What is red?

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"Mere colour, unspoiled by meaning, and unallied with definite form, can speak to the soul in a thousand different ways." Oscar Wilde

The representation of colour in the world we experience has been the subject of debate and introspection for centuries. The colour red is synonymous with blood, life, death and revolution. Blue is associated with cold and sadness, dehumanising nature more than any other colour (according to Nietzsche) whilst being oddly rare in the natural environment. Yellow is sickly, golden and the gilt of royalty; green is envious, the colour of chlorophyll – the root of humanity. Artists, philosophers, neuroscientists and psychologists find common ground in the discussion of the experience of seeing colour, and of all aspects of vision it is the most likely to arouse interest (and lust[1]) in the scholar, student or casual acquaintance. The aim of the lectures is to do just that – inspire interest and a desire to know more rather than bombard you with a myriad of detail – of which there is no doubt that there is.

I hope that it is now becoming clear that despite this universal appreciation of the sense of colour, and the wealth of quantitative data on the neurophysiology and behaviour of the visual system, we lack a sound coherent framework in which to place the wide range of experiences we associate with our colour vision. One of my major research aims is to provide such a framework, or at least its bare bones, by taking the enduring issue of excitation and sensation in colour vision[2] and challenging and perhaps changing the way we think about the operation of the system from the very beginning of the visual signal.

The scientific approach to the question of how we see is to take a particular visual stimulus and to quantify the behaviour of the organism, or output of the neurone, in terms of the properties of the stimulus. The philosophical question of 'what is the world?', however, tends to be overlooked by referring back to the stimulus when assessing the performance of the system, or of any particular model or theory. If one seriously entertains the possibility that the world is a construction of the brain[3], then this constant reference to the input becomes less tenable. What we do know about the components of the visual system and its operation at the most gross of levels suggests that contact with the image projected on to the retina is lost almost

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[1] "Colour is the femme fatale of vision. When once seduced, you will never be a free man again." Ragnar Granit to William Rushton

[2] "…the opponent-colours theory and the Young-Helmholtz three-colour theory could, with some modifications, very well exist side by side if one strictly distinguished between the process of excitation and the process of sensation and use the three colour theory for the former and my theory for the latter".
Ewald Hering, 1905

[3] "The apparent world and the true world means - 'the world' and 'nothing'"

Friedrich Nietzsche (after Bishop George Berkeley) immediately and the world we perceive is indeed a construct of the operation of the system. Whether it is a faithful representation of what is 'out there' is probably less important a question than what this loss of contact with the image means for the operation of the system and the potential and freedom that this dissociation offers the mechanism of operation.

As I have said, I find that taking a historical perspective on a particular issue facilitates the construction of an internal framework of understanding. It was with this in mind that I talked about Newton, Young, Helmholtz and Hering for I believe that their insight laid the foundations for what we know about the visual system today. In many ways we have just confirmed their insight.

Isaac Newton (1643-1727) – By showing that white light was made up of all visible colours, Newton inadvertently allowed the visual environment to be quantified in the sense that the relationship between the light source, the reflecting surface and the receptor mechanism could be clearly described and considered. Without this stage, it is unlikely that the question of how we see that environment would have progressed very far. Put most simple, Newton allowed the problem of vision to be clearly defined which is the essential first stage in any research.

Thomas Young (1773-1829) and Hermann von Helmholtz (1821-1894) – Both Young and Helmholtz realised that to postulate a receptor or detector that independently signalled every colour we could possibly see, at every point in space that we could possible see it was biologically unfeasible. Instead, they took the observation of Newton that white light constituted all visible colours, and related that to what they could see through the operation of their own visual system. I believe one of the key observations they must have made was that although all visible colours are created by decomposing white light, the same white light could be reconstructed from just three colours. Thus it was possible that our visual system constituted just three receptoirs at the outset and by somehow comparing the output of these receptors we were able to reconstruct all colours seen. Thus the concept of Trichromacy was developed with very little knowledge of retinal structure, just careful observation and thought.

Ewald Hering (1834-1918) – Hering did not entirely agree with this idea because he made a further observation, namely that prolonged exposure to a stimulus produced an afterimage, and the appearance of that internally-generated stimulus was not a copy of the inducing stimulus, but a complement of that stimulus. Thus a red light produced a green afterimage, a blue light produced a yellow afterimage. In conjunction with the observations of Young and Helmholtz, Hering initially suggested an alternative first stage of vision that constituted four, rather than three, receptors wired into pairs in opposition to one another: red-green and blue-yellow. Later, however, Hering realised that these two possible explanations were not mutually exclusive, but complementary in that there could be a first trichromatic stage and then and opponent stage. His insight was quite astonishing for this is exactly what we now know to happen – in as much as we know anything about the visual system.

Colour spaces

A colour space is a method by which a particular light and colour may be represented such that its definition is unique and replicable. They are just a tool that we use in research but a critical one if we are to compare data across studies and modalities. They also provide a quantitative framework on which to build a view of the system's first stages. Generally, if both colour and brightness are to be represented, three axes are required to define the space. Although the two dimensional, (x,y) coordinate system of CIE space is the standard 2-D 'unit' by which colours are described in vision, it tends to be less utilised in research and the description of data as there is, by default, no luminance, brightness or intensity dimension (although this can be added). It is more intuitive to use a stimulus description that has some relationship to the underlying mechanisms one is trying to define and in this context the three examples commonly utilised in vision are Cone-space, Cardinal space and Munsell space. Others that may be familiar to you are CMYK space and HSV space, both utilised in graphics and printing applications.

While any visible coloured light can be expressed in any of the three colour spaces each can be thought of as relating best to a particular level of processing within the system. In terms of the distinction between excitation and sensation offered in the lectures, the Cone (L,M,S) and Cardinal (L-M, S-(L+M), L+M(+S)) colour spaces relate to the 'excitation' stage of processing, the Munsell space relates to the sensation of colour. This latter representation can be distilled into a 'Unique hue' (Red-Green, Blue-Yellow) space for convenience; the important aspect being the *perceived* colour as opposed to the elicited cone excitation. I made the point that while Hering's insight into the underlying mechanisms was impressively accurate, his opponent mechanism existed both at the level of excitation and sensation.

Cardinal colour axes: The Cardinal axes of colour space (Krauskopf, Williams and Heeley, 1982) are so called because of the way in which these axes are defined. Since Hering's original observation, the theory that colour is coded in three opponent channels has gained much supporting evidence. The theory of colour opponency is illustrated in its most basic form by the existence of the Cardinal axes of contrast detection. The cardinal axes or directions in colour space describe the sensitivity of three independently adaptable detection mechanisms which have the effect of breaking down the colour (hue, saturation and brightness) of any point in the visual image into three numbers describing deflections along each of the three axes from the point of constant adaptation.

The cardinal colour space consists of two chromatic axes and one achromatic axis. Movement in the plane described by the chromatic axes changes the colour of the stimulus but not the luminance and movement along the achromatic axis changes the brightness of the stimulus without changing the colour. These psychophysically-defined axes correspond *approximately* to the sensitivity of the mechanisms thought to underlie our ability to detect chromatic and luminance stimuli. For the convenience of initial description the two chromatic axes will initially be termed red-green and blue-yellow but, as will become clear, this nomenclature alone highlights the problem this work aims to deal with. Modulation along the red-green chromatic axis would be detected by a mechanism taking the opposed outputs of Long wavelength-sensitive (L) cones and Medium wavelength-sensitive (M) cones (Stromeyer. Cole and Kronauer, 1985). Movement along the blue-yellow axis is likely to be detected by a mechanism taking the outputs of Short wavelength-sensitive (S) cones alone ((Boynton & Kambe, 1980)). Modulation along the achromatic axis is likely to be detected by a mechanism taking the summed output of L and M cones (MacLeod & Boynton, 1979). When properly located, movement along the red-green cardinal axis should not modulate the output of S-cones; movement along the blue-yellow axis will not change the difference between the output of L- & M-cones but modulate S-cones. Movement along the achromatic axis will only modulate the output of the mechanism taking the sum of the L and M cones. These axes however do not lie on the colour direction describing the maximal sensitivity of the underlying detection mechanism. The important point is that each axis lies at the point of minimal excitation, or null, of the other two opponent mechanisms. The other critical issue is that none of these axes, most particularly the S-(L+M) axis, correspond to a modulation between the colour perception of red and green or between blue and yellow; they are specifically axes of excitation. Two important points therefore come out of this description: 1) The axes are psychophysically orthogonal. 2) The axes should not be termed red-green and blue-yellow or given any other colour-name as they correspond to L-M and S-(L+M) cone excitation.

Unique hue axes: A different approach to orthogonality or opponency, and one more consistent with the classical observations of Hering, was to examine the unique-hue axes. These are defined around the perception (or sensation) of colour (Hurvich & Jameson, 1957) rather than simply its detectability (the excitation) and they rely on observers identifying a colour, usually presented at suprathreshold contrasts under free-viewing conditions, as being only one of four colour name options: Red, Green, Blue and Yellow. Thus unique yellow is neither reddish nor greenish (each of which tinge is mutually exclusive) and unique yellow cannot co-exist with blue. Each other primary has a similarly unique hue generated through the same subjective experience. This is what Hering was talking about when he described the sensation of colour. Unique-hue axes may be drawn up using naming-based experimentation such that another set of colour axes are generated which can then be compared to the Cardinal colour axes. The search for a direct physiological analogue of colour perception would be all but ended if the chromatic axes of each space superimposed but they do not. Furthermore it is clear that there is an intermediate stage between the Young-Helmholtz trichromatic representation and the Hering opponent representation; that stage is described by the cardinal axes of colour detection. A Unique hue measurement is designed to examine the sensation of colour but does so through the categorisation and naming of the colour. This process introduces another level into the hierarchy based in language . Some consider that this level of representation of colour is directly related to the underlying neurophysiology of the visual system (Kay & McDaniel, 1997; Berlin & Kay, 1969; Kay, Berlin & Merrifield, 1991); this remains a contentious claim and, in my view, is unsupported.

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