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PHYSICS AND BIOLOGY OF COLOUR AND VISION

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ABSTRACT

The essential notions of the physics and biology colours are presented, starting with the rainbow, a phenomenon studied by Newton. Colours are properties associated to the larger or smaller deviation of light caused by a glass prism which correspond to different light wavelengths. The white light emitted by the sun includes all colours, while a laser light is monochromatic. There is invisible light of various types, i.e., light which do not correspond to colours: their wavelengths are smaller than that of the violet and larger than that of the red. In view of our evolutionary history in a planet near the Sun, a star which mainly emits visible light, we see only this kind of light. Our identification of colours takes place in the retina in three kinds of receptors called cones, associated with the capture of red, green and blue light. Primates see, in general, in a way similar to humans, but there is a range of animal species whose vision is not trichromatic: This range goes from monochromatic whales to the extreme multichromatism, due to 16 types of cones, of stomatopods, which are marine crustaceans. As the genes encode the cones of each species, one current area of research is the disentanglement of the genetic history which enabled vision enhancement in some animals and not in others. Darwin's theory is at work: the adaptation to the environment was instrumental in the process that led to the development of vision in animals.

KEYWORDS Colour; Light; Vision; Eye; Evolution

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1. Introduction

We see everywhere colours in Nature, whether on Earth or in the sky, not only the seven colours traditionally attributed to the rainbow but also all nuances between them. We also see colours in artificial objects, for example the paintings painted by great artists which we admire in museums. Only an extremely rare defect prevents some people from seeing colours, limiting them to see the world in black and white.

From the point of view of physics, the colour is associated to the wavelength of light (or, equivalently, to the frequency). Since the time of the English physicist Isaac Newton (1642 or 1643 according the calendar, Julian or Gregorian - 1726 or 1727, *idem*), which created, with the help of a glass prism, a rainbow in his room, we know that white light, in particular sunlight, is a mixture of various coloured lights (FIG. 1).

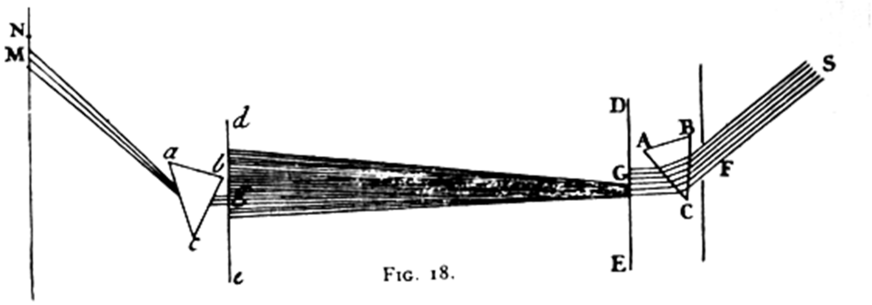

FIG. 1 - Newton's experiment with two prisms as presented by himself in his book *Opticks* (1704).

In an experiment performed by the great sage in 1665 or 1666, the sunlight coming from a window entered a prism and, within the glass, the rainbow colours appeared, while the beam suffered deflection. At the exit of the prism a similar deflection took place, widening the colour splitting. When he focused only red light, conveniently isolated from the light with other colours, in a second prism the red beam entered the new prism and was deflected by it, but remained red. The explanation could only be that the white light was composed of light of all colours, which only emerge isolated within the glass. Newton conceived a corpuscular theory of light, according to which the different colours would correspond to different particles of light, but in the nineteenth century the wave theory of light took the lead since it was able to explain the phenomena of diffraction and interference in contrast with the Newtonian theory. The overlapping of waves of different wavelengths had to obey the general principle of wave superposition. In particular, two waves can completely cancel each other. In 1865, 150 years before the International Year of Light, the Scottish physicist James Clerk Maxwell (1831-1879) realized that light waves were electromagnetic waves, i.e., the propagation in space of a periodic perturbation of the electrical and magnetic fields, the two intimately associated. There was a complete light spectrum to be discovered (FIG. 2).

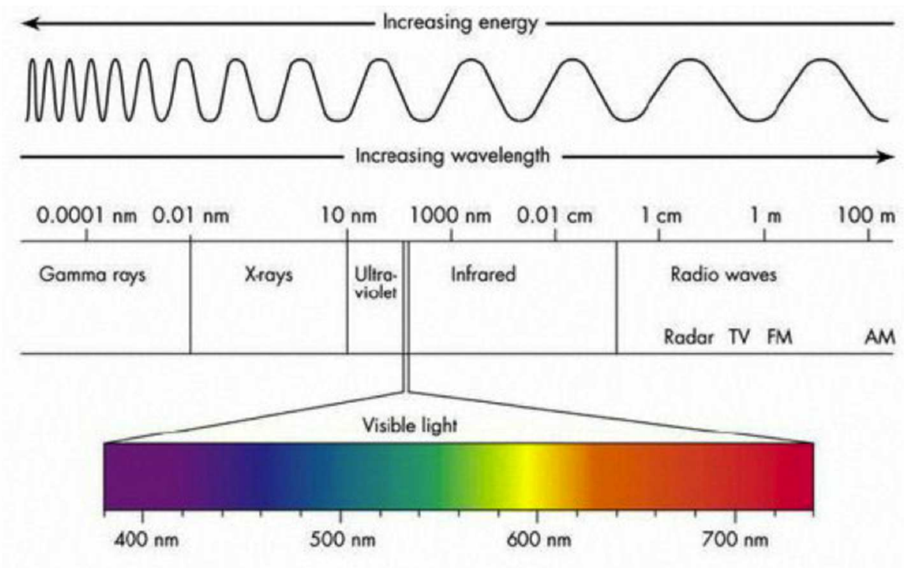

FIG. 2 - Light spectrum, with a zoom of the visible zone.

http://sdhydroponics.com/2012/06/13/par-the-light-spectrum/

Light may be visible or invisible as our eyes see it or not. The visible part corresponds to a range of wavelengths between 3900 and 7000 angströms (between 390 and 700 nanometers, being the nanometer a subunit of the International System, defined as a millionth of a millionth of a millimeter), which is a small part of the total spectrum of light (light with all possible wavelengths). Before Maxwell, infrared waves and ultraviolet waves were already known. Infrared light was the first kind of invisible light to be discovered, and its first observer was the Anglo-German astronomer and physicist William Herschel (1738-1822), who, in 1800, with the aid of a prism and a thermometer, made an experiment similar to that done by Newton in which he detected radiation with wavelengths somewhat greater than those of red light: he called it "calorific rays", since the thermometer showed in the infrared area of the spectrum an higher temperature than in its surroundings (FIG. 3).

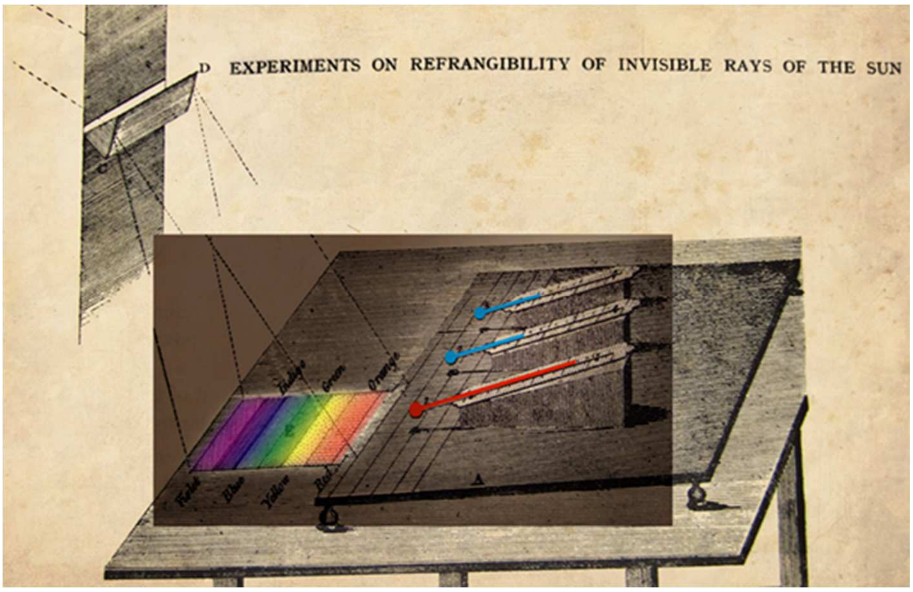

FIG. 3 - Herschel's experiment which led to the detection of infrared light (1800), based on the original Herschel's picture.

http://elte.prompt.hu/sites/default/files/tananyagok/InfraredAstronomy/ch01.html

Ultraviolet radiation was found one year later by the German physicist and chemist Johann Wilhelm Ritter (1776-1810), who noticed the darkening of silver chloride placed in the zone beyond the violet, where the light had wavelengths somewhat smaller than those of violet light: he called it "oxidizing rays" to emphasize its chemical reactivity properties. As the wavelength is a number which varies continuously, we infer that there is light of all wavelengths, that is, of all colours, in between red and violet: an infinite number of wavelengths were possible. After Maxwell, other invisible radiations were discovered such as, on the side of red, radio waves and microwaves (in 1886, by the German physicist Rudolf Heinrich Hertz, 1857-1894), and on the side of the violet, X-rays (in 1895, by the German physicist Wilhelm Conrad Roentgen, 1845-1923) and gamma rays (in 1900, by the French physicist Paul Ulrich Villard, 1860-1934).

We may say that the nineteenth century was the century of invisible radiation: it started with the discovery of infrared and ultraviolet radiations and ended up with the finding of gamma radiation, at the beginning of the nuclear age. We learned in the twentieth century, with the development of atomic and nuclear physics, that most radiations come from electronic transitions in atoms, molecules and solids, but that gamma radiation comes necessarily from atomic nuclei. In the same century, the processes of capturing light emitted by stars was refined: their light had been observed in the range of the visible, using the so-called optical telescopes, but they also came be seen from the Earth also with invisible light, either infrared (infrared telescopes) or microwave or radio waves (radio telescopes). Ultraviolet rays, X-rays and gamma rays' telescopes have to be placed on satellites in Earth's orbit since the atmosphere blocks light with wavelengths lower than those of violet. These types of light, called ionizing radiation, are harmful to life (if the atmosphere did not exist, life would not exist on Earth, at least in the form we know it, based on the genetic code that resides in the DNA).

Our eyes are blind to light with wavelengths which are not in the visible part of the spectrum, from red to violet. There is little variation in the human species in the ability to capture visible light. It is curious that, in a dark environment, we rapidly adapt our eyes to see a little more in the red side. We cannot see ultraviolet light, since the eyeball is made in a way not to allow the passage of this more energetic and therefore more dangerous radiation. Moreover, the Earth's atmosphere protects us from the ultraviolet rays of the sun through the ozone layer while it blocks completely X- and gamma rays. Situations of abnormal vision occur in patients who have undergone cataract surgery. A case which is often mentioned in this context is that of the French impressionist painter Claude Monet (1840-1926), who had a surgery of this type in 1923, and went on to paint with somewhat different colours, especially with more vivid blues. Probably he acquired a limited ultraviolet vision.

The sun emits light of all wavelengths but, having a temperature of 6000 kelvins at its surface, has a sharp peak in the middle of the visible light, but there are stars which emit mainly in the infrared or the ultraviolet (FIG. 4).

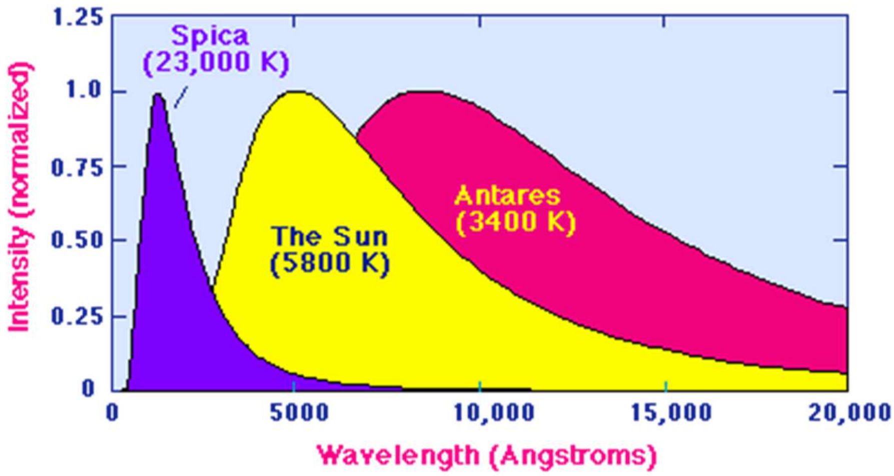

FIG. 4 - Intensity of emitted light (normalized to one for all stars) versus wavelength.

http://csep10.phys.utk.edu/astr162/lect/stars/cindex.html

The sunlight is white due to the mixing of all colours. Clearly we have adapted us along the slow path of biological evolution to better capture the light that our star emits the most. If we would live in the neighbourhood of a star which mainly emitted infrared light, most likely our eyes would be like infrared cameras, which are able to see in complete darkness. From the Earth, we do not see the sun as a white disk, since the atmosphere captures a part of the light falling on it, but the astronauts in orbit in the International Space Station see the sun as a disc with a very intense whiteness.

We prefer white light to work and a white light lamp mimics, although imperfectly, sunlight: filament lamps have already been replaced in lighting by compact fluorescent lamps and these are now being replaced by LED lamps, which are not only more efficient but also more durable. Today we have lasers, with plenty of applications, which emit light, either visible or invisible, with a well-defined wavelength (the first lasers were using microwaves; we have now infrared, ultraviolet and X-ray, but not yet gamma rays lasers).

2. Human vision

In the environment of our planet, our eyes adjusted very slowly along the path of biological evolution, in order to distinguish colours. The eyes are no more than natural cameras (FIG. 5): in the eyeball, there is a lens (just behind the pupil, protected by the cornea) and a photographic film (the retina, the inner membrane of the eye, in which an inverted image is formed).

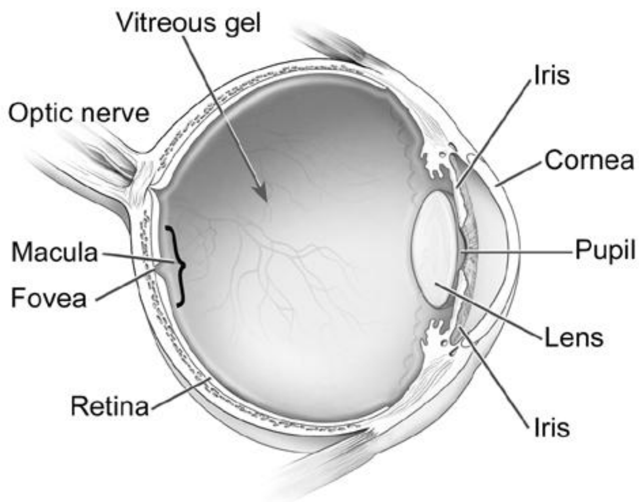

FIG. 5 - Scheme of the human eye.

http://www.familyconnect.org/info/after-the-diagnosis/working-with-medical-professionals/the-human-eye/135

Responsible for our colour perception are cells, located in the retina, of two types: rods and cones. These are photoreceptors or sensors that convert the light that enters the eye into a tiny electrical current, which is conducted by the optic nerve to the brain, which eventually decodes the transmitted signal. The cones, six million in each eye, are of three types. Each type captures better each one of the three basic colours - red (called L. for long, centred in 559 nanometers), green (M, for medium, centred in 531 nanometers), and blue (S, for short, centred in 419 nanometers) - with which all the others can be made (FIG. 6).

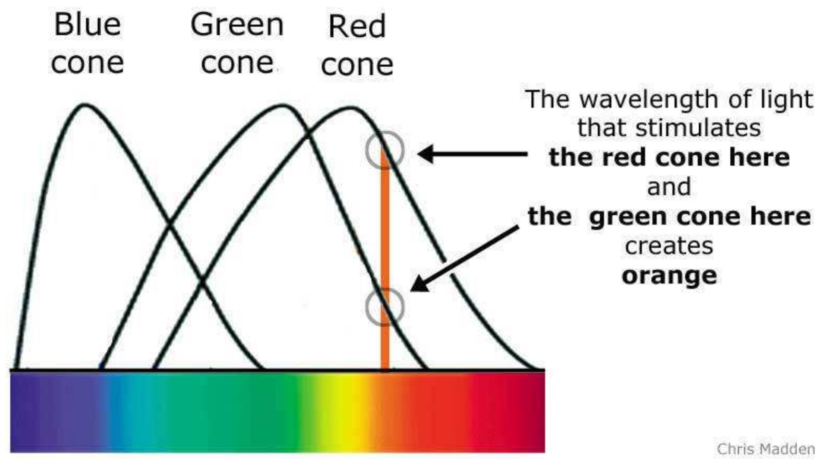

FIG. 6 - Sensibility of the three cones in the human eye to colour.

https://weirderthanyouthink.wordpress.com/2013/02/09/colour-vision-and-the-colours-of-the-rainbow/

Moreover, the rods, centred in the green, are able to capture much less intense light: they are the sensors which provide night vision. As, unlike the cones, rods, in far greater number than the cones (there are about 120 million!), can be located in the retina periphery, they are great aids for peripheral vision. People say that “all cats are grey in the night” since in the dark we can only see with the help of rods, which do not allow a large chromatic discrimination.

In our two eyes, there are therefore about 250 million sensors (the sum of the number of cones with the number of rods in both eyes). This value corresponds to 250 megapixels, a resolution far superior than that of a modern digital camera, which has, if it is of good quality, only about 18 megapixels. To top it off, our view has natural mechanisms to interpolate between pixels, similar to those that some cameras use based on man-made algorithms.

The colour blindness of some people is due to number reduction or operation deficiency of cones. Colour-blind people cannot distinguish some colours, especially green and red. With the blue, there are, as a rule, no problems. Colour blindness affects about eight percent of men (some of them are not aware of their defect although there are simple diagnostic tests, which consist of patterns made up by circles with different colours), but only 0.4 percent of women. It is an incurable genetic defect associated with the X-chromosome, a chromosome which arises alone in males (XY) but matched in females (XX). There are various types of colour blindness, since the cones can be affected in their number or in their operation in different ways. The genetic origin of colour blindness was unknown in the nineteenth century, when the English chemist, physicist and meteorologist John Dalton (1766-1844), a forerunner of atomic theory, studied the abnormality which he detected in himself. In modern times, it was possible to do a genetic test of Dalton's cells which confirmed, beyond any doubt, his colour blindness, even clarifying its precise type.

The extreme vision defect consists of complete blindness to the variety of colours: this disease is called achromatopsia. It happens when the cones do not exist or do not work. People having that defect, who are called monochromats (basically they see greyscale), only see typically with their rods (FIG. 7). They are no more than 0.003 percent of the population (one in 30,000 people). The neuroscientist, medical doctor and English writer Oliver Sacks (1933-2015), in his book *The Island of the Colourblind,* wrote about this type of vision defect, referring to the case of an atoll in Polynesia, where five per cent of the population is affected. Although very uncommon in humans, there are atypical monochromats, who only see with a given kind of cones. Moreover, one of the three types of cones (red, green and blue) may be lacking or failing: people affected by this defect are said dichromats.

FIG. 7 - Simulation of achromatopsia in comparison with normal vision.

http://psych.ucalgary.ca/PACE/VA-Lab/Brian/acquired.htm

The colours, whose perception arises in the brain, result from three factors: the light source, the object which reflects or diffuses some of the received light (the occurrence of reflection or diffusion depends on the regularity of the object surface; usually both phenomena coexist with the prevalence of one of them), and our eyes, which perceive the colours.

A modern visitor of a museum perceives colours of a painting which are different from that which were seen by its author or to its first observers who had other types of lighting. And, as people do not see exactly in the same way, each painting provides a different aesthetic experience to every observer. Not only the perception of colour is different in the retina, but there are also different brain processing mechanisms. When, going through the optic nerve, the electrical signal containing information about the received light reaches the brain, the emergent sensation of colour is necessarily subjective. Very interesting cases of kinesthesia, i.e., sensations junction, are known, for example the appearance of sound sensations driven by visual stimuli. The French poet Arthur Rimbaud (1854-1891) spoke in verse of the colours of vowels: "*A black, E white, I red, green U, Blue, vowels, / I shall tell, one day, of your mysterious origins.*" ("Vowels" sonnet, 1871). Regardless of the pathologies, which are always curious, the fact is that our perception of colour has an eminently cultural side, as we have always associated colours to facts and feelings. That is to say, colours have cultural histories.

3. Animal vision

The other animals see colours like ourselves, as can be easily checked by simple tests, but in a different way: in general, they do not have our three types of cones which allow people without defects to see about a million colours. In fact, only a restricted number of animals have a vision similar to the human one: the most obvious group is formed by some primates, who are like us trichromatic. But not all primates are trichromatic. Evolution led to separate developments: many New World monkeys have only dichromatic vision, because they followed a different evolutionary path. Kangaroos and bees also have trichromatic vision, although the case of bees is very particular, since they do not see red, as we do, but instead ultraviolet, getting to locate the sun, even on a day of thick fog. Ultraviolet vision is not exclusive of bees, belonging to other insects and to other orders (goldfishes, for example, can see ultraviolet).

The overwhelming majority of mammals, which are not primates, have dichromatic vision: they are colourblind, being unable to distinguish between red and green. And there are mammals with monochromatic vision such as some marine mammals: this is the case of whales, living in the open sea and therefore not requiring a good sense of colour. But many animals have more types of cones than humans: several species of reptiles, amphibians, fish, birds and insects possess higher colour recognition ability than humans: their vision is tetrachromatic. Some insects - such as certain species of butterflies - and some birds – such as probably pigeons - are even pentachromatic, having five types of cones. The world is, for them, far more colourful than it is for us: one pentachromatic species may, at least in principle, distinguish ten thousand million colours.

The most extreme case of colour vision ability in the animal world is that of the stomatopods or mantis shrimp (called "lacraias do mar" in Brazil), which are marine crustaceans that capture in a very efficient way their prey (shrimps, crabs, small fishes, etc.) thanks to their very keen sense of sight (FIG. 8). They have 16 types of cones, 12 types sensitive to light and four types that filter light allowing them to detect polarized light (i.e., light with a well-defined plane of vibration of the electromagnetic field). These animals can see ultraviolet, but it is unclear whether they can see infrared (such as some snakes, which have night vision).

FIG. 8 - A stomatopod (or mantis shrimp): *Ontodactylus scyllarus.*

4. Evolutionary history

The evolutionary mechanisms to achieve a better view of some colours have, in general, to the improvement of food capturing. A good view of the red was very helpful to our prehistoric ancestors to catch some fruits that have that colour, whereas, for the bees, which do not see it, it was more useful to see ultraviolet vision in pollinating flowers (there are not many red flowers). As for the bees, ultraviolet vision is also very useful to some birds.

Birds are, among all animals, those who have more visual capacity, both in discerning shapes and colours. One talks of "eagle eye": this is four to eight times more capable than the human eye. The extraordinary sight of eagles has to do not only with the variety of cones (the degree of chromaticism), but also to the number of rods and cones (the number of megapixels) and, of course, with the size and sophistication of the other optical components of the eye, since a good photography results not only from the sensors but also from the lenses and control devices. An eagle or a hawk are birds of prey: they can see a mouse in a meadow when they are flying over a kilometre high, since the size of their eyeballs is huge for the size of their bodies and since they have good systems to focus along the flight. "Lynx eye" is, in some languages, somewhat equivalent to "eagle eye”. Indeed, lynxes are animals with highly developed visual ability, although that expression may have more to do with the supernatural vision capability attributed to the lynx in Greek mythology (this mythological aspect explains the name *Accademia dei Lincei*, the very first science academy, of which the Italian physicist Galileo Galilei, 1564-1642, was a member). Both in the air and on land, the vision has evolved in the animal world over millions of years so that each species could more easily find its food and, besides that, see their prey without being seen by their potential predators, thus ensuring their survival. The colour vision in animals, particularly in birds, also plays an important role in sexual selection.

The evolutionary history that led to the colour vision in the animal world is extraordinary, still containing many riddles to be solved (FIG. 9).

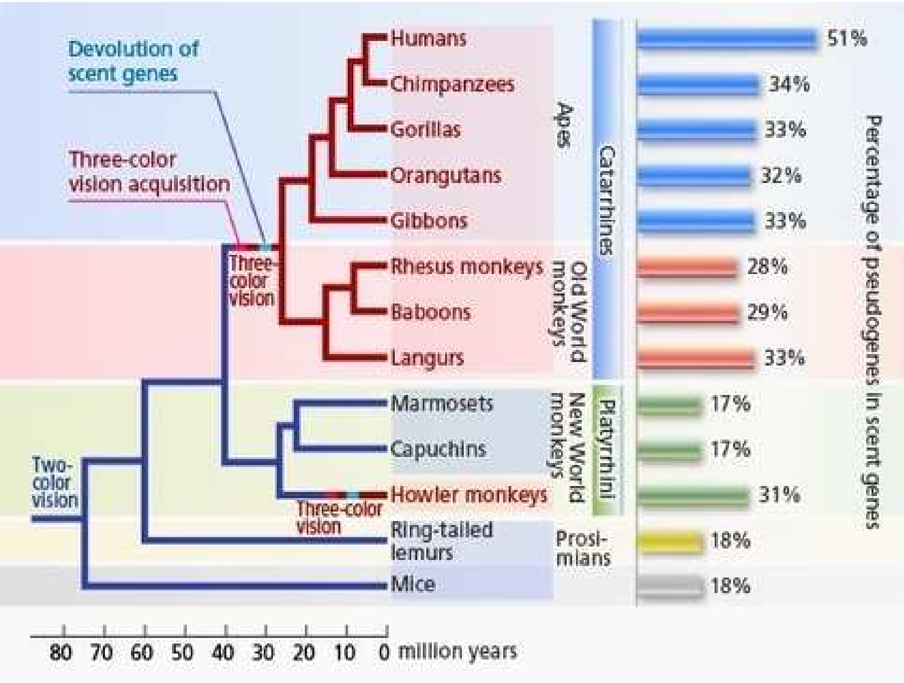

FIG. 9 - Evolutive history of animal vision. It is interesting to note that our branch of the tree started to lose olfactory capacities while getting more visual capacity (scent pseudogenes, i.e. inactive, are indicated on the right).

https://www.quora.com/What-are-the-human-inactive-genes-that-we-inherited-and-are-active-in-other-animals

The variety of situations is huge, because there is quite a variety of genetic histories. A very remote ancestor of primates must have been tetrachromatic, but, at some point at the time of dinosaurs (who lived between the Triassic, 231 million years ago, and the Cretaceous, 66 million years ago), the ancestors of today's mammals lost by a mutation (an occasional modification of DNA in the auto-replication process), a good deal of colour vision, staying with only two of the four existing cones. Primates reacquired in the Lower Tertiary, over twenty million years ago, some of their ability to see colour, by a phenomenon called gene duplication (dubbing mechanism of a DNA region containing a gene). Paleontologists, geneticists, biologists, physicists and chemists work together nowadays to clarify mysteries that remain on the origin of the amazing ability animals have to see the colourful world around them. Although many unclear aspects remain, all advances have confirmed so far the theory of the great English naturalist Charles Darwin (1809-1882), according to which, after species differentiation, adaptation to the environment is crucial.

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We indicate a couple of references, both scientific and popular science, which allow the reader to deep into the matters which were here only briefly exposed. We follow alphabetical order in each section.

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