APPENDIX A[1]

Edwin Land's colour-constancy demonstration

Introductory

Chapter 1 describes the dogmas of Professor Bohusz-Szyszko, one of which is that there should be no repetition of colours in paintings. He justified this rule with reference to the variability of colours in nature. His claim was that, as a consequence of the inter-reflectivity of surfaces and the inevitability of different viewing angles when looking at different parts of a scene, "no two colours in nature can ever be the same".

Since this physics-based logic applies in all cases, it will do so to colours painted on a picture surface. In other words, it is theoretically impossible that any two colours in different places in a painting, even ones from the same tube, can reflect exactly the same wavelength combinations into our eyes. If so, how is it possible to obey the no repetition rule? When I first became aware of this paradoxical state of affairs, I was completely stumped. My first hope of finding a resolution to it came when reading a paper by Edwin Land,[2] *the inventor of the Polaroid camera, which described a powerful demonstration of* ***colour constancy****, a phenomenon that demonstrated that different wavelength combinations can be perceived as being the same colour. Could this possibility lead me to answer to the paradox? As my book shows, the answer was to be "yes".*

A precursor

Towards the end of the eighteenth century, in 1789, the French mathematician and scientist, Gaspard Monge (1746-1818) gave a demonstration to the French "*Académie Royale des Science*s".[3] It was very simple. He asked his audience to look at piece of red card through a red piece of glass. Much to their sur-

1 This text is an edited version of *Chapter 13* of "*What Scientists can Learn from Artists*".

2 Land, E.H., 1979, The Retinex Theory of Colour Vision. Scientific American

3 Described in John Mollon, 1995, Seeing Colour. In: *Colour Art and Science*, Eds.. Lamb and Boreau, C.U.P.

prise the red became "*white*". Monge related this counter-intuitive phenomenon to another in which he was interested, which can be demonstrated as follows. First focus two beams of white light from two separate projectors on the same white-coloured screen. Place a red filter in one of the beams so that it filters out all but the long wavelengths of light. In this *red* beam place a ping pong bat or some other opaque object so that it casts a shadow on the screen. Since the shaded region is illuminated only by the white beam, common sense would indicate that it would appear to be white or grey. But it will not do so. Rather, it will be seen as very pure looking *green*. It is an example of *induced colour.*

Taking these two phenomena together Monge was both able to make the imaginative leap required both to associate them with a third, now known as *colour-constancy*, and to produce a plausible sounding explanation for it. Monge's logic depended on two assumptions. Firstly, that the colours were being viewed in the context of other colours and, secondly, that human visual processing systems can compute *ratios* between the triplets of signals provided by the three,types of wavelength sensitive receptor (the ones that provide us with the three primaries).

In 1979, very nearly 200 hundred years later, Edwin Land reached much the same conclusions from not dissimilar evidence. His theory also depended on seeing colours in the context of a multicoloured display and the brain computing ratios. Since Monge's hypothesis had been long been forgotten, Land thought that his idea was new. The problem with the ratio-based hypothesis is that, though fitting the evidence and being mathematically sound, it lacks *neurophysiological plausibility*. Calculating ratios is not the kind of thing that the neural networks used in the first stages of visual processing can do. However, since the these networks are indeed capable of mediating *colour constancy*, there must be some other way of arriving at the same conclusion, using neurophysiologically plausible mathematics. In the next an *algorithm* is described that fits these two requirements. Before describing this, it is appropriate to look, first, at some earlier ideas on the subject of colour constancy and, then, at Land's demonstrations of the phenomena which show just how powerful it is.

Colour-constancy

If there actually were a direct correspondence between wavelength of light and colour, then an analysis of the wavelength composition of the light entering the eye would always predict the colour experience. In some cases, such as those of the rainbow or individually illuminated patches of pigment, such a prediction will be fulfilled. However, in the majority of cases it will not be. Thus, in complex and everyday scenes, the colour of an object tends to stay remarkably similar regardless of the light illuminating it. For example, a red apple seen in daylight will to look much the same colour throughout the day even though the conditions of illumination are constantly changing. Nor does it seem to change much if at all when viewed under tungsten light.

As just mentioned, this phenomenon of colour-constancy had already been a subject of interest in the eighteenth century, when Gaspard Monge gave his talk. Various other scientists added their ideas in the nineteenth century. These included Hermann von Helmholtz (1821-1894) and Ewald Hering (1834-1918).

Helmholtz attempted an explanation of colour-constancy pointing out that, if the effect of changes in the source of illumination could be neutralised or discounted, the colours of surfaces would not vary. He further suggested that such a neutralisation could be achieve by shifting what he called the "*achromatic point*" in colour-space to correspond to the average of all the colours in the scene. He thought that this process would require some form of unconscious inference (in modern times this might be translated as *higher level processing*). Sadly, he suggested no mechanism by which this calculation could be accomplished.

The name of Hering is associated with the discovery of *opponent-colour cells* which work on the principle of *lateral inhibition*. In a paper published in 1874 (coincidentally, the same year as the first 'Impressionist' exhibition) he argued that colour-constancy could be explained by the visual system processes that produce the phenomena of *simultaneous contrast* and *sensory adaptation*.

There is no need to understand the ideas of Helmholtz and Hering in detail. What is important is that these early speculators on the subject of colour-constancy, following in the footsteps of Monge, had already understood that any explanation for the phenomenon would lie in the activity of the brain. They also had ideas as to the sort of computations that would be necessary. However, since neurophysiology was in its infancy, they were in no position to engage in serious speculation about the precise location or mode of functioning of the neural mechanisms in question.

During the next hundred years, despite various efforts by scientists, little significant progress was made. Two possible explanations for this tardiness are worth mentioning. The first is that mainstream of colour-perception scientists were working within the prevailing tradition of studying colour responses via small patches of colour or light either individually or as adjacent pairs. This means that their experimental design cut out the contextual effects that makes colour constancy possible. The second possible explanation is the low status of colour in visual perception theory. Until very recently and perhaps to this day there has been an overwhelming tendency to assume that edges and lightness variations (shading) are the key variables and that colour is an almost expendable, "*last minute*", evolutionary bolt-on. After all, we can make perfect sense of black and white films. This being the case, the possibility that *colour-constancy* might be of fundamental importance of to human visual perception had been largely overlooked.

In the event, it was not Land's theories but his two experiments that were to wake up the scientific world. One reason for their great influence was their clarity. Though it could be argued that they showed nothing new, they put the evidence before our eyes in a way that was clear, unequivocal and astonishing. The first experiment produced the data upon which his *Retinex Theory* was based. The second, which might more legitimately be called a "*demonstration*", produced an undeniably powerful experiential proof that wavelength and colour are not at all necessarily the same thing.

The light 'primaries'

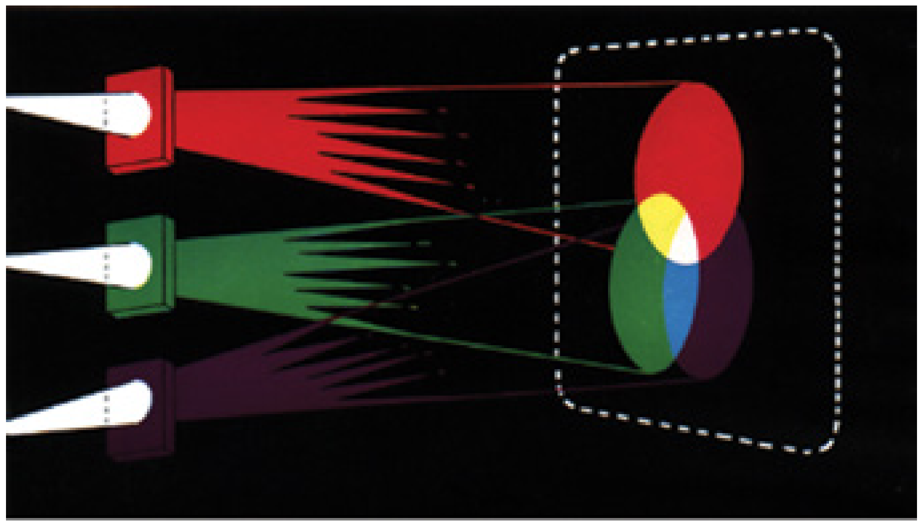

Figure 1 : Three projectors creating overlapping discs of the three primary colours.

From my students I have learnt that a great many people do not know much about the light primaries and their mixtures. For this reason, when I explain Land's demonstration to my students, I start at the beginning, introducing them to the light primaries. *Figure 1* shows three projectors, one with a red filter, one with a blue filter and one with a green filter creating three discs of coloured light on a white painted screen, in a dark room. Colour mixtures occur where they overlap. Thus: blue and red make violet; blue and green make blue-green; and, red and green make yellow. Where all three discs overlap, white is created.

Many people are surprised to find that the three light primaries do not include yellow. To help them get a feel for the situation, I explain that adding two light sources always results in a beam of increased intensity. It follows from this that the most intense or brightest colours will be mixtures. Thus: white is a mixture of all three primaries, and, therefore, is the brightest. Similarly, violet, blue-green and yellow are brighter than the colours from which they were mixed (henceforth, referred to as "*parent colours*"). In short, *parent colours cannot be the brightest*. Looked at this way it becomes logical that yellow, the experientially the brightest colour, must be a secondary.

Coloured lights making the full gamut of colours

It is easy to see that, if the beams of light from the three projectors are moved inwards so that they overlap progressively more and more, the area of white will become larger and larger. When the beams overlap completely, as in *Figure 2*, the effect will be the same as that produced by one projector projecting white light. With this arrangement it is easy to demonstrate light-mixing in a different way. First, each projector can be switched on independently, thus providing a sequence of three discs corresponding to the three light-primaries, red, green and blue. Alternatively, any two of the three of projectors can be switched on (that is to say, blue and red, blue and green and, red and green) producing the light secondaries, violet, blue-green and yellow.

More pertinent to the ideas about to be presented, the number of coloured light mixtures can be enormously increased by adding a dimmer switch (rheostat) to each of the projectors. In this way, the intensity of each light-source can be varied infinitely and, consequently, an infinite number of wave-length combinations can be projected at the screen, producing a very large number of different colours. My students often seem to think that this number should be infinitely large, but this reflects the confusion between the physical properties of light and the psychological phenomenon of colour. The students forget that colour is a product of the visual system and that the sensitivity of that system is limited. However, though not infinitely large, the number of different colours to which the eye-brain is sensitive is pretty impressive. One estimate is seven million another a mere two and a half million..

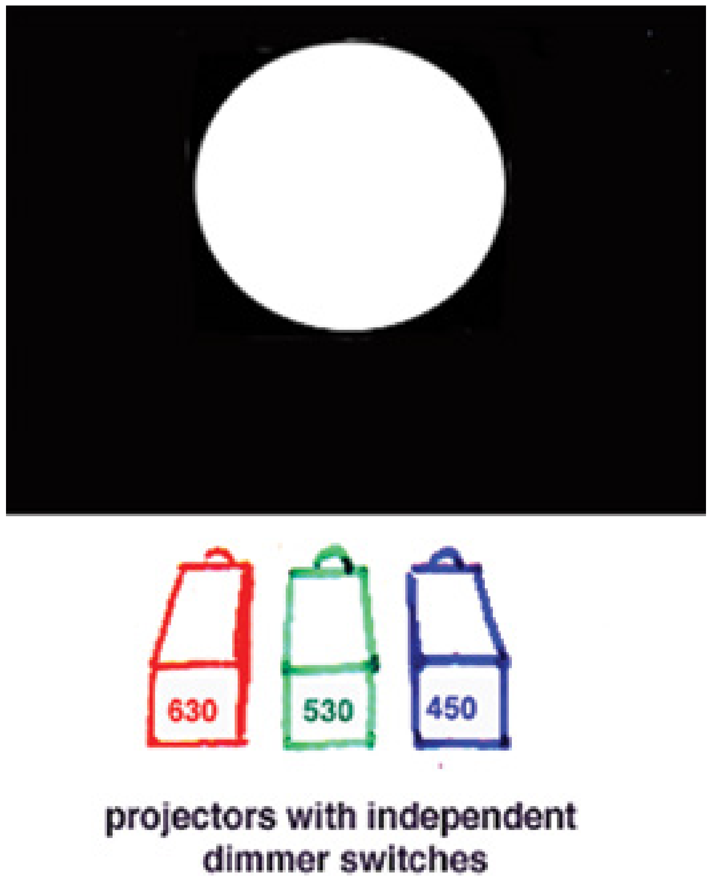

Figure 2 : Three projectors projecting three discs of light onto the same region of a white board.

The Experiment

Land's experiment is very simple. The set-up was as just described, using three projectors, three rheostats and a screen, but with three crucial differences:

- The screen was covered with various sized rectangles of coloured paper, as illustrated in *Figure 3*.
- A telescopic photometer (a light-meter that can take readings of small areas of the screen from a distance) has been introduced to provide a means of monitoring changes in lighting conditions.
- A scientifically recognised colour reference chart has been introduced.

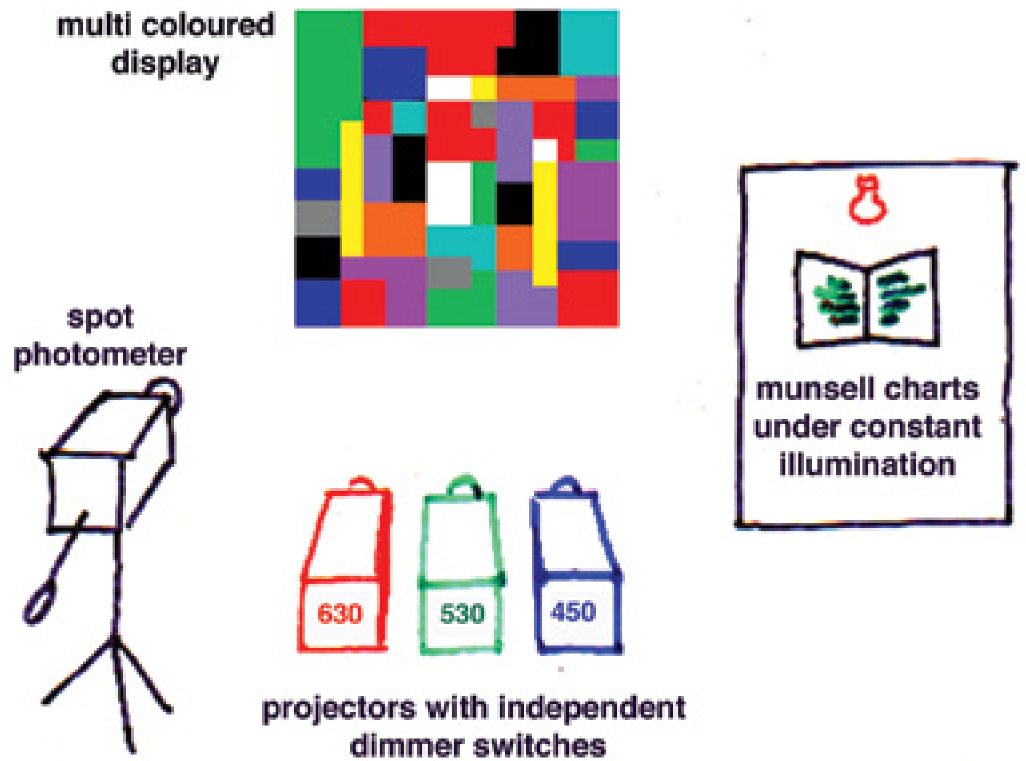

Figure 3 : The set-up for land's first demonstration. The numbers written on the back of the projectors correspond to the wavelength used.

From the scientific point of view, the arrangement of coloured papers could have been arbitrary. All that was required was a representative range of colours, including the primaries, the secondaries, black and white. However, for idiosyncratic aesthetic reasons, Land took a great deal of trouble over the appearance of his display and he was proud enough of the result to feel justified in calling it a

"*Colour Mondrian*", in homage to the Dutch Constructivist painter of that name. Though the attribution may have made the fastidious Mondrian turn in his grave, the relevance of Land's gesture in the present context is that it calls attention to the MCD can be described as "*an arrangement of colours on a flat surface*" (the words famously used by the artist Maurice Denis to describe all paintings). Clearly the findings of the experiment, if they turned out to be interesting, would be relevant to the experience of looking at paintings.

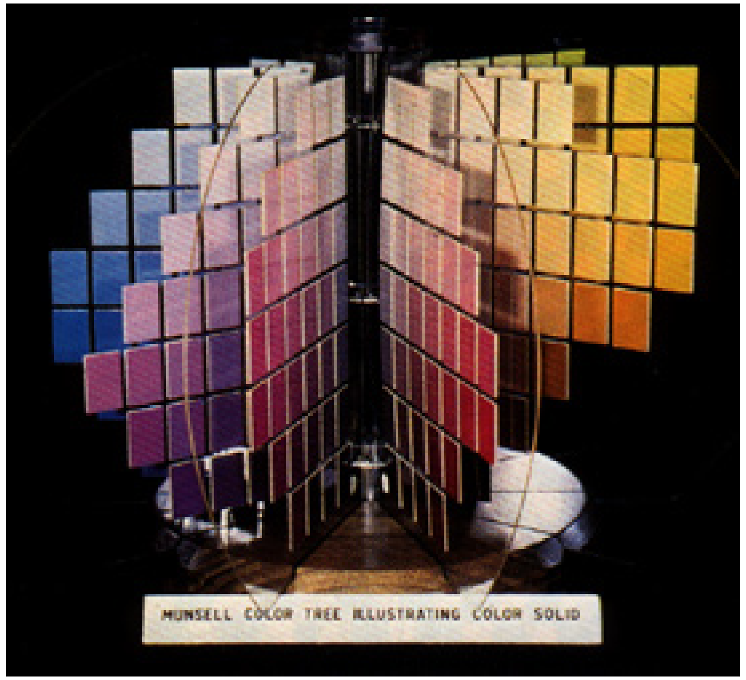

Figure 4: A Munsell "solid" showing a selection of "chips" laid out according to the scheme found in the munsell book of colour.

A colour reference chart used by Land was the Munsell Book of Colour[4] illuminated by a constant white light source. For those who have not come across this book, it is worth mentioning that it is the generally accepted scientific reference for the classification of coloured surfaces. It consists of seventy-two pages of samples (usually referred to as "*colour chips*"), with each page dedicated to a different hue. The chips in any vertical column vary in respect of lightness (what Munsell calls "*value*") and, in any horizontal column, in terms of satura-

4 Munsell Color, 1976, Macbeth Division of Kollmorgen Corporation, Baltimore.

tion (what Munsell calls "*chroma*"). In this way it provides a fairly comprehensive mapping of colour space.

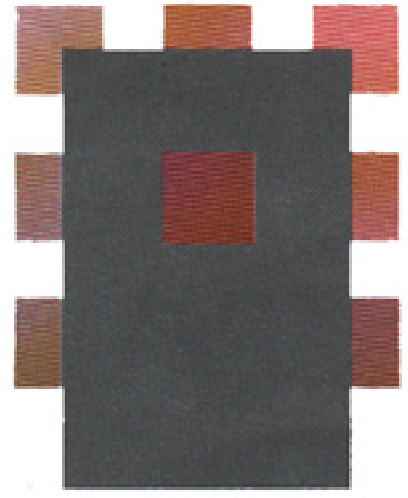

FIGURE 5: A part of a page from the munsell book of colour., with grey card to surround each colour tried out

Figure 4 gives an impression of the form of this colour space by displaying a view of the chip-array from a small number of Munsell pages. *Figure 5* illustrates a detail of one page. The grey card is used to minimise lightness-contrast effects which might otherwise interfere with the judgement of those attempting to match particular chips with coloured surfaces.

The experimental task

For his experiment, Land's experimental subjects were asked to compare colours in the multicoloured display with chips in the Munsell Book of Colour, using one eye to look at the former and the other, to look at the latter. Their task was to find the Munsell chip which most closely corresponded to a selected colour in the multicoloured display. When they had made their judgement, records were taken, using the *telescopic photometer*, of the light reflected from the selected colour when illuminated by each of the three coloured light sources in turn. The upshot was three reflectance readings, which Land termed *reflectance-triplets*.

This first trial having been completed, the rheostat settings for the three projectors were changed such that they would produce different combination of photometer readings. When the adjustments had been made, the experimental subjects were asked to repeat the same procedure as before and make another set of matches between the identical sequence of colours in the multicoloured display and the Munsell chips. For each new combination of light sources, the set of *reflectance triplets* was recorded. Sufficient experimental subjects were used to give statistical validity to the findings.

The main result of the demonstration was extremely simple. As long as all three of the light sources were contributing to the illumination of the multicoloured display, then, no matter what the reflectance triplets, the experimental subjects *matched the same display colour with the same Munsell chip*. In other words, no changes occurred in the appearance of the variously illuminated colours. According to Land's way of measuring, they remained absolutely constant.

Neutralising painted colours

We are now ready to introduce Land's second way of demonstrating the same phenomenon. For this purpose, it will help to explain how a slightly modified version of the equipment just described can be used to neutralise brightly coloured surfaces. This takes us back to fundamentals. The green appearance of green paint is due to the fact it absorbs all but the predominantly green wavelengths which give rise to the colour impression it generates. Roughly speaking, this is the same as saying that it absorbs the red light. It follows that if there is only red light illuminating a region of green paint, all of it will be absorbed and the surface will be deprived of its colourfulness. Likewise, a red surface illuminated by a complimentary green light or a blue surface illuminated by a complimentary yellow light will be deprived of colourfulness. In all cases the outcome will tend towards an absence of light, which is somewhat prosaic way of describing "*black*". This being the case, it is easy to see that just the right mixture of white and red light could be used to neutralise a region of green, while leaving some white light still reflecting from it. The result could be a perception of *dim white* or, as it is usually called, *grey*. Similarly, it should be evident that with appropriate manipulations of the rheostats, the equipment described is capable of neutralising any other painted colour.

Land's second demonstration

Whilst not having had the luck to be one of the subjects in Land's first experiment and, therefore, knowing of it only from the *Scientific American* article, I did have the opportunity to experience his second demonstration. The reason was that my interest in the phenomenon of colour-constancy led me to visit Semir Zeki, *Professor of Neurobiology* at the *University of London*. Professor Zeki had been using Land's multicoloured displays to investigate the neurophysiological correlates of colour-constancy and, by 1980, he was publishing interesting results, associating a specific location in the visual area of the brain with colour constancy.

In his laboratory he showed me the set-up illustrated in *Figure 6*. It is essentially the same as the previous one, except for two variations: (a) the projectors had been arranged in such a way that, by means of a prism, their light could be fused into a common beam, and (b) a diaphragm had been positioned such that the beam could be narrowed down or opened up at will.

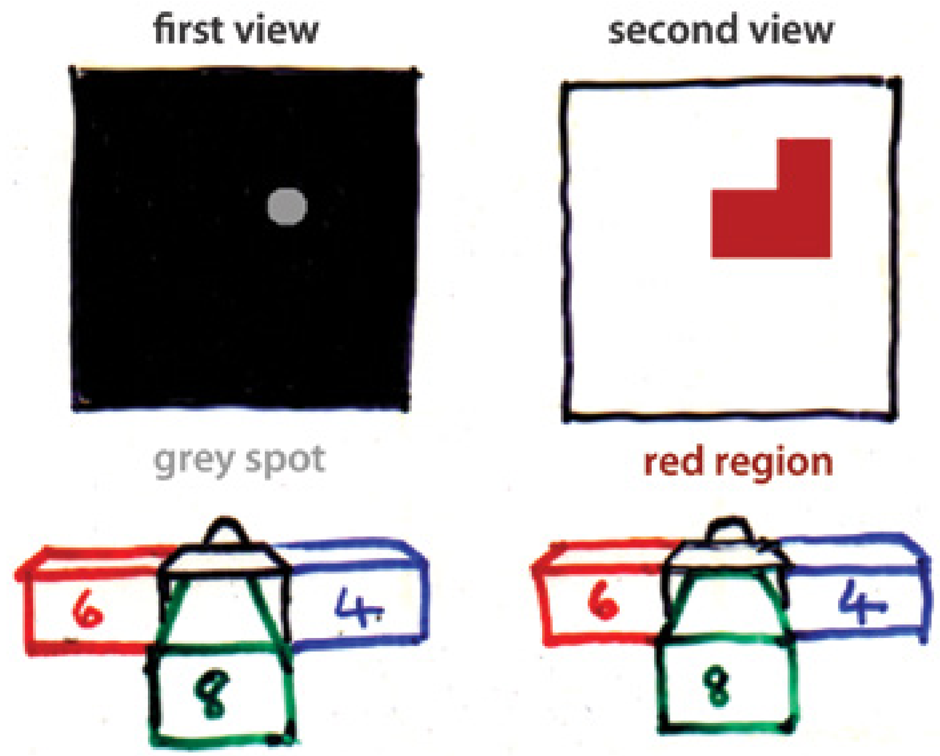

Figure 6: The set-up for Land's second demonstration. Here the red shape is isolated, but for the experiment it was part of a multicoloured display.

To start the demonstration, Professor Zeki focused a narrowed-down beam so that it shone on one and only one of the colour areas in the multicoloured display. As it happened, on this occasion, he had chosen a bright red area. As the light was now illuminating a uniform region of colour, that part of the multicoloured display became equivalent to the uniformly coloured blank screen, described above. This meant that manipulations of the three rheostats would now bring about changes in colour appearance. In particular, the red patch could transformed into a neutral grey, as shown in the illustration.

The miracle occurred when the diaphragm was opened out for, although the wave-length combination of the illuminating light remained unchanged, the colour appearance of the grey patch did not. Dramatically and spectacularly it was transformed into its former glory, becoming as brilliant a red as ever it had been. Professor Zeki told me that equivalent transformations could be wrought for all the different colours on the multicoloured display and that they occurred for one hundred per cent of people with normal colour vision.

So what had brought about this miracle? Since the transformation occurred at the moment when all the colours of the multicoloured display became simultaneously visible, there was no escaping the conclusion that it was due to interactions which occur only when numbers of colours are viewed at the same time. In other words, the critical factor was ***contex***t.

Implications

Why was I so excited by all this? The answer is quite simple. What Land's experiment clearly shows and what his demonstration so vividly confirms is that regions of surfaces of identical pigmentation can be perceived as the same, though reflecting different (sometimes very different) wave-length combinations into the eye of the viewer. Though, in this case, the composition of the reflected light was varying over time rather than over space, was this not exactly the same paradox that had troubled me in relation to the dogmas of Professor Bohusz-Szyszko? From this moment on, I knew that, if ever I could find a way, I had to get to the bottom of the mystery of colour constancy.