INTRODUCTION TO THE SCIENCE OF LIGHT AND COLOUR

The purpose of this "Introduction" is to provide a guide to a number of scientific ideas that underpin the practical suggestions found in this volume. Although some of these could prove to be a challenge to all but specialists in areas relating to the study of visual perception, neurophysiology and computer modelling of brain systems, a full understanding is not necessary. All that is required is a general awareness of the issues they raise. What follows concentrates on three subjects that many people find confusing. They are:

- *The meaning of the word "colour".*
- *The nature of light.*
- *The ways in which eye/brain systems separate out reflected-light from body-colour.*

The knowledge required for giving the definitions of "light", "colour", "reflected-light" and "body-colour" used in this book were all recently available when the young Impressionists first developed their revolutionary ideas about painting. However, they are still widely used in ways that lead to many misunderstandings.

The science that explained the separation of "body-colour" and "reflected-light" by eye/brain systems was not established until the 1980s. As we shall see, its findings play a key role in this volume.

Colour and confusions of meaning

In everyday life, most people feel comfortable in their use of the word "colour". However, in the context of painting, certain kinds confusions are common. Four examples of situations in which these regularly occur are:

- *When trying to answer the old chestnut question as to whether "black" and "white" are colours.*
- *When faced with using pigment-colours to create effects of surface, space and light.*
- *When painting shadows.*
- *When painting interreflections between adjacent surfaces that are impossible-to-see consciously, but possible to perceive subconsciously.*

To clarify the situation it is necessary both to understand more about the nature of light, and to get a better idea of the eye/brain systems that use information *residing in it to create perceptions of colour, surface-form, space and ambient illumination.*

Light as wavelengths of electromagnetic energy

The information presented in Figure 1 is well known from physics text books. In it, light is conceived of in terms of ***wavelengths*** *within an electromagnetic spectrum. Notice that light occupies a very small proportion of the totality of this spectrum and takes its place amongst many other ranges of wavelengths. These include, radio waves (the longest), microwaves, infrared rays, ultraviolet rays, x-rays and gamma rays (the shortest). Notice also that the different wavelengths of light (the narrow band in the central band of the display which is expanded in the bottom band of it) are represented by colours. This is because the factor that distinguishes the wavelengths that we call "light" from all the other wavelengths is that it is only these that activate the light-sensitive receptors in the eye.*

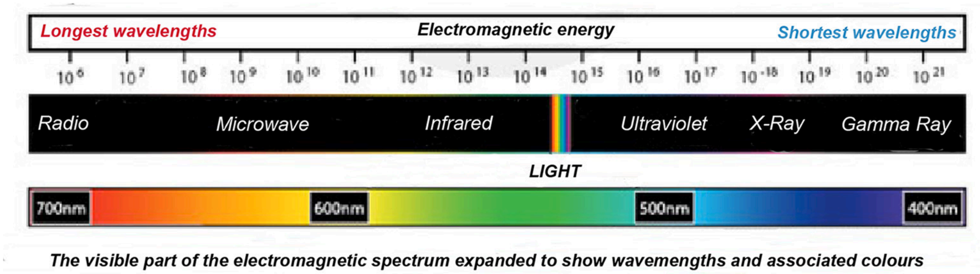

Figure 1 : A diagrammatic presentation of the electromagnetic spectrum.

Light and visual experience

What distinguishes light from the remainder of the electromagnetic wavelengths is the fact that it alone can stimulate conscious visual experience. If we ask how this is achieved, we find that the first part of the answer lies in the array of light-sensitive receptors which can be found in the retina at the back of the eye (diagrammed in Figure 2). Their job is to transform the patterns of light of varying intensity and wavelength combinations that enter the eyes into patterns of neural activity distributed across the retina. It is these that provide the information-base for the perception of both colour and surface.

To understand the nature of visual processing it helps to keep in mind the difference between the processes involved in:

- *Giving meaning.*
- *Controlling actions.*
- *Creating conscious experience.*

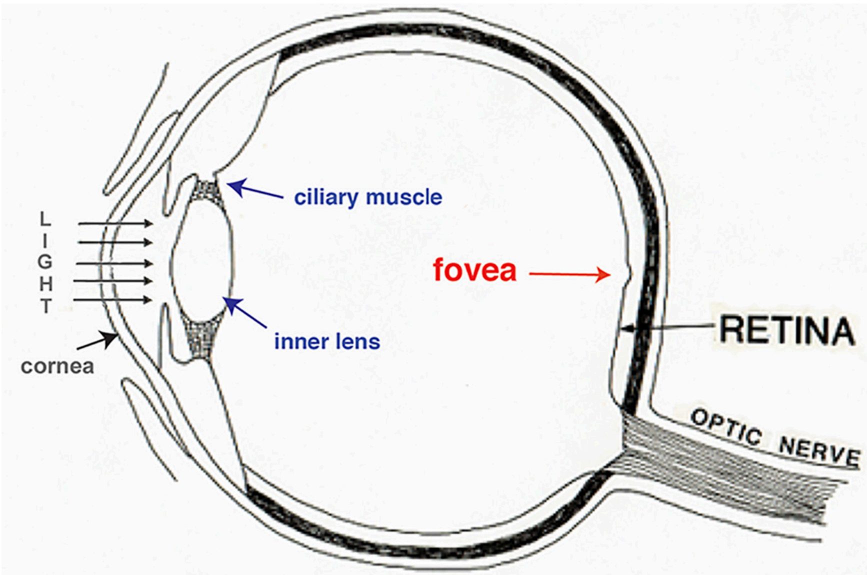

Figure 2 : A diagram of the eye indicating a lens system at the front and the retina at the back.

In particular, it is important to realise:

- *That the majority of the visually-derived information that is used either for giving meaning to whatever it is that we are attending to, or for guiding actions, never reaches the level of* ***consciousness****.*
- *That there are components of our conscious visual experience, including a sense of* ***surface****, of* ***space*** *and of* ***light*** *that cannot be experienced in a way that is analogous to the direct in which we all experience colour. This is important to realise for it means that these fundamental properties of experience cannot be analysed by the eye/brain's visual analytic systems.*

If we want to imbue our paintings with a sense of these phenomena, we must find ways of using pigment colours that enable us to recreate the conditions which give rise to them.

Fortunately, over the centuries, artists, with much help from scientists, *learnt that an important part of the solution to this problem lies in acquiring a mastery of two kinds of whole-field relationships, namely:*

- ***Whole-field lightness relationships****. The first steps in this direction were taken by artists of the Italian Renaissance when they began to explore the possibilities of the method that we now know as "chiaroscuro".*
- ***Whole-field colour relationships.*** *The story of how artists learnt to master these and how scientists came to understand why their solutions worked is the main subject of the first of the two books in this volume, "Painting with Light". Crucial to the new understanding was a diagram similar to the one presented in Figure 3. It is to this we now turn.*

The diagram

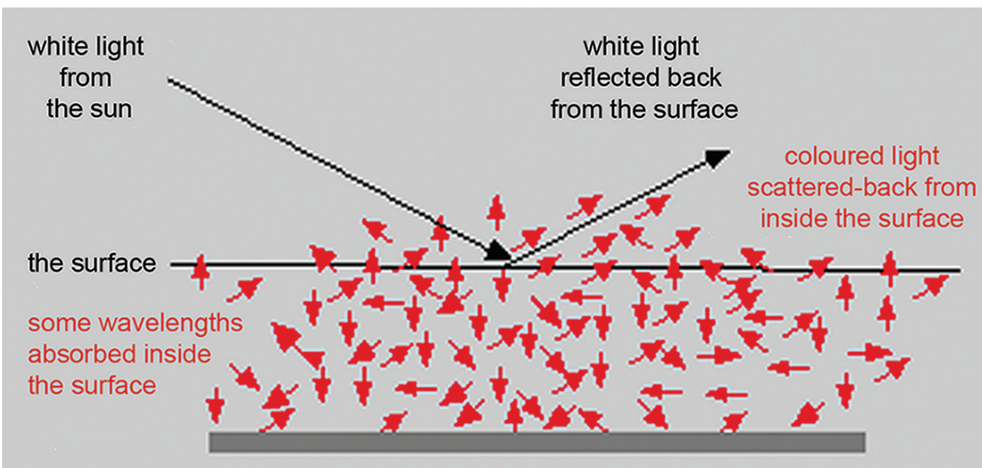

Figure 3 : The physics diagram that revolutionised painting.

The importance of this diagram in the history of art cannot be overestimated. It was the source of ideas that were to spark a revolution in the use of colour in painting. It did so because of the crucial role it played in the theorizing of Georges Seurat, whose ideas either directly or indirectly liberated a generation of forward-looking artists from various misconceptions and paved the way for a completely new look in paintings. "Indirectly" because the repercussions *of Seurat's researches:*

- *Went far beyond the narrow confines of the "Pointillist" method developed by him and his friend Paul Signac.*
- *Were to have a transformative effect on the work of innumerable artists, including Cézanne, Van Gogh, Gauguin, Matisse and Bonnard and, indeed, to some extent, whether consciously or unconsciously, practically every artists since.*

*By no means coincidentally, the same diagram provides a key to a new approach by scientists to the subject of "**colour constancy**" that surfaced in the early 1980s, almost exactly one hundred year after Seurat came across it.*[1] *It was also key to the work that I undertook with the help of colleagues at the University of Stirling relating to the perception of **surface-solidity**, **surface-form**, **illusory pictorial space** and the creation of **effects of light** in paintings.*

Defining "reflected-light" and "body-colour"

One of the reasons why Seurat saw significance in the diagram was that his mind had been prepared by developments in the science, which had been making fundamental advances in the understanding of "light" and "colour", the two phenomena with which this book is concerned.

The relevant part of the history of these started, towards the end of the 17th century, with Isaac Newton's celebrated experiment on the composition of light. First, Newton demonstrated that when a beam of white light is shone through a prism, it is split up creating a display of all the colours of the rainbow (sometimes referred to as the "prismatic colours"). Then, Newton showed that when this gamut of colours is shone back through the prism, they recombine to produce "white" light. In this way, he had demonstrated that "white" light is a composite of all the wavelengths.

Today scientists are likely to describe Newton's demonstration without reference to colour. Rather, they talk in terms of a range of wavelengths of electromagnetic energy stretching from relatively short to relatively long (diagrammed in Figure 1). The Impressionists, thinking of the colours produced by Newton's prisms, referred to these as the "prismatic colours", a continuum ranging from blue (short wavelengths) to red (long wavelengths).

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1 Annie Hulbert, 1986, "*Formal connections between lightness algorithms*" Journal of the Optical Society of America A Vol..3, page 1684

It was nearly a century after Newton's experiment, that scientists began to develop a whole new conception of colour. This emerged as a result of a break-through that, although less well publicised than Newton's, was nevertheless an epoch making event. It was based on an accumulating body of evidence which showed that colour is neither a property of light nor one of surfaces found in an external world. Rather, it is an ***experience made in the head*** *created, as we now know, by the complex of neural networks that enable the functioning of the eye and the brain. Clearly, from now on, the word "colour" needed to be thought of as being on a separate level of description to that of "light", as posited by Newton.*

Key to the development of this new way of thinking was the discovery of:

- *"Induced colours".*
- *"The existence of three primaries capable of combining into all the other prismatic colours".*
- *"Colour contrast effects".*
- *"Colour constancy".*

All of these phenomena were well known by the 1860s, when the young Impressionists were developing their ideas. Most importantly in the context of this book, the new ideas were available to Georges Seurat in the early 1880s, when he happened across the diagram presented in Figure 3. What he learnt from it was that physicists, building on the ideas of Newton, had found that when natural light, which contains all the wavelengths of the spectrum, strikes a surface, it interacts with it in two very different ways to provide separate information from ***reflected-light*** *and* ***body-colour****.*

Reflected-light

One part of the light that strikes the surface is reflected directly back from it. During the process of reflection the wavelength composition of the light remains unchanged in precisely in the same way as the composition of the light reflected from the surface of a mirror is unchanged.[2] *We seldom see coherent mirror images in everyday life because very few surfaces that we come across are mirror-smooth. On the contrary, the overwhelming majority of surfaces are made up of innumerable tiny projections, bumps or undulations, all with multiple facets that are facing in many directions. As a result the light is reflected back in a multiplicity of directions such that the surface in question produces a confusion of reflec-*

2 Known to scientist as "*specula reflection*".

tions that we perceive as being on the continuum"matt" to "glossy"[3].

*However, whether coherent or fragmented, whether mirror-like, matt or glossy, the word-combination used for this component that never enters the surface is always a subdivision of "**reflected-light**".*[4] *One of the keys to understanding what follows in this volume is that, in all natural contexts, this reflected-light always contains the entire spectrum of wavelengths of light.*[5] *The focus of "Painting with Light", the first book in this volume, is on simple ways in which this complexity can be exploited by artists.*

Body-colour

*The remainder of the light enters into the surface, where some of its wavelengths are absorbed by the pigment/medium combination of which the surface is composed, while the remainder is scattered around inside. What we experience as the "colour" of the surface is largely determined by the wave-length composition of the proportion of this internally scattered light that is eventually scattered-back-out again in the direction of our eyes. It is this within-surface activity that enables us to perceive the green of leaves, the red of red roses, the skin colour of skin, the stone-colour of stone and the characteristic colours of all other surfaces, including those produced by each and every one of the colours in the entire range of artists pigments. The word-combination we use for what we perceive is "**body-colour**". It is ways of making use of this can that provides the focus of "Painting with Colour", the second book in this volume.*

Two visual systems

A century after Seurat, game-changing initiatives, advances in neurophysiology and computer modelling made it possible to identify two different visual systems: one dealing with body-colour and the other with reflected-light. Each of these had very different properties.[6] *Thus:*

- *According to widely accepted but certainly a little oversimplified theory, perceptions of body-colour are created on the basis of informa-*

3 Known to scientists as "*diffuse reflection*".

4 I this book an important distinction is made between "*reflected-light*" with a hyphen and "*reflected light*" without one. The latter corresponds to the common usage in which "body-colour"and "reflected-light" are compounded as if they were one phenomena (see Glossary).

5 It is only in very unnatural contexts, when scenes are lit by narrow waveband light sources (for example, by sodium lamp lights) that this is not the case.

6 As also explained in the *Introduction* to *"Painting with Colour".*

tion being fed through the tiny area of the retina known as the "fovea" (see Figure 2), using very small sizes of receptive field depending on input from three receptor-types tuned to three specific wavelength ranges. It is this system that provides the basis for the colour theory found in art books.

- *Perceptions of effects due to reflected-light are derived from information coming from the entirety of the visual field, fed through the whole extent of the retina, using large numbers of overlapping receptive fields of greatly varying sizes and depending on different sets of wavelength-sensitive receptors (including wavelength sensitive rod receptors). The products of this system cannot be described in terms the three primaries theory.*

Not surprisingly the visual experiences provided by the different systems also have very different properties, a fact which has fundamental implications for artists. Some of these were worked out by the artists themselves on the basis of a combination of the science available in the nineteenth century and personal experimentation.[7] *Others are based on more recent research and are presented in this series of books for the first time.*

Colour constancy

There are two kinds of colour constancy:

- *Spatial colour constancy is the phenomenon by which areas of identical pigmentation, situated on different parts of a surface, appear as being the same, despite variations in the reflected-light occurring across the surface, which mean that the wavelength combination entering the eye from the identically pigmented regions is actually different.*
- *Temporal colour constancy is the phenomenon by which regions of identical pigmentations perceived, at different times, under different lighting conditions (that is to say different combinations of wavelengths) are perceived as being the same.*

Both these phenomena depend on the eye/brain using information coming not only from the separate or separately viewed regions of colour themselves, but also from other parts of the surface on which they are situated.

7 See "*Chapter 1*".

Although the phenomenon of colour constancy is of marginal interest to most artists, the way the eye/brain achieves it is of fundamental importance to the experience of looking at paintings. The reason why is that it depends on separating out surface-reflection from body-colour and using the information contained in both to provide us, not only with colours that remain stable under different lighting conditions, but also with experiences of surface solidity, surface form profile, 3D spatial separation and quality of the ambient lighting conditions.

Visual systems

It had long been established that visual perception depends on various different visual systems and subsystems. For example, some gather information from the edges and contours of objects (the subject of "Drawing on Both Sides of the Brain") while others extract it from their surfaces (the subject of this volume on "Painting with Light and Colour"). Our research findings added to the available knowledge both by refining earlier understandings and by identifying a number of new subsystems. In the process it provided answers to two basic questions:

- *Why artists face intrinsic difficulties when they come to analyse scenes and the objects within them that they believe themselves to be seeing so very clearly?*
- *What can be done to resolve the difficulties?*

The use of science in previous how-to-do-it painting books

Reference to science in how-to-do-it painting books has been commonplace. Unfortunately, too often, the findings referred to have been out of date or misunderstood. Progress in the relevant areas of research has been particularly significant in the last 40 years, not least because of the investigations undertaken by myself and colleagues at the University of Stirling. In essence these were concerned with how the eye/brain combination makes use of the information contained in the light that enters the eyes. Our project benefitted greatly from a cross-fertilization of ideas and information coming from many different disciplines. It touched on most aspect of visual perception, but its main focus was on three of them, namely:

- ***Recognition** and how this provides preconscious access to the memory.*
- *The **action instructions** that guide **analytic-looking** and **mark-making** when drawing or painting from observation.*

- *The dependence of analytic-looking systems on the computations that give us the* ***constancies*** *of size, shape, orientation, lightness and colour, and how this causes problems for anyone who is seeking accuracy when drawing or painting from observation.*
- *The knowledge-base required for creating effects of* ***surface-form****,* ***light, space*** *and* ***harmony*** *in drawing and paintings.*

Implications

*From perspective of what follows, the most important part of this "Introduction to the Science" is the distinction between "****body-colour****" and "****reflected-light****". The following pages provide many reasons why artists would do well to consider the fundamental nature of the difference between these two pillars of visual experience.*[8] *The purpose of this volume is to show how a comprehensive knowledge of them can help artists when:*

- *Analysing scenes with a view to representing them*
- *Attempting to give life to collections of marks and/or colours applied to a picture surface, whether or not they are perceived as figurative.*

8 See also the "*Glossary*".