# Where does colour come from?

The colours we see everyday come from a variety of sources. We’ve always assigned colour to objects depending on their chemical makeup. This is especially true when we consider pigments and dyes, which can be seen as colour in physical form. However, there are other colourful phenomena; such as the rainbow, which are not coloured by pigments. Even then, colour can’t come purely from physical factors as there are people who look at the same world but see a vastly different colour palette. In addition, colour can also be directly linked to emotions and language which cannot be explained by anything other than the brain as the source of colour.

Even though we live in a vibrantly coloured world, only a small number of chemical compounds are actually coloured (Gray, 2014). When light strikes a compound sometimes a specific photon of light is absorbed by an electron, temporarily moving it to a higher energy state. The size of the energy gap between the two states determines how much energy is required to make this promotion. As the energy of a photon is determined by its wavelength, and colour is also determined by wavelength, only certain colors of photon can be absorbed. When a photon is absorbed that colour is removed from the spectrum and the absence of the absorbed colour gives the compound its colour. Most of the energy gaps require high energy photons, such as UV photons, and so most compounds appear white as none of the visible spectrum was absorbed.

For organic molecules the amount of energy required is dependent on the atoms and how they are arranged around the active centre of the molecule. Changing these atoms changes the bonding strength and therefore the energy and colour of light required to dislodge the electrons (Gray, 2014). Mauveine was the first synthetic dye and was discovered by accident. While trying to create quinine from aniline in 1856, W.H. Perkin accidentally created a black sludge. When this was boiled with ethanol and then cooled, purple crystals of mauveine were formed (Gordon and Gregory, 1985, p7). Synthetic organic dyes have been engineered to absorb any combination of light by manipulating the atoms, allowing very intense dyes of pretty much every colour. However, these can easily be broken down if the bonding electrons escape making them temporary. To counter this some molecules, such as Quinacridone red which is used for stop signs, are made to be especially long lasting (Gray, 2014).

Inorganic compounds, such as transition metal ion salts and semi precious stones, can also be very colourful and have the advantage that they are not degraded over time as the crystal structure keeps all the atoms in place. However, these are much rarer and more expensive as only some colours exist and the most colourful ones come from semi precious stones. Transition metal ions are responsible for most of the inorganic colour which stems from their partially complete d orbitals. The electrons in the d orbitals interact with the electrons in ligands when they bond, causing electron repulsion and increasing the energy of the d orbitals. The number of ligands bonded to the ion and their arrangement in space means that the energy of each d orbital is not raised equally but is instead split into two groups, one with a higher energy and one with a lower. In a tetrahedral complex there are two low orbitals and three high energy orbitals while the opposite is true for octahedral complexes. The size of the energy gap between the orbitals is dependent on which transition metal ion is present and also the type of ligand as different ligands have different electrical field strengths and a stronger field leads to a larger gap. As the d orbitals are only partially filled it is possible to promote an electron from the lower energy orbital to the higher energy orbital, which is not possible if the d shell is either empty or full as no other electron transition absorbs visible light (Clark, 2003).

We can observe a similar but reversed effect in the Aurora Borealis. Charged particles from the sun reach the earth and strike the atoms and molecules in the atmosphere. This causes the electrons to gain energy and move to a higher energy level. When they fall back down the excess energy is released as a photon which is the coloured light we see. Different atoms have different energy levels so release different coloured photons, for example oxygen tends to emit green light while nitrogen emits blue light (Imster, 2018).

However, electron energy states are not the only source of colour. Structural colour occurs when a structure is able to interfere with the light as it passes through, separating and scattering the spectrum. For example Morpho butterflies have irregular structures called lamellae on their scales. These cause their characteristic blue colour. A lamella causes interference when light hits it and is reflected by the many layers, causing the other colours to destructively interfere and cancel out, leaving the blue colour. The ridge heights of the lamellae are randomly distributed which means neighbours don't interfere with each other. This creates a uniform colour from any angle. In addition, the brown colour of the butterfly helps absorb some of the red and green light which further enhances the bright blue colour (Kinoshita, Yoshioka, Fujii, Okamoto, 2002).

Other natural phenomenon can be explained by refraction. A rainbow is formed when white light hits water droplets in the sky and is forced to slow down, bending towards the normal and refracting into the droplet. This causes the white light to split into a spectrum as each colour has a different wavelength so is refracted a different amount. Once this light reaches the back of the droplet it is reflected back towards the front and then refracts again, this time speeding up and bending away from the normal as it reenters the air. This causes a clear separation of the colours with most falling between 40° and 42° from the angle of the sun's initial ray. The red light exits at about 40°, a steeper angle relative to the ground, while the blue exits at about 42°, a shallower angle relative to the ground. Every droplet refracts all the colours but depending on where we stand different colours reach us from each droplet. We see rainbows in their classic semicircular shape with red on the outside and blue on the inside as we only see the red from the droplets at a steeper angle relative to us, as the blue is refracted over our heads, and the blue from the droplets at a shallower angle relative to us, as the red is refracted towards our feet. This creates a circle with red on the outside, blue on the inside and all the other colours in between but we only see half of it as the earth gets in the way (physicsclassroom.com).

However, physical factors can't be the only ones that affect colours. We can see that biological factors come into play as colour blindness exists. If colour was purely based on chemicals and wavelengths then everyone would be able to see colours which is simply not the case. Two types of photoreceptors that exist in the retina of the eye, the rods and cones. There are over 100 million rods which work at very low levels of light and are used for night vision. However, they don't detect colour so can only help us distinguish light from dark. By contrast cones require much more light but allow us to see in colour. There are about 6 million cones of three varieties: red, green and blue. Each cone is most sensitive to one colour of light, which they're named after, but can detect a range of other colours too. We are able to see different colours depending on how much each cone is stimulated and our brains turn those signals into the corresponding colours (askabiologist.asu.edu). The fovea has no rods but a very high density of cones. These cones are smaller than the ones on the periphery, which also have larger spaces between them. These spaces between cones are filled with rods. In the central fovea the red and green cones are randomly distributed in a ratio red:green of 1.5:1. There are no blue cones in the centre 0.34° and the total ratio of red and green:blue in the retina is about 100:1 (cis.rit.edu). Each cone can see about 100 shades. This means most people see 1,000,000 colours.

However, those who are colour blind can only see 10,000 colours. Colour blindness is an inherited disorder where a person's ability to identify certain colours is limited as they only have two functioning cones. The most common form of colour blindness is red green colour blindness where it is hard to distinguish those two colours. To help counter this, glasses and contact lenses have been developed. They help by absorbing certain wavelengths that were activating both the red and green cones, making it easier to determine if something is red or green. There are many benefits to using the contact lenses over the glasses as they cover more of the eye and also allow prescription glasses to be worn. Scientists at Birmingham University have developed lenses that are made with a relatively cheap non-toxic rhodamine dye. These have been tested and it has been verified that they help enhance red green colour perception. Following their success, Birmingham University are currently working to find a dye to counter blue purple colour blindness and to find a combination of dyes to help with both simultaneously (Birmingham.ac.uk).

In addition to dichromats who are able to see less colours as they have one less functioning cone, there are also tetrachromats who possess an extra cone and can see more colours than usual. Tetrachromats have four cones so can see 100,000,000 colours. It is thought that tetrachromats might experience colour ‘with each familiar hue fractring into a hundred more subtle shades for which there are no names, no paint swatches. And because perceiving colour is a personal experience they would have no way of knowing they see far beyond what we consider the limits of human vision’ (Greenwood, 2012). In 1948 HL de Vries, a dutch scientist, was conducting tests where colour blind men had to mix a standard shade of yellow from red and green light. As dichromats have two normal cones and one mutant one which is less sensitive to either red or green, making it hard to distinguish the two colours, the men added either more red or green than trichromats to compensate. One of the daughters who was not colour blind was also tested but she added more red than most people. De Vries hypothesised that she had three normal cones as well as the mutant cone which was allowing her to see extra colours. In the 1980s John Mollon and Jordan did tests on mothers of colourblind sons where they had to match a colour, thinking that a tetrachromat would never be able to match it as to them the colour would always appear slightly off. Jordan estimated that as many as 12% of woman were tetrachromats; however, all of the women tested were able to make the matches which led them to suspect that the fourth cone was inactive. In 2007 Jordan conducted a different test where three coloured circles would flash in a dark room. One of the circles was not a pure colour which he suspected a tetrachromat would be able to identify. This was tested on 25 women who possess the fourth cone and one woman, cDa29, got every answer correct, becoming the first identified tetrachromat. Jay Neitz suspects that there are women who possess the fourth cone but aren't tetrachromats as “most of the things we see as coloured are manufactured by people who are trying to make colours that work for trichromats” (Greenwood, 2012) and that there may not be enough colour variation in the natural world for the brain to call upon the fourth cone. He also thought that if the women went back to the labs and were encouraged to tell very subtle shades apart they might be able to awaken the fourth cone to see the new colours. By contrast, Concetta Antico is a tetrachromat artist who is able to see these extra colours. It is believed that she has unlocked the ability as she has been painting since age 7, surrounding herself in colour and allowing her brain to take advantage of the fourth cone (Ossola, 2014).

In addition to the eyes, the brain also plays a large role in determining colour. This can be demonstrated by the existence of phosphenes. Once the eyes have adjusted to darkness, a person is still able to see wispy clouds and specs of light in pastel blues, greens, oranges and yellows. These colours can not be caused by light entering the eye in the conventional way as there is no light. These phosphenes appear spontaneously when there is a lack of visual stimuli. For example prisoners alone in dark cells, those who meditate in the dark, pilots flying at high altitude in a cloudless sky and truck drivers driving for long distances in a snowstorm may all experience these phosphenes. Children are more sensitive to phosphenes than adults and are able to induce them more easily. Phosphenes can be induced physically by applying pressure to your eyes with your fingers. Phosphenes are also the stars you see after a nasty blow to the head. Phosphenes can also be induced by hallucinogenic drugs and these can be any colour, with complimentary colours sometimes appearing together or one after the other (Carr). This suggests that colour is more of an abstract idea than a physical property of objects.

Synesthesia is further evidence of colour being heavily influenced by the brain. In his book 'Synesthesia: A Union of the Senses', Richard Cytowic said that 'Once we understand that colour can be dissociated from the visual means by which we see an object and determine its shape, we can see how colour can exist separated in synesthesia and be attached to non visual objects with which it is not normally associated. In other words colour is quite independent of object vision' (Cytowic, 2002, p323). He is suggesting here that colour is not directly linked to vision and is its own independent sense. When a person has synesthesia their sense are very different as the stimulation of one sense will automatically trigger a response from a secondary sense. For example a person with synesthesia said that 'what strikes me is the colour of someone's voice, [V--] has a crumbly, yellow voice, like a flame with protruding fibres' (Cytowic, 2002, p1).

This idea that colour is independant is further suggested by colour constancy. Objects appear to be the same colour even when the light changes. This shouldn't happen but our brains adjust the colour to make it more consistent and easier for us to understand (Cytomic, 2002, p323). This can be seen when a banana and a square of the same colour are held in different light. They appear to be different colours even though they are the exact same shade of yellow. This is because our brains know what the colour a banana should be so adjusts accordingly but without a reference for the square its colour wasn't corrected in the same way. Artists are some of the only ones who really notice that colour constancy is in fact an illusion as can be seen in the way light and colour is presented in their art. Our colour vision can also be tricked. If you look at the centre point between a green and red square then look at an image, both sides will look different as the brain has corrected the colours assuming the red and green was still there. We all agree on the colours we see but there is no physical property that determines a one to one relationship between the colour we see and the object it comes from (BBC, 2011).

Colour is also heavily linked to emotions. Meghan Sims is a colour blind artist but she is still able to paint in colour, dye her hair and match her clothes. She has learnt to match shades of grey to different colours. For example; she associates the grey of a granny smith apple with a bright apple green. She also links colours to emotions such as red for danger and blue for sadness and loneliness (BBC, 2011). Our linking of colours with certain thoughts and feelings can be traced back to some of our earliest ancestors. Initially single celled organisms depended on colour interpretation to survive as red and yellow light was good for energy while blue and UV was damaging. This gives us an intrinsic association of blue with cool and yellow with warm. Red, green perception was a much more recent development which came from early primates who needed to find fruits and to avoid nature's warnings. This means we had to learn about red and green as they are newer colours.This could also explain why these colours feel more manufactured and why we associate them with more human concepts; such as danger, love and envy, which are more advanced than the warm and cool of yellow and blue (BBC, 2011).

Furthermore, colour has been irrefutably linked to language. It has been shown that colour perception is not something a person is born with but it develops over the first 3 months of life. Infants who don't have the language are still able to distinguish the 11 colour categories (red, blue, green, yellow, orange, black, purple, white, brown, pink, and grey). Initially they use the right side of the brain to do this but once they learn the colour words activity switches to the left side of the brain, which is also linked to language. This link to language is further shown by the Himba Tribe in Namibia who only have 5 colour words (vapa which is yellow and white; zuzu which covers most dark colours including red, green and purple; buru which is blues and some greens; dambu which is red, brown and the other greens; serandu which is reds, browns, oranges and some yellows). When told to pick the different square out of 12 coloured squares they were able to easily identify two slightly different shades of green as they fell under different names but the were unable to tell a turquoise from a green as they both fell under the same term (BBC, 2011).

There are many physical factors that contribute to colour and, when asked about it, those will be the first ones that come to mind. However, I believe that overall the biological factors are more important and in particular the brain itself. As said by Dr Beau Lotto ' colour is effectively an illusion right, it's an illusion that helps us see the world in a way that's useful to see.' (BBC, 2011). I believe that the concept of colour originates from within us and is entirely independent of vision; however, we've come to associate it so heavily with sight that the two are now almost indistinguishable from each other and all the other factors are easily forgotten.

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