ft by 8 ft with a maximum depth of 3ft. 6in. The temperature is kept at 32°C. For children who are spastic and who move with difficulty the warm water gives them support and helps them to move more confidently. In this respect the installation is not unusual. But we have arranged the lighting so that the water space appears to be full of light in an otherwise dark room. The lighting units are built into the walls of the pool just below the surface of the water so that nearly all the light is reflected downwards from the under surface of the water. The pool is lined with grey tiles (about Munsell N 5) so that when a child enters the water its body is brilliantly lit in contrast with its surroundings. This effect is so striking that some children who previously had little awareness of their own limbs at all, now begin to take a lively interest in their own movements.

The lighting consists of two circuits which can be dimmed independently, and which we have coloured pink and blue. These seem to be the most acceptable colours. The pink lighting seems to stimulate the children to greater activity while the blue inhibits and calms them. Usually we only have two children in the water at any one moment so that the two-colours can be used therapeutically to great advantage. To cross-fade from one colour to the other is sometimes an important experience for the child.

An interesting technical point is that with thoroughly filtered water there is a pronounced Rayleigh scattering effect even in such a small expanse of water. This means that colours with no short-wave component such as yellows and reds do not scatter and therefore produce hard dark shadows while colours with some blue component have soft bluish shadows. In this respect the blue-pink colour was found to be much more acceptable than a golden yellow or amber.

GENERAL OBSERVATIONS

These are a few of the specialised ways in which we are regularly using colour in our institution. Though we are seldom in a position to isolate the effect of one particular therapy we have every reason to believe that these experiences of colour play a real part in the very considerable improvement of the mental condition of our children. One thing however can be misleading. All displays of changing lights and colours have a novelty value which can be therapeutic in itself and may mask the effect of the particular colours being used. This must be duly taken into account.

I would like to stress once more that the intellectual critical faculties of these children are almost nil, so that their reactions to colour are deep-seated and genuine. From this point of view the most relevant factors are the immediately perceptible qualities of colour rather than the physically measurable properties. These qualities tend to arrange themselves in natural polarities:

Yellow/Blue

> is related to Active/Passive, to Expansion/Contraction as well as being the obvious representative of Light/Dark.

Red/Cyan

> is related to Warm/Cold, but is not beautiful in itself.

Red/Green

> has the effect of a real polarity although it is not strictly a pair of complementaries. In the solid rather than the watery sphere it represents Warm/Cool and can be very beautiful. One might call it Polarity within the limited totality of Yellow.

Green/Pink (pale magenta)

> this is an important polarity and is related to Outside/Inside, or, as Goethe said, to Earthly and Heavenly qualities. It is the most restful polarity there is.

Red/Blue

> this is not a complementary pair but is a polarity in a more physical sense. Red is nearer to thermal radiation, blue is nearer to chemically active radiation. This corresponds to the polarity of Willing/Thinking in the human being. We find that for those who lack life forces, warm or red colours in the surroundings are a help, while for those who lack consciousness, blues and greens are better.

Another factor which must be taken into account is the "mode" in which colour is seen. "Illumination mode" works subconsciously on the general mood of the beholder and certainly produces unconscious adaptation. This is evident in our patients. "Object mode" works more consciously; a dark form on an otherwise empty screen will attract far more attention than the colour of the general illumination. Our own experiments show that in order to produce the most powerful effects colour needs to be contained within form. This is why the designs for our therapy-room consist of carefully worked out forms as well as colours. The changeover from one mode to another, or the change from a positive to a negative form, is a moment of special significance to some children.

SUMMARY

The therapeutic effect of colour depends on the level of consciousness of the beholder. With patients who know what they are doing the therapy consists partly in the sheer concentration and the discipline of hand and eye and partly in identification with the schemes of colour which are given to them. At a lower intellectual level the therapy lies in entering into the action and mood of what they are doing and creating.

At still a lower level the reactions are more instinctive. A patient's choice of colour may be a diagnostic clue. Encouragement in the use of a particular colour may be a part of the therapy. At this level there are two possibilities. A colour may produce its own mood, or the exact opposite. (For example, red may produce activity, or it may produce calm). This seems to be an individual matter. Where there is little or no awareness of self the reactions will be wholly instinctive and only partly conscious. Watching a cycle of colour changes may do the same for a child's emotional condition that massage does for its bodily condition.

With some children, perception itself seems to be undeveloped. Here the crudest effects are necessary if any impression is to be made at all. This borders on the purely medical use of colour, where in general red radiation will stimulate the metabolic processes and blue radiation the nerve processes.

Therefore for the therapeutic use of colour I think it is more relevant to consider colour as a form of artistic experience than as a type of physical radiation.

Developments in Colour Measuring Instrumentation

In April 1970 a meeting was held at which various speakers described instruments which had recently been designed to measure colour. These instruments all had features which were novel; some of them had recently become available commercially but others were, at that time, only in the prototype stage.

It is considered that brief details of the features of these instruments together with further references would be of interest to all concerned with colour and a synopsis of the meeting is therefore given.

a) **Fibre Oprics Photo-electric Colorimeter**

Details of this instrument were given by Dr G. R. Ishak of the Paint Research Station who has led development of the instrument there. Since the meeting was held the instrument has been further developed by their Applied Research Laboratories who exhibited the firet prototype at the OCCA Exhibition in June 1971. Detailed descriptions have appeared in OPTICA ACTA; 1970 vol. 17 No. 10, pp 725 - 732 and in J.O.C.C.A.; vol 54, No. 2 1971. The most important novel feature of the instrument is the use of fibre optics to transmit both the incident light to, and the reflected light from, the sample. This allows the instrument to be used in a number of ways which have hitherto been impossible.

The colorimeter, as described by Dr. Ishak, contains a light source running at 2854K. This source illuminates one end of a fibre optic element which transmits the light to the sensing head and illuminates the sample normally. The light diffusely reflected from the sample at 45° is collected by six other fibre optics spaced symmetrically around the head. These collecting elements transmit the reflected light to the detector where it falls onto a ground glass screen and then passes to the cathode of a photomultiplier via three tristimulus filters. The output of the photomultiplier, when connected to a suitable load resistance is indicated by a digital voltmeter reading directly in tristimulus fealues. The spectral response is not sufficiently close to CIE specifications for absolute colorimetry but they are close enough for differential colour measurement, and closer correspondence to CIE specifications can be achieved if necessary.

Advantages of the instrument are:-

1. Interchangeable heads enable different illumination/collection conditions to be compared.

2. Limitations on the number and types of correction filters that may be fitted are less than usual.

3. The spectral response can be measured directly and corrected with comparative simplicity.

4. Versatility in use; for instance measurements on bulk wet paint, can be made thus making in-line control of pigment dispersion possible.

Other uses can be envisaged; the compact colour sensing head connected to the main body by a flexible linkage, possibly several yards long, overcoming obstacles which previously ruled out practical colour measuring systems.

b) **Tristumulus Spot Colorimeter**

This instrument was developed at the BBC Research Department under the guidance of Mr. H.A.S. Philippart. It enables the chromaticity of small areas to be measured from a remote distance with a field of view of approximately 2°.

Light entering the objective lens of the instrument is split by a semi-transparent mirror; a portion of the beam passes to the eyepiece used for aiming the instrument and the remainder passes to the detection system.

This detection system comprises an aperture followed by measuring filters mounted in a wheel, after which the light falls onto a photomultiplier tube. There are six filters in the wheel, it being necessary to take six readings from which X, Y and 2 may be computed. This arrangement was found necessary because of the X spectral characteristic (double-hump) and the variation between photomultiplier tubes in the red region.

The instrument is designed as a fully self-contained portable unit carrying its own power supply and fitting into a small suitcase-sized carrying box.

It was initially designed and built to fulfill the specific requirements of colour television, in particular the comparison of colour reproduction from studio scene to television screen and the measurement of the chromaticity of colours on colour television screens.

A very high accuracy was not the main criterion but it has been found that the instrument even though it was designed for comparative measurements, will measure surface colours to a relative accuracy of about one j.n.d.s. (0.004 u,v units) at quite low luminances.

It is quite apparent that the instrument has applications other than to colour television; any instrument which offers the facility of being pointed at a surface colour and giving a numerical value to it in an accepted scheme of reference must surely be an asset on many investigations. That this is so is shown by the fact that the instrument has now been marketed by Joyce Loebl and Co. Further details of the instrument are also given in the lillC Engineering Division Monograph No. 65, December 1966.

c) **A variable geometry spectrophotometer**

A fully illustrated description of the versatility of this relatively new, commercial spectrophotometer was given by M.C. Neveu of Leres.

For many years commercial spectrophotometers have standardised on either 0°/45° geometry or on the integrating sphere. The limitations of these standards are well known and the behaviour of colours when viewed at different angles is familiar to all, particularly in the paint industry (overhead colour and downhand colour) or the textile industry (face colour and flop colour)•

With the advent of metallic paints and flake pigments these problems have become more acute and the need for a more versatile instrument was felt to exist.

It was considered necessary to retain the integrating sphere geometry as a basic requirement but to design the instrument so that other viewing arrangements could be used.

The instrument now available is based on a grating monochromator with slits for lOnm and 3nm bandwidth and a 0.05nm slit for calibration. The beam generated in the monochromator is split on emergence to form a reference and a sample beam. These are chopped and, at the same time, two infra-red beams are also chopped; these two additional beams drive electronic gates which are thus always perfectly synchronised with the photomultiplier signal.

In the sphere mode the beams are arranged to strike the samples (a) normally, in which case the specular component is excluded since it returns through the entry port or (b) at 8° to the normal, in which case the specular component is included.

By fitting a field mask into the condenser system a reduction in illuminated area from the normal l l/l6" x l ^{3}/8" to approx l/5" x l/5" is possible and the electrical gain is automatically increased to restore sensitivity with negligible noise increase.

The variable geometry is achieved by placing mirrors in both sample and reference beams. The mirrors can be moved synchronously on a curved ramp by means of a front panel control knob. Illumination of the sample and standard can therefore be varied, and by moving the stage on which they are located the viewing angle can also be adjusted. The solid angle of viewing is 19° while that of illumination is 2°. These angles were chosen after extended testing indicated that they gave the best correlation with visual observation.

Fluorescing samples can be measured using a filter corrected source giving D6500. Direct illumination and viewing of the sample and standard is used and the angles can be changed by rotating the sample-holders. The sphere mode was not chosen for this application since the reflectivity of the sphere wall would need to be carefully controlled outside the visible region and also fluorescent light emitted by the sample would be reflected onto the standard and give rise to errors.

Samples for transmission measurement are located where the beams are parallel, but for turbid or diffusing samples the cells are set at the sphere entrance and this then allows either total transmission of the sample to be measured by using a diffuse white at the sample port, or by using a black velvet at the sample port, only the light diffused by the sample itself is measured.

Other features of the instrument are the 100% line compensator and its low impedance which enables direct linkage to computer or tri-stimulus integrator to be made.

On Art and Colour Vision

R.A.Weale

The address given by the retiring Chain Colour Group.

I want us to consider a specific group of paintings in the light of scientific principles and see where this gets us.

Other cranks have attempted this before now and this is why we should define our objectives. I think our approach should exclude value judgements except in so far as they involve agreement or disagreement on the extent to which an artist demonstrably achieved what he set out to do. Hence we do not wish to say "this painting is more beautiful than that", but we might say "The relative spatial arrangements in this painting are correct or not" as the case may be. Given a set of conventions we can express this numerically and move into a sphere where our views are amenable to experimentation. There is, for instance, no optical system (other than television) which reproduces the nearer of two equally large sheep or trees as smaller than one which is further away. The transform of a given set of points from the real world to that pictured in a certain engraving of Hogarth's is,however, not only non-linear but differs from place to place and we say that Hogarth's space is distorted. Note that we don't use the words good, bad or indifferent except perhaps to underline the implicit humour. As a further example consider the Laughing Cavalier in the Wallace Collection. How, you may ask, can we experiment with this? When English was still a compulsory subject and the study of English literature considered desirable we would be told about a useful principle: delete a character from a novel or a play and see what's left. This provides a measure of the character's importance; e.g. Lear without Lear would be as silly as John Wain's Contenders without Robert Lamb. But the Merchant of Venice might survive, admittedly on a less humorous level, without Launcelot Gobbo. What happens to the Laughing Cavalier e.g.if we shave him? We wipe away his laugh. This simple experiment shows that the Cavalier is not laughing at all, that the contrary impression arises in part from the fact that his hat reflects the cockiness of the baroque age and in part from the circumstance that his moustache is twisted upwards like that of the German Kaiser - who neither laughed nor was baroque.

The approach we are following is basically analytical, where possible, and experimental where necessary. In every case we shall try to be honest.

Technique is of the prime importance in the scientific analysis of art because it is a vital link in the chain of communications between the artist and his public; it permits no ambiguity. The artist by intention can make his subject ambiguous, as is well demonstrated by the deliberate 'ambiguous drawings[1] which illustrate the textbooks of perception. He can, however, achieve this only by the technique which he employs. Clearly, if the drawing were coloured the ambiguity would be destroyed. In addition if it were carved or sculpted, it would arouse an entirely different type of interest and would invite us to circumainbulation. You see, therefore, that, while there may be diversity in the stimulus and in the response which it evokes, the technique has, as it were, an eigenvalue.

There are few examples which stress this with more force than do pointillist paintings. I noticed this not so long ago when I made one of ray periodic visits to the Courtauld Gallery in battered Woburn Square. I was struck by the apparent greyness of Seurat's painting of his mistress powdering her face. At first blush you might think that this is precisely what the painter had intended. After all, she is sitting at her dressing table and whirling through the air a powder-puff the size of a small melon. If. however, we examine the picture more closely, while the atmosphere is misty, we cannot see any powder settling on the small table, or on the cabinet on the wall at the back or on Maria Knobloch[f]s bodice or on her carefully coiffured hair. Then why does the painting look relatively grey? Well, of course, from close quarters it does not• As you approach it breaks into colour and, as you get within reading distance, as it were, it appears loaded with countless hues but its contours disintegrate like those on Ishihara Plates. This is the sort of phenomenological description which Professor William Homer Innes has given us in his monumental study of "Seurat and his Science." However, it offers us no insight as to why we perceive these variants at different viewing distances or why, to put it bluntly, Seurat failed to achieve what he set out to do (as even his contemporaries told him) or why, in a peculiar sort of way, pointillism is punctuated with ironic tragedy.

Why pointillism? Why paint, as it were, by numbers? Why dab the canvas with myriads of dotty areas when, for centuries, not to say millenia, before the l880's and again since, painters have used brush strokes of varying length, but strokes nevertheless? The answer is to be found in the fact that pointillism was consciously based on scientific principles.

Let me survey very briefly what was known about 100 years ago that had a direct bearing on the problem. I am not concerned with the chemistry of pigments or anything similar, but rather with the physiology of vision. Notable advances had been made in the study of the anatomy of the retina, the thin light-sensitive tissue which lines the inside of every eye. For instance,the German anatomist Max Schultze published in 1865 the greatest comparative study of the retina of all time. The light-receptors, called rods and cones had in fact been discovered by Leeuwenhoek of Delft, the inventor of the microscope. But Schultze put them, as it were, on the market. These receptors act as energy transducers: they absorb certain parts of the electro-magnetic spectrum. By virtue of the pigments contained in their outer limbs their absorptivities are limited essentially to the visible part of the spectrum. After the absorption of a quantum the pigments change, the electric charge distribution changes, I think that the birefringence of the receptors changes also, and the upshot of this physico-chemical upheaval is the initiation of the visual message which is sent packing on the obstacle race to the brain.

But let us return to the receptors. In order to be able to see colours you need at least two groups of receptors with different absorption characteristics. Only then can you distinguish green from red. With one lot of receptors the best you can achieve is a difference in lightness between e.g.two stamps. All this was becoming known at the time of Seurat's activity. It also had been known since about the middle of the eighteenth century that any colour can be matched by a mixture of three matching colours by varying the relative amounts. This empirical fact was generalised by Thomas Young- into the Trichromatic Theory which states that human colour vision is a function of three independent spectral variables.

Now I have just been deliberately inaccurate: I spoke of mixtures of colours but should of course have said coloured lights. We all know that if we mix coloured **pigments**, as painters had been doing for centuries before Seurat, the mixture is clearly subtractive. Pigments reflect light selectively, after absorbing some of the light illuminating them. If light is subjected to absorption by one type of coloured pigment and what is left of the light is absorbed by one or more different admixed pigments before reflexion can occur then less and less light is going to reach the eye of the observer, a problem tackled analytically by one of our former secretaries, namely the late Dr. Duncan. Suppose, however, you mix coloured lights instead of coloured pigments. Then light of spectral distribution A is added to light of spectral distribution B. When you add the two you obtain a different but brighter, i.e. additively mixed light.

This is the fundemontal principle which was grasped by Seurat (who was born in 1859) and applied to pointillism. The object was to enhance the luminousness of paintings by colour mixtures produced by juxtaposing small coloured elements and letting the eye do the mixing. The idea is that the eye picks up these small parcels of spectrally different lights and fuses them optically. And how can it do that? Well, this brings me back to the receptors. If every little bit of light can illuminate one or more receptors then clearly the colour resnonse of the relevant channel leading to the brain will depend on the spectral distribution of the light in a particular patch imaged on the retina and the visual pigments in the group of receptors illuminated by each. Now suppose the dots are so far away from the eye that they cannot be individually resolved: then any one group of receptors is going to receive light from more than one coloured patch and optical fusion will take place.

The problem is complicated, however, by the fact that when two colours, light or pigments, are set side by side they interact with each other. This is known as simultaneous contrast. If, for instance, you place a red stamp on a grey piece of paper the latter assumes a greenish tinge. In other words, it assumes a little of the complementary colour of the original light. Seurat was fully aware of this result of the juxtaposition of different colours and designed his spectral mosaics accordingly.

According to what? According to the laws of Chevreul, who was really the spiritual father of pointillism. Chevreul was a remarkable character; lie lived to the uncommon age of 102, dying in 1889 and schoolboys will tell you that he did some dyeing before that but we'll come to that later. He discovered various organic processes, including some which were useful for saponification and also the production of margarine. But what matters especially to us is that, at one time, he was in charge of the dyeing section of the Gobelin tapestry works in Paris. Is it too far-fetched to suggest that pointillist paintings are tapestries transferred to canvas? Chevreul constructed a contrast circle on the circumference of which he placed coloured pigments so that complementary colours, and hence high contrast colours, came to lie at opposite ends of the diameters. His system of colour harmony is based on the idea that the greater the contrast between two colours the greater the angle between the radii joining them to the centre of the Chevreul circle. Like the three-body problem, the problem of the harmony of three colours was ineluctable.

Now what Seurat missed,although Chevreul was obviously aware of, is -that contrast with large patches is easier to achieve than with small ones. Chevreul tells us, quite clearly, to take three threads of one colours and to place them side by side if we wish to achieve contrast. He illustrates this in his book, of which there are but few copies available.

Before we make our final assault on the problem of pointillism it might be a good idea to survey how far we have got at this point. We have discussed two types of mixing colours, obtained either by mixing pigments or by mixing lights. If new colour sensations are obtained by mixing coloured pigments, then subtractive colour mixing is employed. Note that what is substracted is luminance rather than colour: the more coloured pigments are mixed together the more neutral and muddier the ultimate result. This is readily expressed quantitatively in terms of the reflexion coefficient of the pigment mixture. The other type, namely the mixture of coloured lights, leads to an enhancement of brightness, and is, as we know, called additive. Such mixtures can also produce neutrality or white. Again, it is the luminance of the components which are being added and not the colours. Pointillism uses the latter method in order to enable the painter to enhance the luminance of the painting, and relies on optical fusion of the minute coloured points. We note that optical fusion is based on our failure to resolve fine detail: if our eyes or, to be more precise, our retinae cannot segregate the parcels of light reflected from neighbouring painted coloured patches then the parcels add their respective effects in stimulating the retinal cones which signal colour to the brain. We also note that simultaneous contrast may modify the appearance of neighbouring areas and that Seurat had made a careful study of Chevreul Laws of contrast.

The fact that Seurat had failed to achieve what he set out to do was clear no later than 1889 when his work was being exhibited in Brussels. His contemporaries said the paintings looked grey, and I think it is significant that this objection was not raised when they were first exhibited in Paris a few years earlier. Let us put ourselves into the two situations in Paris and Brussels respectively. Allow me to remind you that it was in 1884 that Seurat conquered Paris overnight. He exhibited Un Dimanche d'été a 1'île de la Grande Jatte, and thereby made his name. Pointillist or divisionist in detail, almost Renaissance in design with its undisguised frontality and layering in depth, with its volumes reminiscent of those of Piero della Francesca, it provided surprisingly, as John Russell observes, the French critic Fénéon with a manifesto whereby to explain the technique. You can imagine how it was examined by lorgnetted ladies and myopic gentlemen to whom the physiology of seeing of even the nineteenth century was double-dutch. "Ah oui, mais c'est formidable," they would say, more impressed by the coloured dots than the underlying vision. Then they see this and other pointillist pictures in Brussels four or five years later. They remember the coloured dots taken in at close quarters, and recognise Seurat's works as they enter the hall at a much greater distance: but from a distance, the paintings appear grey, and the second impression is therefore one of loss of colour.

It is easy to mimic this. I obtained two sets of slides of Seurat's paintings at the Courtauld Gallery. I set up two projectors so that the image produced by one was linearly three times larger than the other. I also equated the two projections for white luminance by means of neutral density filters. This rendered colour balance unnecessary. I noted that in every case diminution, equivalent to distant viewing, leads to loss of colour. You can repeat this with a non-pointillist painting, e.g. Cezanne's Lake Annécy, without any apparent loss of colour. Pissaro, the well-known contemporary and a follower of Seurat, was at great pains to explain away his master's limitations. A painting, he says, should be seen as Nature is seen, namely at a sufficient distance to allow colours to blend.

Pissaro quantifies the little matter of sufficiency, and puts it at three times the diagonal of the painting. Note how Fissaro's thinking is influenced by his art: as Nature is not a pointillist painting, her colours do not need optical mixing; they are blended to begin with. Furthermore, the advice offered by Pissaro provides a devastating testimonial on how far his scientific grounding falls short of Seuratts. It may seem impertinent for a scientist to indulge in art criticism and, worse still, in the criticism of an artist. Note, however, that I am taking; to task, not Pissaro, the great artist, but Pissaro, the quantifier of a rule that's rough but not ready. Pissaro's advice regarding the "sufficient" distance from which to view pointillist paintings could begin to make sense only if the size of the dots of the painting bore a fixed relation to its size. If the attribution of this rule to Pissaro is authentic then, I am afraid, we can conclude only that this artist was utterly ignorant of ocular optics in particular and the working of geometrical perspective in general.

Let us nevertheless try and see if this so-called rule offers a lower limit to the viewing distance. Let us assume that the diagonal of a given painting is 100 cms in length and the component dots are 3 mms in diameter. At Pissaro's minimum distance of viewing each dot subtends at the eye an angle of about 3 minutes of arc. Now the minimum angle of resolution of the normal human eye is nearer 1 min of arc and can be less than this. However, this angle is determined with high-contrast targets: with low contrast between target and background, the value computed approaches Pissaro's. Any moderate visual defect, such as slight short-sight, might well put Pissaro on target. Allow me to stress, however, that I have fixed the ratio of the diameter of the dots to the length of the diagonal of the painting. Seurat's Chahut has a diagonal less than one third of this length; it is a tiny picture about as large as a book but the size of the dots is, if anything, larger than the 3 mm I assumed.

Although the matter of resolution, or rather, non-resolution, clearly bears on the problem of optical mixture at one end of the range of useful observing distances, other weighty difficulties arise. I said earlier that the whole business is ironically tragic: let me now explain why.

Seurat had absorbed in detail all the relevant visual science and facts relating to colour vision. He had mastered them to the point of being able to reproduce them instinctively. He died, a young man like Mozart at the age of

37, in 1891 and three years later Arthur Kttnig made the discovery which, had it been made ten or fifteen years earlier would, 1 think, have robbed the world of pointillism altogether, fe'e all know that there is a difference between equally bright green and blue on the one hand, and equally bright yellow and white on the other. What Ktfnig found, however, was that when the green and blue are small patches, and also with yellow and white and some other colour pairs, that we tend to confuse them. We can't tell the difference between green and blue; we match one with the other and this is known to us as foveal tritanopia.

Now these colour confusions occur with normal people for patches some 20' of arc in diameter or less. In other words, Seurat put large dollops of oil paint on his palette and normal colour vision would operate in these circumstances. He would then paint a patch on his canvas the diameter of which would subtend at his eye an angle of about 1°. He might step back to make sure that everything was right, and if he stepped back three or four paces, he would be approaching the danger-line for the break-down in normal colour vision but he would be unlikely to cross it. When, however, you view the painting from Pissaro's minimum distance, normal colour vision no longer operates for any one small dot. Of course, König did not investigate what happens to an assembly of dots, and, as far as I know, no one has yet analysed this problem. That there is an overall loss of colour sensation seems to be proved by Seurat[1]s test pieces.

Incidentally, you can observe a similar sort of loss of apparent hue with tapestries. A few months ago I saw some much older tapestries than those made at the Gobelin factories. There is some superb fifteenth century work in Rheims and in Beauvais which looks silvery grey at a distance, but assumes vivid colours as you approach it. This observation seems to confirm the link between tapestries and pointillism.

There is one last laboratory experiment which has, 1 think, a bearing on what we have been discussing and this relates to some experiments on the eyes of goldfish. There is good reason to assume that goldfish can distinguish between different colours: their own appearance is a shining example in support of this view. Nigel Daw, who now works in the States, has recently studied the electric responses of goldfish retinae in an imaginative manner with the use of coloured lights. When you tap an optic nerve fibre or one of the retinal cells directly connected to such a fibre with a micro-electrode you can pick up small spikey potential changes if the light-receptors leading to this cell or fibre are illuminated. A number of receptors are linked to one such unit and they constitute the receptive field of the unit which you are tapping. Some receptive fields lead to potentials when the light is switched on, some only when it is turned off, and some respond both to on and to off.

In general, the response of the surround of a receptive field antagonises that of the centre of the field. For example, if the centre of the field is illuminated you may get a response when the light is turned on. Now put a ring round the central moon, and your tapped unit will only record a voltage change when the annulus is switched off. The two parts, moon and ring, are clearly antagonistic. The ring, as it were, sharpens the response to the moon. Nigel Daw studied this moon and ring effect with different colours. When the central moon was red he recorded a given discharge. When the moon turned green, the burst of signals only followed its disappearance. With the red moon, the discharge following the switching on could be enhanced by surrounding it with a ring that was green. As you might expect, a red ring diminished the response. Note how this system is geared to simultaneous contrast: a green ring round a red moon produces the biggest response. But, and this is where we get back to Seurat, Daw discovered that, if the central red moon is too small, the green ring is of no avail.

We see, then, that both the colour discriminating power of our eyes in the form of tritanopia and their contrast sensitivity are such as to counteract the basic scientific principles of pointillism. Seurat's magnificent failure would seem to me to be attributable not to psychological difficulties, not to problems of style or of aesthetics, but to the way in which our retinae are organised.

Publication of Articles

Many of the papers given at Colour Group meetings are subsequently published in journals specific to the subject of the lecture. There is little object in republishing this material but readers may wish to know where these articles can be found. The following list is therefore given which represents papers presented to the Group in the period covered by this edition and which, to the best of our knowledge, have been published in any form. We apologise in advance to any contributors to meetings whose work has been published elsewhere and which does not appear in the list overleaf.

1. November 1969.

a) Measurement of the Colour Sequences in positive Visual After - Images by C.A. Padgham - Vision Research. 8. 939 - 949. 1968.

b) Lop-sided ellipses of colour sensitivity - by B.II. Crawford published as 'Just perceptible Chromaticity Shifts' - Proc. AIC 'Colour 69' Stockholm, Band I, p 302.

2. December 1969.

Ceramic Colour Standards by F.J.J. Clarke, G.E. Lambert and F. Malkin -To be published.

3. January 1970.

Colour Passing - Visual or Instrumental? by K. McClaren, JSDC, 86, 389 - 393, 1970.

4. March 1970.

Some other Turbid Medium Theories by S. Orchard - see this issue of Journal.

5. April 1970.

Developments in Colour Instrumentation - see this issue of Journal.

6. Newton Lecture 1970.

What use is Colorimetry? by G.J. Chamberlin - see this issue of Journal.

7. November 1970.

a) 'Colour Difference heasurement' by J.S. Mudd and M. Woods, JOCCA, 53, 852, 1970.

b) Kubelka - Munk Theory and Colour Matching by D.F. Tunstall, JOCCA, August 1971.

8. December 1970.

Objectives in Colour Reproduction by K.W.G. Hunt, J.Phot.Sci. 18, 205, 1970.

9. January 1971.

a) Colour Matches which include equality of scotopic luminance - by D.A. Palmer.
I) Proc. AIC 'Color 69' Stockholm.
II)Vision Research, 10, 563 - 573, 1970.

b) Parafoveal Colour Vision Responses of four dichromats by Dr. K. Ruddock. Vision Research, 11, 143 - 156, 1971.

10. February 1971.

Colour in Therapy by M.H. Wilson - See this issue of Colour Group Journal.

11. May 1971.

'On Art and Colour Vision' by Dr. K.A. Keale - see this issue.

Printed by Robert Martins (Printers) Limited, Holt_House, Flamstead lind, Cheshunt, Herts and published by The Colour Group (Great Britain), Institute of Ophthalmology, Judd Street, London, W.C.I,