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Perception of Colour

OBAID SIDDIQI
Molecular Biology Unit,
Tata Institute of Fundamental Research,
Bombay 400 005, India.

1. INTRODUCTION

In the early sixties Sir C. V. Raman became interested in the subject of vision, specially of colour vision. He carried out psychophysical experiments which are described in a series of papers and in a book entitled *Physiology of Vision,* published by the Indian Academy of Sciences. Raman disagreed with many of the tenets of the accepted theories of colour vision. He denied the distinction between night vision (scotopic vision) and day vision (photopic vision) and rejected the trichromatic theory of Young and Helmholtz. It is not my purpose to present a critique of Raman's views. Instead, I will take this opportunity to give you a brief outline of the current understanding of colour perception as a tribute to the memory of a great soul who interested himself deeply in the long-standing, and in many ways unresolved, subject of colour vision. Richard Feynman once remarked that there is no scientist of any distinction who has not been interested, sometime or the other in his life, in colour vision. This distinguished line includes, Aristotle, Dalton, Newton, Helmholtz and Göethe. It may not be out of place to note that the error of judgement Raman made is shared by others including Newton and to some extent Helmholtz.

THE TRICHROMATIC THEORY

The idea that the colour of an object depends upon the relative amounts of red, green and blue lights coming to the eyes goes back to Newton. This idea forms the basis of most commonly believed theories of colour. The trichromatic theory of colour vision was first proposed by Thomas Young at the beginning of the 19th century. Young thought it was unlikely that the eye has separate detectors for every wave length in the range 400 mm to 700 mm. He made a neat mathematical argument that in order to see the entire visible spectrum, a single detector or even two would not do, but three detectors might be enough. Young, therefore, suggested that there were three light absorbing substances. The excitations of these were combined by the brain to produce the sensation of colour. Forty years later, James Clerk Maxwell and Herman von Helmholtz demonstrated that all colours could be matched by mixtures of three suitably chosen lights.

There are two types of photoreceptors in the human eye, rods and cones. The cones mediate colour vision. In 1964 McNicholl and Wald found that each cone contained only one of the three pigments. These pigments absorb maximally at 445 nm (blue), 535 nm (green) and 570 nm (red). The cones are concentrated at the centre of the fovea, a small central portion of which is rod-free. This is the region which is principally responsible for colour vision. As the optical image in the blue region is blurred by chromatic aberration, the high-acuity central fovea is also kept free of

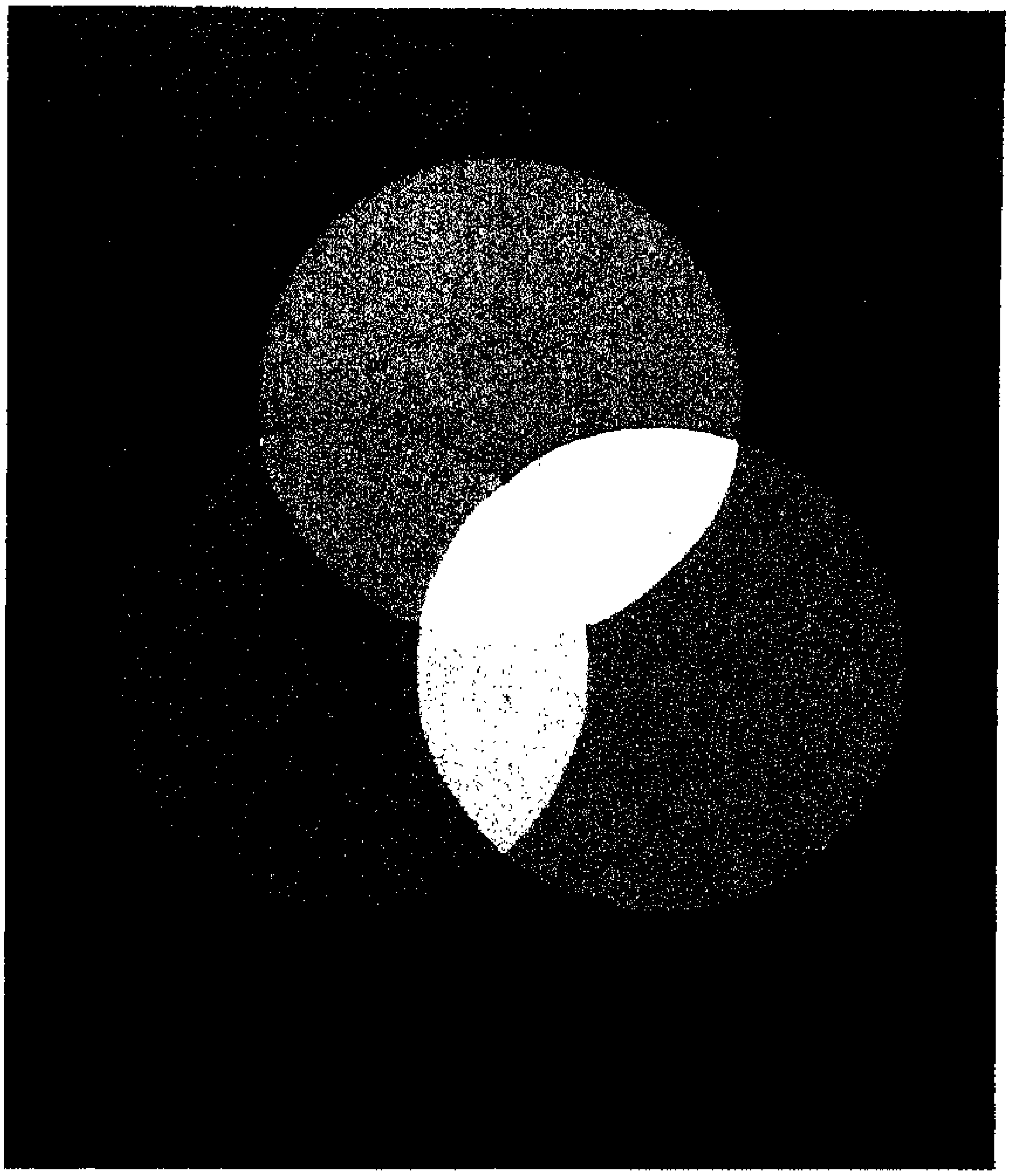

Figure 1. This painting illustrates the idea that by mixing three primary colours, all other colours of the spectrum can be generated. Jame Maxwell and Hermann Helmholtz demonstrated that all colours can be matched by mixtures of three properly chosen lights. This idea seems to underlie most popular theories of colour vision. (Hattersley, *Guide to Colour Photography* Dolphin Books, N.Y.).

blue cones. The blue cones are relatively coarse, so that colour vision becomes dichromatic when objects are small. With still smaller objects, colour vision deteriorates completely. Single photoreceptors are colour-blind. A small proportion of humans lack one or more types of cones. When all three cones or any two are missing, the person is totally colour blind or achromatic. Deficiency in one of the cone types leads to different patterns of restricted colour blindness.

Genetic Defects in Colour Vision

Type of Defect	*Incidence (% males)*
Trichromats (3 cones present)	97.4
Dichromats (2 cones present)	
Protanopia (red cone absent)	1.3
Deuteranopia (green cone absent)	1.2
Tritanopia (blue cone absent)	0.001
Monochromats (achromats)	
Typical (all cones absent)	0.00001
Atypical (two cones absent)	0.000001

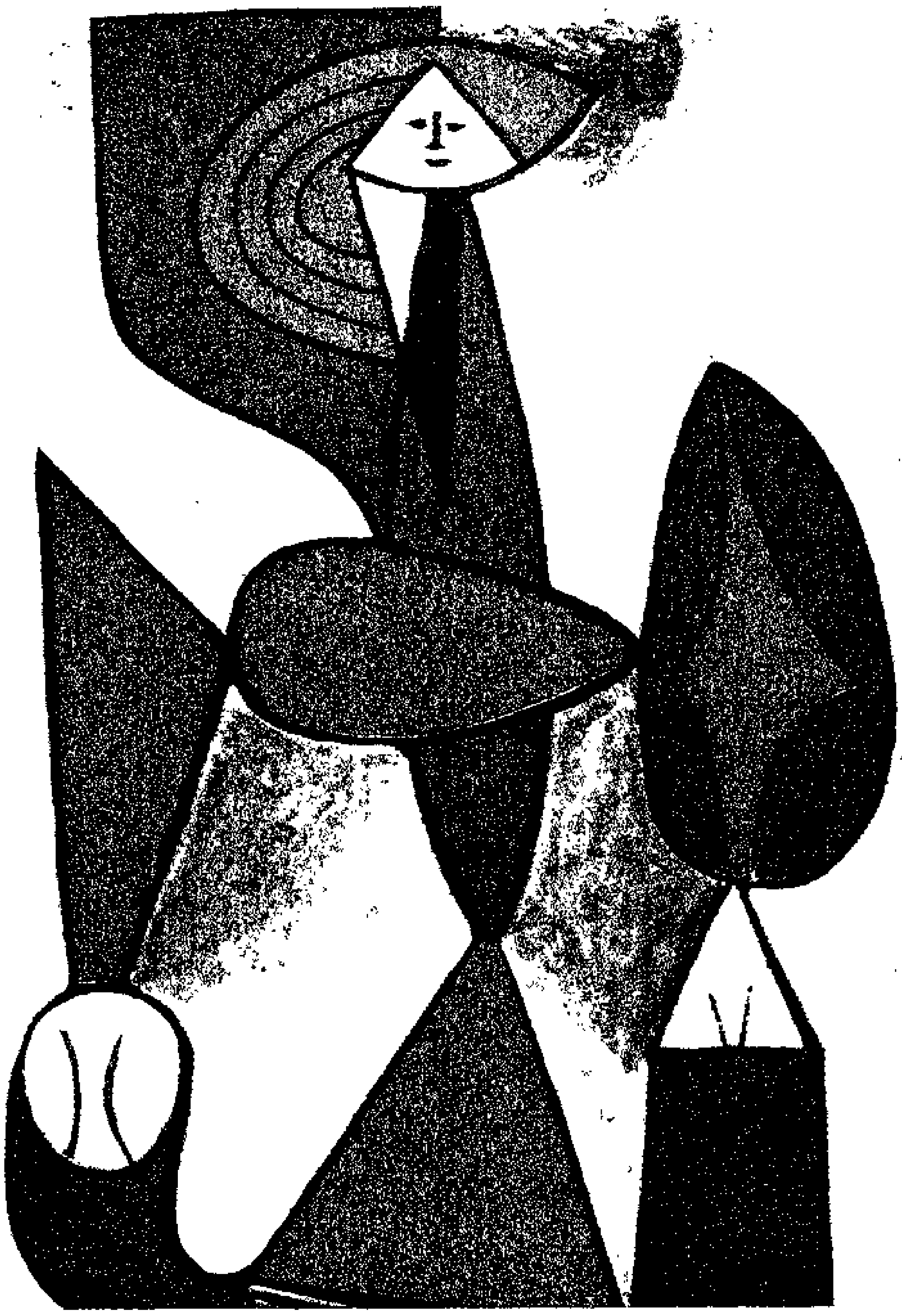

Figure 2. The lightness of a coloured surface depends upon its reflectance for the illuminating wavelength. If you view this Picasso through a red filter – a transparent red paper will do – the red areas appear light and the complementary areas dark. If the filter is changed to blue or green, the relative lightness of different areas changes. Perceived colour depends upon relative lightness of surfaces seen through red, green and blue channels.

COLOUR CONSTANCY

The colour of an object which is part of a larger scene does not change much with changes in the proportions of red, green and blue in the illuminating light. We perceive the object as having the same colour, whether we see it in the bluish light of the morning, the reddish light of the evening or the yellow light of the fireplace. This invariance of colour is the key to understanding the mechanism of colour vision.

There are two important points to note. For us to sense colour, more than one kind of cone must be activated. Secondly, our brain does not evaluate the wavelength and the energy of light. The action spectra of photoreceptors are broad and the brain cells are unmindful of absolute levels of illumination. On the other hand the brain compares and analyses the light coming from an object in relation to other objects. Colour is not experienced in a uniform and edgeless field of colour devoid of pattern. When staring too intently at a cloudless blue sky, pilots sometimes experience a temporary but total loss of colour vision called "greying out".

Ewald Hering (1925) was the first to grasp the significance of colour constancy and to construct a proper theory of colour vision. Hering suggested that the perceptual apparatus surveys the whole field of vision and picks out the object that reflects all colours of the spectrum nearly equally as "white". The light coming from other parts of the scene is then interpreted in relation to the light reflected by the object defined as white. According to Hering's theory, the perceptual apparatus adds "phantom light" of a colour complementary to the illuminating light, so that the object defined as white is actually perceived as white. I will not discuss Hering's theory any further but outline a more modern version of this idea. This is the Retinex theory of Edwin Land, the inventor of the Polaroid camera.

RETINEX THEORY

Consider a scene with objects of many colours. If we take a photograph of this scene through colour filters on suitable films whose maximal sensitivities correspond to the red, green and blue cones, and make black and white prints, the objects appear "light" or "dark", depending upon the filter that was used. The same phenomenon is observed if we view the objects with coloured filters before our eyes. The illumination can be changed so that there is a greater flux of light from a dark region, yet the "dark" objects will continue to look dark and the "light" regions will continue to look light. The objects in the scene can be moved around but they maintain their lightness. This remarkable ability of the eye to perceive "lightness" independently of the flux of light or the position of the object is the key to the understanding of colour perception. The visual system measures these "lightness" values in three independent channels, long, middle and short wave. From the information so obtained it computes a fully coloured image.

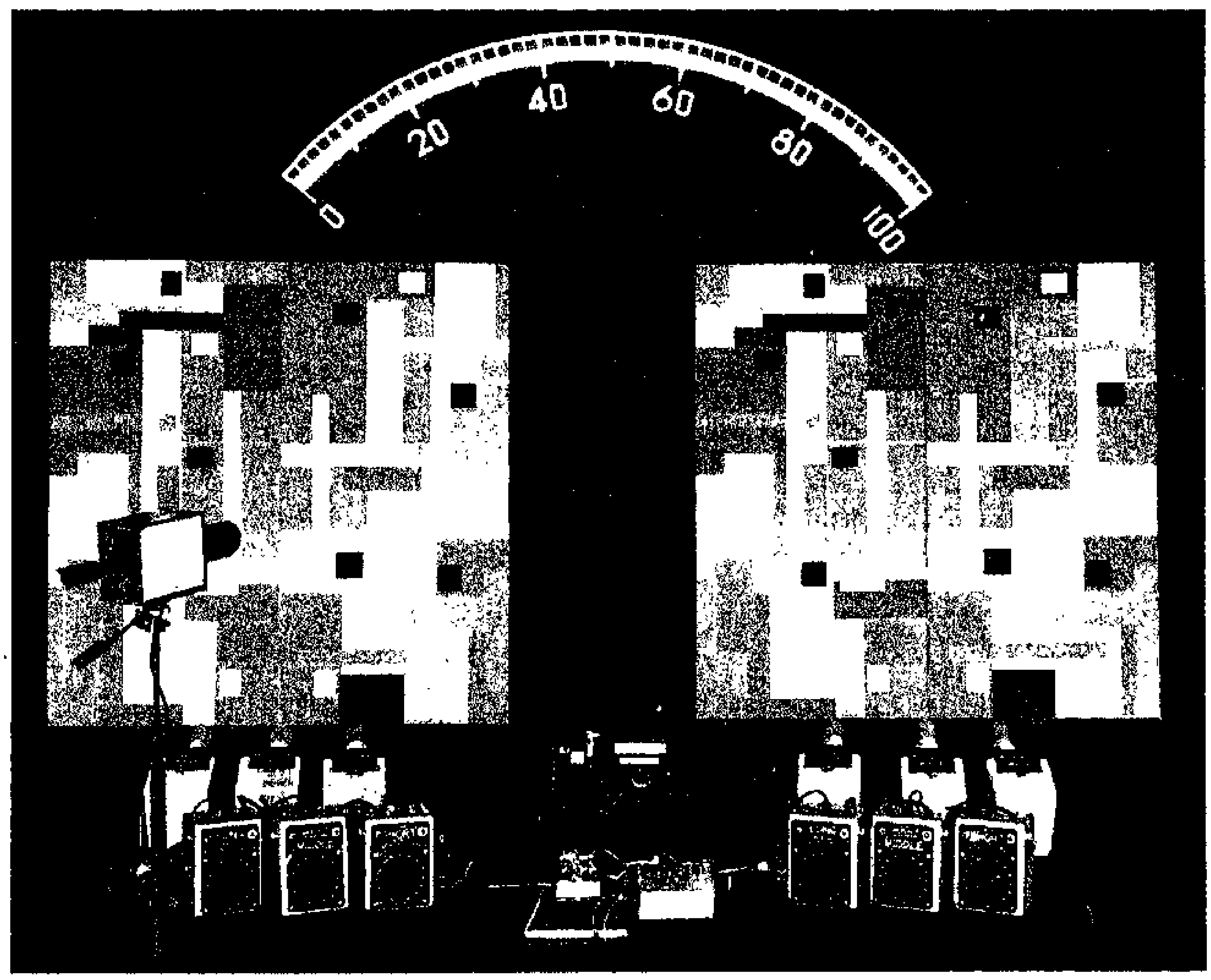

Figure 3. Land's Experiment: The coloured Mondrians are illuminated with red, green and blue lights whose intensities can be independently varied. A telescopic photometer measures the reflectance of strips. The three reflectances are used by our brains to compute colour.

Land and his associates analysed the nature of lightness by means of experiments with colour Mondrians. A Mondrian is a collage of coloured papers named after the Dutch painter whose paintings had a similar appearance. About a hundred strips of different shapes and colours are pasted on boards. The papers are so arranged that each piece is surrounded by five or six pieces of different colours. Each Mondrian is illuminated by three projectors equipped with narrow band filters at long, middle, and short wave lengths. The amount of light from each projector can be independently varied and the level of illumination can be measured by a telescopic photometer aimed at any region of the Mondrian. It can be easily shown that the perceived colour of the strips is relatively independent of the amount of light energy at the three wave lengths. The same coloured area on the two Mondrians can send to our eyes entirely different "triplets" of light energy. Conversely the same "triplet" of energy at the three wave lengths can produce entirely different colours.

Land made a systematic study of seventeen colours under different illuminating lights. He found that the invariant property of a coloured strip was its "reflectance relative to white". This "integrated reflectance" is the same thing as the "lightness" that we discussed earlier. Each of the three systems of cone vision views the world in a broad region of the spectrum and forms an independent "lightness" image of the world. Colour is an outcome of comparing these images.

How does the brain compute the "lightness" values of objects. I will not go into the specific algorithms that have been proposed but try to explain the general idea. The key to this computation lies in taking the ratio of flux between two adjacent points that are reflecting light. If we process the entire image by taking the ratios of luminances at closely adjacent points, we obtain a set of numbers that are independent of illumination but indicate changes in reflectance. At the boundaries of different areas, these numbers give the ratio of reflectances between adjacent areas. As we multiply the ratio at one edge with the ratio at a second edge, we obtain the ratio between the first area and the third area. We can thus obtain reflectance ratios of non-adjacent areas by multiplying the ratios at the intervening boundaries. The brain can thus, ascertain relative reflectances without placing the comparison standard next to an area. Once the triplet of reflectances has been obtained, the colour corresponding to a triplet can be visualised.

NEURAL PROCESSING OF VISUAL INFORMATION

The information originating in the retina is carried into the brain through a series of stages, each leading to successive abstractions. The main stages are:

Retinal Ganglion Cells — Lateral Geniculate Nucleus — Visual Cortex

Our understanding of information processing in these regions of the brain is based upon the work of neurophysiologists who have studied the responses of neurons in each region to patterned stimuli. To summarize this line of work briefly, retinal ganglion cells respond to small, light or dark, spots of light. These cells connect to the LGN whose neurons in turn project to the primary visual cortex. The cells of the cortex in the areas called 17 and 18 behave as detectors responding to edges of a given orientation in a certain part of the visual field. The simple cortical cells are wired into complex cells which respond to oriented edges, independently of their precise location. Finally the complex cells are connected to form hyper-complex cells of various orders of complexity. These respond to line terminations, corners and various directional movements.

A major step in understanding the physiology of colour vision was the finding that a certain proportion of the visual neurons are colour-coded. They detect "opponent colour contrast" in the same way as the achromatic neurons respond to light/dark contrast. The colour-coded neurons belong to different classes responding maximally to contrast between red and green ($Red^+/Green^-$ or $Red^-/Green^+$) or blue and yellow ($Blue^+/Yellow^-$ or $Blue^-/Yellow^+$). Like the achromatic cortical neurons, these neurons too can be simple, complex or hyper-complex.

We are now ready to raise the question - do the neurons at any stage of the visual pathway exhibit a behaviour predicted by Land's Retinex theory? S. M. Zeki working in the University College, London, discovered a special area in the visual cortex called V4. The neurons of V4, unlike the cones, have a sharply tuned response over a narrow band. Also unlike the cones, there are not three but very many different wave bands covering the entire range of perceived colours. This suggests that the activity of these neurons corresponds to perception of colour rather than light. Zeki carried out experiments with monkeys who were looking at Mondrians while the activity of their V4 neurons was being recorded. With the monkey looking at a red strip, the Mondrian was illuminated with long wave length. The red strip appeared very light but the "red" neuron in

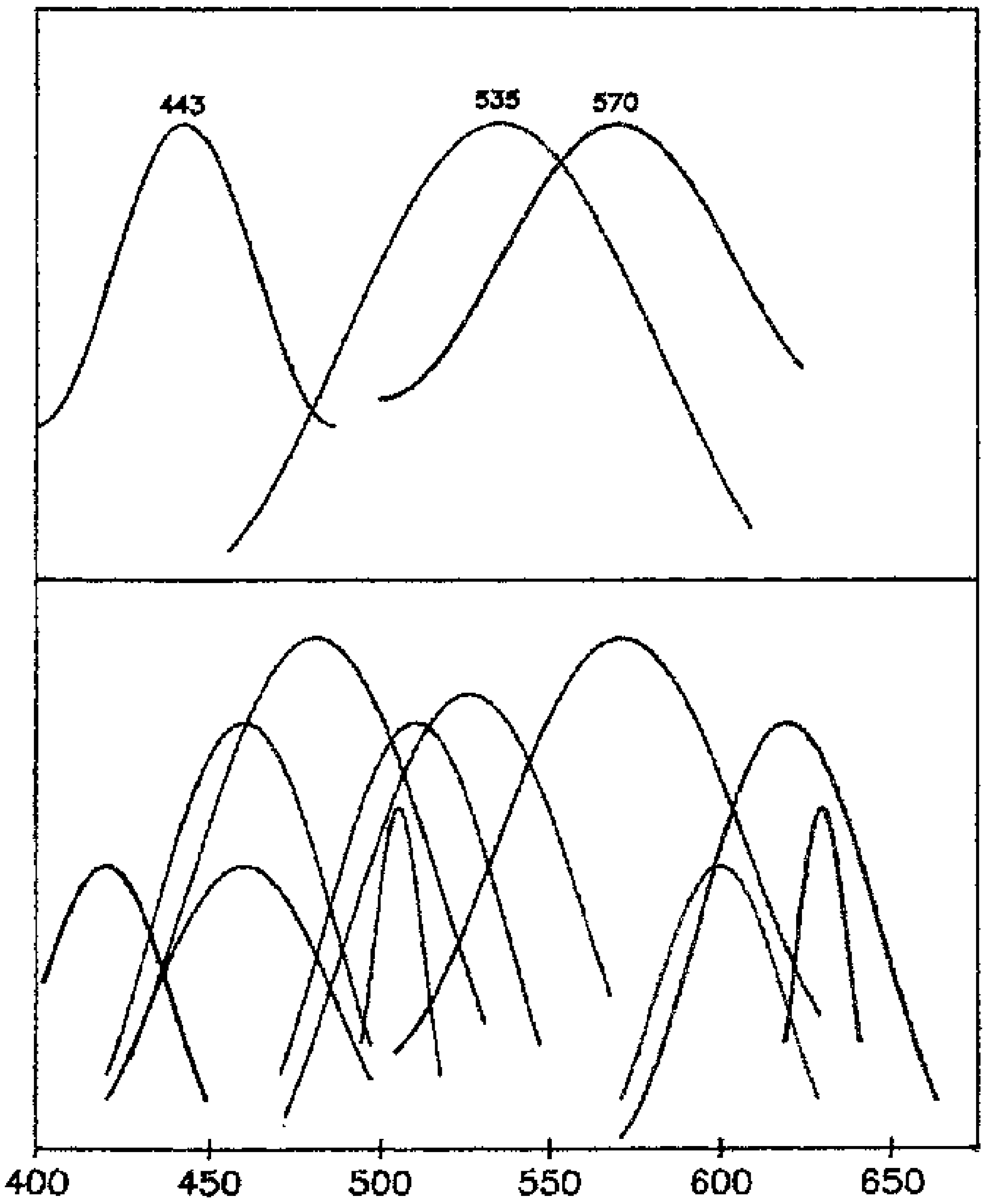

Figure 4. The action spectra of the three types of cones (top curves) are broad and overlapping. In contrast the neurons of V4 are sharply tuned. Each neuron registers the sensation of a given colour. These neurons fire vigorously only if the objects are illuminated by mixed lights. The computer generated representation of the Zeki Neurons (bottom curves) shows a small number of types. In fact there are many V4 neurons which detect a much larger range of colours.

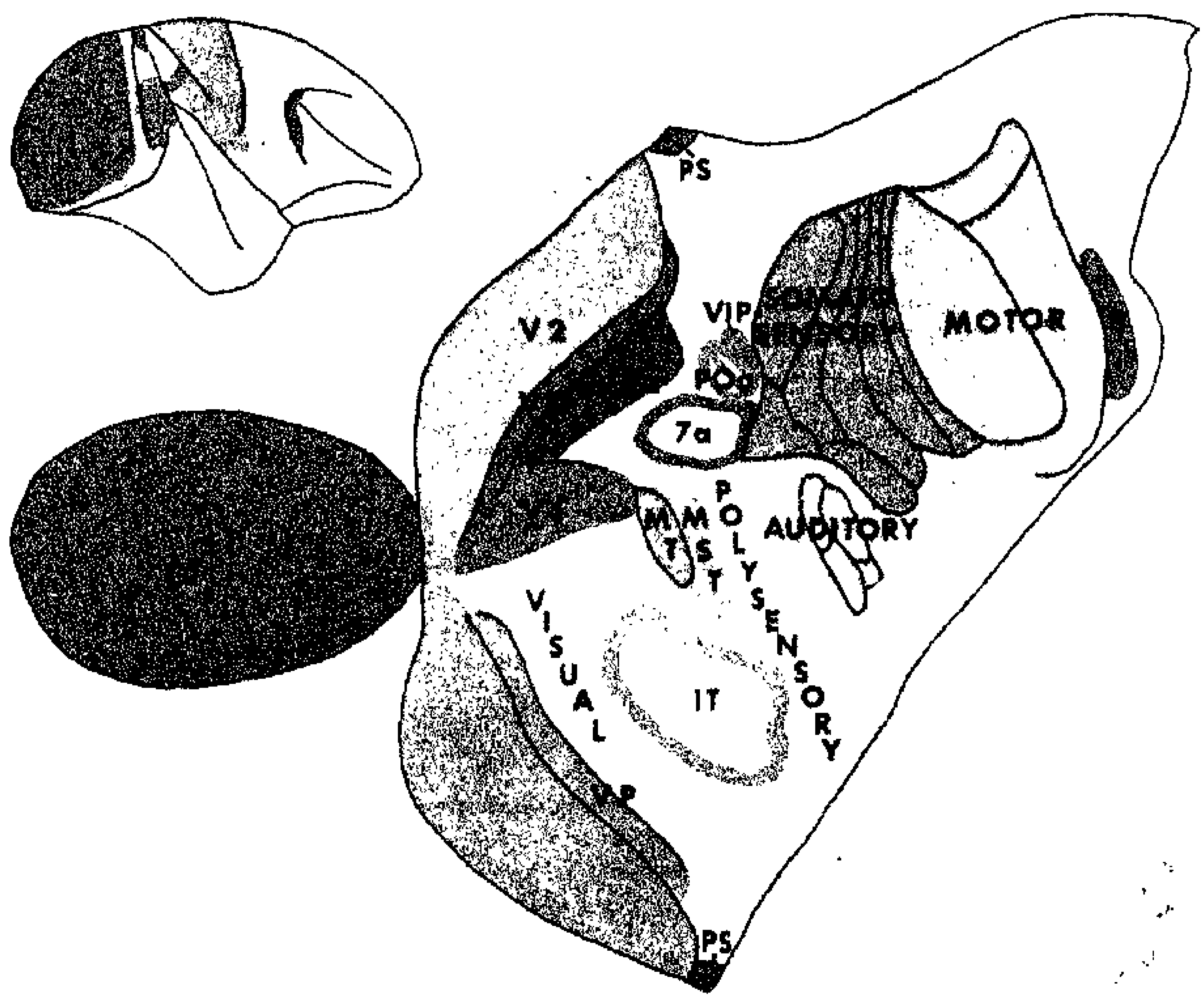

Figure 5. The cortex of our brain is a convoluted sheet, 2 mm thick. In this diagram the cortex of monkey has been spread out to show the different areas that deal with visual information. The activity of neurons in V4 corresponds to perceived colours. (Van Essen and Maunsell, *Trends in Neurosciences*, 1983).

V4 did not respond. However, when suitable amounts of green and blue light were added so that the strip appeared rich red to the human observer, the V4 cell fired vigorously. The same was true of green or blue. The V4 neurons registered the sensation of colour and not the flux of light.

The information from the retina to different parts of the brain projects in serial as well as parallel streams. The map of the visual world in the areas of the primary cortex remains topographic but as we go to higher areas, the information about colour or movement or depth separates out in distinct regions and is processed in parallel. These areas are consequently organised somewhat differently from the primary sensory cortex.

Parallel processing of colour separately from surface geometry has an interesting consequence that artists often take advantage of. A few strokes of colour in the right places even though imprecisely drawn will spread to fill the visible surface. The phenomenon is called colour bleeding.

Figure 6. The brain deals with information about colour and the geometric features of objects in parallel streams. This gives rise to the phenomenon of colour bleeding whereby imprecisely drawn colours appear to belong precisely to objects ('Mother and child' by Picasso).

Conclusion

What then is colour? I have tried to show that it is a property invented by our brain in which we clothe the world around us, using reflectances of surfaces, detected in three different wave bands. Perception of colour has many subtle features some of which I have neglected and others which remain enigmatic but, I hope, I have given you some feeling of how this remarkable operation is carried out by our brain.

Acknowledgement

I wish to thank Rasheed Mistri for help in preparing this lecture. Figure 1 is from the *Beginner's Guide to Colour Photography,* Dolphin Books, Doubleday and Co., N.Y. and Figure 5 from *Trends in Neurosciences,* September, 1983, Elsevier Publishers, Cambridge.

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