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Dispatches

Colour Vision: The Wonder of Hue

Understanding the brain requires a kind of thinking outside the main tradition of natural science: the biology has to be linked to something intangible, a private experience. Physiologists have recently recorded from neurons that promise to help make the link in the case of colour experience.

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The restaurant hostess seats our children with paper colouring placemats and gives each a pack of crayons — red, green, yellow and blue, recognized by children everywhere who intuitively understand that there is something 'unique' about these *four* colours. In this issue of *Current Biology*, Stoughton and Conway [1] relate the fundamental nature of these colours to individual neurons in the brain.

According to Albert Einstein, great advances in our understanding of nature have originated from an "intuitive grasp of the essentials of a large complex of facts [which] leads the scientist to the postulation of a hypothetical basic law or laws. From these laws he draws conclusions". This formula that has proved useful in illuminating the cosmos could be fruitful in fathoming the complex workings of the brain. Neuroscientists have yet to agree, however, on which hypothetical laws should be adopted. One grand postulate that has guided attempts to understand the brain is the 'law of specific nerve energies' or Müller's law, after Johannes Müller (1801–1858): "Each type of sensory nerve ending, however stimulated (electrically, mechanically, etc.), gives rise to its own specific sensation; moreover, each type of sensation depends not upon any special character of the different nerves but upon the part of the brain in which their fibres terminate."

The postulate of an individual neuron at some location in the brain giving rise to a specific sensation provides the link between the firing of a neuron and perceptual experience. In the case of colour vision, a goal is to discover the mechanisms that establish the relationship between the wavelength composition of light, the physical stimulus, and colour — the perception. We can imagine that for each discriminable point in the retinal image there are a set of receptors that transform light absorption into electrical signals. As these signals are transmitted to higher centers, characteristics of each tiny part of the image are extracted to form the basis of percepts.

The brain's representation of a small segment in a visual scene must be somewhat, but not perfectly, analogous to a pixel in a video display. For each pixel, the colour and brightness of light are represented as three numbers that indicate intensities of red, green and blue. In our visual brain, the characteristics of each small subdivision of a scene are experienced as some combination of fundamental colour sensations, the 'unique hues', red, green, blue, yellow, plus black and white, explaining why no fewer than four crayons added to the black and white page of a colouring book will satisfy our children as representing the real world. Stoughton and Conway [1] have now discovered a brain region, the posterior inferior temporal cortex, where the tuning of chromatic sensitivities of neurons cluster around the unique hues. The significance of this discovery can be understood from a historical perspective. The major question has been: how do *three* types of cone photoreceptor ultimately relate to the *six* fundamental colour percepts, black and white plus the *four* unique hues, red, green , blue, and yellow?

Thomas Young (1773–1829) recognized that representing the wavelength of light, a continuous variable, would require a set of receptors that encode the relative amount of light in discrete spectral bands. Because the visual system has to analyse the wavelength content of each point of an image, the constraints of biology would require a limit on the number of detectors with different spectral sensitivities, "as it is impossible to conceive each point [in the retina] to contain an infinite number of particles..it becomes necessary to suppose the number limited…each sensitive filament of the nerve may consist of three portions, one for each principle colour". Hermann von Helmholtz (1821–1894) championed Young's idea and, being a student of Müller, he extended it to link the proposed receptors to human perceptions, saying "Young's hypothesis is only a special case of the law of specific sense energies" accounting for the sensations of red, green, and violet [2].

Ever since Helmholtz's statement, the quest for a theory of colour perception can be understood in terms of attempts to match up the properties of neurons to our perceptions. Ewald Hering (1834–1918) argued that the *three* receptors postulated by Young and Helmholtz did not correspond to the number of unique hues we experience. Figure 1A shows how an equal energy spectrum might be perceived if three photoreceptors accounted directly for hue perception. Hering pointed out that there are not *three* but *four* colours, blue, green and red plus one more that did not seem to be explained by trichromatic theory — yellow. These four seemed to have a simplicity that other colours do not and although colours may be described as tinted with one or two of the four psychologically simple colours, for example, a small patch of colour can be depicted as blue, green or blue-green but colours are never described as being simultaneously red and green or yellow and blue.

Although the subject of a great deal of argument during the century from the 1870s to the 1970s, in modern textbooks this problem is often explained as being resolved by a two-stage model of colour processing proposed by Hurvich and Jameson [3], in which the outputs of the three types of cone (the first stage) are combined by neural circuitry (the second stage) that compares the quantal catches of cones to form four circuits for hue percepts that exist as

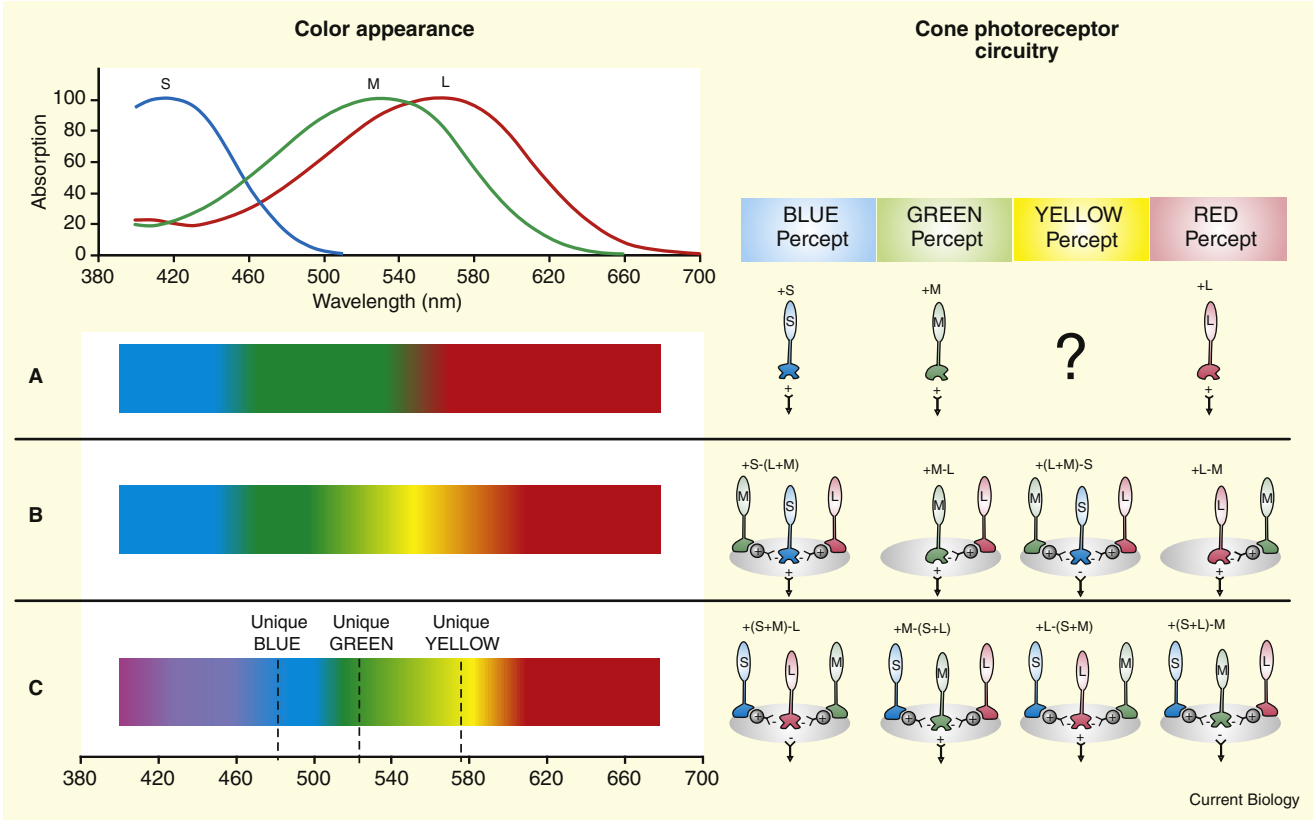

Figure 1. Color processing.

The law of specific nerve energies postulates that, at some level of neural processing, individual neurons produce specific sensations. Absorption spectra of the three types of cones, short (S), middle (M) and long (L) wavelength sensitive are shown at the top left. (A) If the individual cone photoreceptors (illustrated on the right) were directly responsible for hue sensations, an equal-energy spectrum would be expected to consist of only three unique hue sensations (left); the spectrum would, for example, be missing the colour yellow. (B) Neurons in the LGN carry signals from circuits that compare outputs from different cone types. The neural 'wiring' of four types of LGN cells is shown (right) but the cone inputs to these most frequent LGN neurons would be predicted to produce chromatic responses (spectrum at left) very unlike human color perception. (C) The way an equal energy spectrum appears to most normal observers (left) requires neural circuitry in which neurons responsible for the percepts of blue, green, yellow and red each get input from all three cones but in each case the cone signals are pooled using different combinations of positive and negative signs (right).

two opponent pairs, red–green and blue–yellow. The opponent character of the second processing stage explains why mixtures of all visible wavelengths of light yield a percept of white (the absence of hue) [4] and the observation of Hering that no colour is seen as bluish-yellow or reddish-green.

Starting in the 1950s, advances in electrophysiology made it possible to record chromatic response properties of neurons. Most exciting for biologists was that features of the two stage model seemed to be confirmed by recordings from spectrally opponent neurons in the lateral geniculate nucleus (LGN) of the thalamus, a target for axons from the retina carrying information to the cortex. But while there did appear to be two classes of blue (B) – yellow (Y) LGN neuron, +B –Y and +Y –B, which would be expected to correspond to blue and yellow, and two types of red (R) – green (G) neuron, +R –G and +G –R, as needed for red and green, respectively, the 'spectral signatures' of the neurons, illustrated in Figure 1B, do not match human colour perceptions (Figure 1C). Discrepancies were noted at the time of discovery of opponent cells (for example [5]), but these have been largely ignored in textbook accounts.

In the last few decades, the absorption spectra of the three cone pigments have been characterized with great precision (top left of Figure 1). This has made it possible to explicitly describe the difference between the textbook LGN cells and perceptual, opponent hue mechanisms in terms of the way specific cones contribute to each [6–9]. The chromatic inputs differ substantially between the two [10–12]. Textbook LGN 'red-green' opponent cells have no short wavelength sensitive (S) cone input and long wavelength sensitive (L) cone signals are opposed by middle wavelength sensitive (M) cones. In contrast, our red-green perceptions are based on circuitry in which signals from both S and L cones are responsible for red perception, such that the sensation of redness at the long-wavelength end of the spectrum is mediated by L cones, while the redness at the violet end is mediated by S cones. The S and L inputs are both opposed to signals from M-cones responsible for greenness.

Similarly, the best characterized 'blue-yellow' LGN cells have input from S cones which is opposed to the sum of L and M cones, but the spectral locations of unique hues require

blue–yellow colour vision to be based on (S+M) –L circuitry in which blueness above 460 nm is mostly produced by M cones [13], and blueness below 460 is mediated by S cones. Figure 1B illustrates how most typical LGN cells would predict an absence of redness in the short wavelength part of the spectrum, an absence of much blueness above 460 nm and very different locations of the unique hues than observed by humans (Figure 1C).

For years, progress in understanding colour vision in terms of biology has been stalled by the inability to resolve the lack of correspondence between phenomenological colour experience and the properties of LGN neurons, the only cells offered as candidates for mediating hue experience. This has led some vision scientists to question whether it is possible, or even sensible, to reconcile the domains of neurophysiology and phenomenology [12]. The new discovery of cells whose 'spectral signatures' match our hue perceptions, however, opens the way to ultimately solving the circuit that transforms cone signals into colour vision. In the past, the greatest challenge to resolving the discrepancy between the characteristics of colour opponent cells and hue perception has been the difficulty in finding a hypothetical solution that seems logical. The simplest idea is an extension of the two-stage model in which additional processing stages in the cortex would further transform LGN opponent signals, with the wrong spectral signatures into ones that match perception; however, even the most well thought out versions of this idea (for example [6]), raise more questions than they answer. It is not clear how, and even more puzzling why, the cortex would recombine the cone signals.

In contrast to the multistage idea with processing subsequent to the LGN in the hierarchy recombining cone signals to produce colour tuning that matches perception, Calkins [14] has offered the alternative that the most frequently recorded parvocellular LGN spectrally opponent cells are not a substrate for colour vision at all. He points out that, in addition to responding to wavelength, most spectrally opponent neurons are highly responsive to spatial contrast. He says that it is possible that only a small subset of opponent LGN cells, ones that do have the appropriate spectral signatures all along, mediate hue perceptions. Calkins' idea may turn out to be prophetic. This year, in their recordings from macaque LGN, Tailby *et al.* [15] specifically focused on neurons with substantial input from S cones and found small populations of cells with cone inputs that match the circuitry required for human perception of hue. It is possible that our brain exploits the majority of LGN cells for spatial vision by extracting their robust responses to luminance contrast and filtering out the spectral responses. If so, signals from the much smaller population of cells discovered by Tailby *et al.* [15] that already have the correct spectral signatures at the level of the LGN could be used for colour. In any case, it is very welcome news that, at long last, two discoveries have been made in one year of neurons that have the correct spectral properties to mediate phenomenological colour experience, one population in the LGN and the other in posterior inferior temporal cortex. These may represent two levels of a colour processing pathway that begins in the retina and ends in hue perception.

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Centrosomes: Keeping Tumors in Check

Centrosomal abnormalities have been observed in a wide range of tumors, but it is not clear whether these abnormalities alone can induce cancer formation or whether they are a consequence of cancer progression. Recent work in *Drosophila* suggests that centrosome defects in asymmetrically dividing cells can induce tumors at a higher frequency than other conditions known to cause genomic instability.

Laurence Pelletier

Centrosomes are the major microtubule-organizing centers (MTOCs) in animal cells. They are composed of a centriole pair embedded in a proteinaceous scaffold called the pericentriolar material (PCM). In a nutshell, while the number of centriole pairs defines the number of centrosomes present in the cell, the PCM controls the microtubule-nucleation capacity of centrosomes. To build a robust bipolar spindle capable of accurately segregating duplicated chromosomes