Seeing 2

The Retina

There are 4 significant steps in seeing as we do:

1) forming the image - comparatively easy
2) detecting the light - that's where we come in today
3) reading out the detected signal and transmitting it to the brain
4) re-constructing the image of the outside world to make it appear superimposed on real objects. That's the ultimate magic. You'd never have thought it possible if you hadn't seen it with your own eyes!

We're going to look today at the screen on which the image is projected - the retina of the eye.

Notice the two other named areas at the back of the eye - the **fovea**, which is a slightly depressed region with a particularly high density of photoreceptors, and the **optic nerve**, which takes out the signals to the brain. In one sense that description is a bit misleading. I prefer the idea that the eye is part of the brain that has grown to look out at the world.

The first surprise is that we have two interleaved photosensitive screens in our eye, usually called the **rod retina** and the **cone retina,** after the names of the light sensitive cells in each.

Rods & Cones

The rod retina is the low illumination seeing system - for night-time and moonlight work. The cone retina is for daytime use. The second surprise is that the rods and cones are *behind* the nerve cells and blood vessels that feed them. This is little short of weird. It's an interesting fact of evolution that the octopus eye is very similar to the human eye, only in the octopus the light cells point outwards and 'wiring' is at the back. It's as if nature got it right in one case and not quite right in our case. The optic nerve, for instance, produces a blind spot where the nerves all pass through the retina to the brain. Our brain gets used to coping with blanking caused by blood vessels, etc. that shields some of the retina from the incoming light. One strategy it uses is to continually oscillate your eyes so that the part of the image missed at one moment is seen very soon after because the blood vessels now blank out a different part. Sometimes you can see the blood vessels (look up the phenomenon of Purkinje's tree). In passing, I'll add that one argument against the religious view of so-called 'intelligent design' is that plenty of evolved aspects of the animal kingdom are not that intelligently designed, and we could do a better job if we had the chance. That's another story.

Rod Facts 1

Rods outnumber cones by about 25:1 - not a bad ratio for a detector trying to detect low light levels. There are much fewer than 120 million nerve channels leading to brain, so the rods are connected together within the eye. Indeed, there is a significant amount of 'front-end processing' of the signals in the eye so that the rods return signals to the brain that are very sensitive to edges of shapes and to motion. The rods provide a substantial amount of our peripheral vision. At the very centre of our field of view, where our seeing is most sharp, there are no rods.

Rod Facts 2

Rods see only in black and white. Any colour information you receive comes from your cones. Rods are not sensitive across the whole spectrum, being virtually red insensitive. Have you ever noticed how red pillar boxes look almost black at dusk? [The red, white and blue of the Union flag change their relative brightness at dusk - the Purkinje effect]. The peak sensitivity for rods is in the turquoise, at ~500 nm.

Rod pigment, retinene, which absorbs the light in the first place allowing the rods to create an electrical signal, gets bleached by light and hence the rods are actually less effective during the day. They become most sensitive after about 20-30 minutes of 'dark adaptation'. It's curious that we cannot make such a crucial chemical as retinene from scratch but need to eat it, almost ready made, in the form of vitamin A. Raw carrots are rich in vitamin A and so, you see, raw carrots are indeed good for night vision. Long haul sailors found out centuries ago. When they ran out of vegetables, their twilight vision could get very poor.

Cone Facts 1

Cones provide detailed vision.

There are about 5-6 million cones, with a high concentration in the fovea where ~100,000 are confined to a patch about 1.5 mm in diameter. In the very centre of this, the foveola, there is a rod-free region packed with small diameter cones. It is this region, covering <1.5° of view, which we use for fine-detail seeing, such as you're doing now to read this. 1.5° is less than a fingers' width at arms length. Remarkably, the high definition field of view of our eye covers little more than a few letters at a time of normal sized print held at normal viewing distance - enough to see a whole syllable at once but not enough to see the whole of a longer word. Our eyeball is constantly scanning this very small high resolution area over the scene we want to see in detail, by movements that we're not conscious of. You and I think we see a steady picture of the world around us but that steadiness is a marvellous piece of real-time image processing. In reality the image on the back of our eyeball is shaking around all the time and it's the processing of the brain that creates the steady image. Incredible.

Look at the picture of foveola region of an eye on the slide.

Cone Facts 2

The spectral sensitivity of our cone vision differs from our rod vision. Cones provide our colour vision experience. In an evolution of marvellous economy, the whole spectrum of colour experience is provided by just 3 types of cone. At least that is the accepted interpretation. Call them red, green and blue, though each has a broad spectrum of absorption. [In fact the red signal cones will look cyan because they absorb red light].

Colour Vision

Look at the slide to see who has and who has not got colour vision. This pretty well agrees with who needs colour vision.

Two clues: animal behaviour and the structure of the eye. When you look at an idyllic countryside scene with pastures green spread before you, dotted with black and white Friesen cows and grazing sheep, remember that the animals don't see it that way. They graze in grey pastures, surrounded by grey dykes and grey hedges. Sad really. Ever wondered you don't get green sheep, nicely camouflaged? Now you know. The same lack of colour vision is true for out pet dogs and cats. It's a black, white and grey world for Fido and Felix.

Why do we have colour vision?

The scene on this and the next slide shows a tree seen with yellow-blue discrimination and, on the next slide, with added red-green discrimination. For most of us with good colour vision, the difference is dramatic.

Colour Mixing

Most colours can be made by adding together 3 primary colours in varying proportions. See the diagram on how to make yellow, cyan and magenta (and white) from red, green and blue.

3 colour matching

An important consequence of the 3-colour mixing experience is that any colour can be matched by the addition of appropriate amounts of 3 primaries. This is known as 3-colour matching. It is a remarkable phenomenon. One of the remarkable details is that the three primaries are not themselves unique. You can choose the primaries that you use. An implication of this is that although the colour of light is determined uniquely by its spectral content, the reverse isn't true. The same colour can be produced by many different spectral compositions. This phenomenon is called **metamerism** and it underlies the workings of 3-colour matching. You don't have to reproduce the exact spectral content of a colour to reproduce the sensation.

Mathematically, 3 colour matching can be written:

$$(C) \equiv x(R) + y(G) + z(B), \quad \text{where } x + y + z = 1 \ .$$

(C) stands for the colour to be matched; (R) the red primary; (G) the green primary; (B) the blue primary and the fraction of each of these primaries is given by the coefficients x, y, z. The fractions are always written out for unit intensity of the colour (C).

Maxwell's colour Δ

One of Maxwell's great achievements while he was at Aberdeen was to invent and make a device for measuring the x, y (z) coefficients in 3 colour matching when 3 narrow spectral colours were chosen as primaries. Maxwell not only found how to represent the sensation produced by any other *spectral colour* but also for a wide range of general colours. He realised how the mathematical relationship could be represented by putting all the colours in a triangle with the primary colours represented by the corners.

Activate *demo* of "Maxwell Triangle.exe". Emphasise that a mixture of 2 colours lies on the straight line joining them. A mixture of three colours is like finding the centre of gravity of 3 weights of different size. This wasn't abstract science for its own sake. Maxwell realised that by making 3 black and white transparencies, taking photographs of the same scene through red, green and blue filters in succession, and then projecting the red, green and blue images back on top of each other, a full colour picture would result. He did this in the year after he left Aberdeen, in 1861. The class can see the result in a framed reproduction which, for copyright reasons, I can't put on the web.

CIE Diagram

Maxwell's triangle has a couple of practical problems: a few spectral colours lie outside the triangle, which ones depending on the exact choice of primaries. It was 70 years and a lifetime later before an international commission standardised the measurement of colour in 1931 by choosing a new set of primaries, confusingly called (X), (Y), (Z), that everyone has used since. The very odd thing about this choice is that you cannot make colours that are exactly these primaries. They are a mathematical construction from known colours. The story is obviously too long for today. The result is that colours are plotted against the first 2 co-ordinates, (X) & (Y), just like the Maxwell colour triangle and the resulting plot is a sail-like shape called the **CIE chromaticity diagram** within which all real colours are found.

Spectral wavelengths

Single wavelengths provide the envelope of pure colours, around the outside of the figure. The spectrum isn't uniformly spread along the chart, which just reflects an empirical feature of human colour vision.

An example

Any facts to do with colour perception can be, and probably are somewhere, plotted on the CIE chromaticity chart. E.g. how well we distinguish neighbouring colours, the range of colours reproduced by this projector, the consistency of colour coding on electronic resistors, etc., etc. Here on the slide is a different example, showing colours produced by the components used in fireworks. Remember that if two colours are present together, the result is somewhere along the line joining them.

Colour TV

Colour TVs use the 3-colour mixing phenomenon to reproduce all the colours they can. Look closely at a colour TV screen and you'll see it has red dots, green dots and blue dots on it, so close together that you can't see them as separate at normal viewing distance. All the colours reproduced by the TV are made up from varying amounts of light coming from these phosphors. The light is produced by stimulating the phosphors with electrons controlled by the electronic circuitry of the TV. If you want lots of red, then the red phosphors are strongly stimulated. For an orange colour, the red phosphors are quite strongly stimulated and the green slightly, and so on.

The phosphors used on colour TV screens to emit light aren't quite spectrally pure. They are represented by 3 points within the CIE chart that define a triangle. To produce a desired colour the coded signal at one instant must specify the relative amount of each colour emitted and this is part of the international standard. Britain uses the EBU standards. Manufacturers can't change the characteristics of the phosphors. If they did so, the reproduced colours would be wrong. The very important point to note is that only colours within the triangle can be shown by the TV. This includes white and all the hues but no pure spectral colour is shown quite right. Also, there is a gamut of colours outside the triangle that aren't reproduced correctly. We never notice this in real life because we haven't got the original objects beside the TV to compare them with.

(Also shown on the diagram is the set of CIE co-ordinates for bodies heated to increasing temperatures. They follow a curved line passing close to the white point.)

Colour Defectives

8.1% males & 0.4% females (at least for N Americans and Europeans, who have supplied most of the internationally available data) are colour defective. Very few people are truly colour blind, perceiving no colour at all. Most colour deficiency is genetic on the X-chromosome, which accounts for the gender difference. Colour defectives are identified through performance in colour matching tasks. Asked to match 3 primaries to a colour, about 92% of the population agree on the result. They call themselves **normal**. That's democracy for you. Everyone else is **defective**. 2.7% of males can match any colour with only 2 colours - they are called **dichromats**. The possibility of having a single defective type of cone of one of three types gives 3 types of dichromats. The first 2 involve red-green confusions, the rare kind involves lack of blue end sensitivity and discrimination.

Colour confusion loci

The 3 diagrams show the colours confused by different dichromats. These diagrams are not exact in appearance because the full CIE chromaticity diagrams can't be projected, for the reasons already given. Does anyone find difficulty distinguishing colours along any of these lines?

Anomalous Trichromats

Almost 6% of the male population produce what normal people would describe as very odd colour matches. i.e. normal people distinguish the colour and its match produced by anomalous trichromats. There is a whole range of observed deficiencies, from almost normal to almost dichromatic. Anomalous trichromats should not be taking jobs where colour matches are important (e.g. in the clothing industry, in graphic design, ….).

Pseudoisochromatic plates

are one of the most effective tests for red-green problems. A common form is a set of coloured dots of varying luminance. The normal person sees one number and the colour defective a different number. They are produced by drawing a random set of dots and making them variably grey. Then add a number in yellow-blue contrast. Finally, superimpose a second number in stronger red-green contrast that normal sighted people will pick out over the first number and which people with red-green deficiencies will overlook.

The final lecture will discuss how to measure light and how to use lenses so that we can see better.

END