THROUGH *the* LANGUAGE GLASS

Why the World Looks Different in Other Languages

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PICADOR

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APPENDIX

Color: In the Eye of the Beholder

Humans can see light only at a narrow band of wavelength from 0.4 to 0.7 microns (thousandths of a millimeter), or, to be more precise, between around 380 and 750 nanometers (millionths of a millimeter). Light in these wavelengths is absorbed in the cells of the retina, the thin plate of nerve cells that line the inside of the eyeball. At the back of the retina there is a layer of photoreceptor cells that absorb the light and send neural signals that will eventually be translated into the color sensation in the brain.

When we look at the rainbow or at light coming out of a prism, our perception of color seems to change continuously as the wavelength changes (see figure 11 in the insert). Ultraviolet light at wavelengths shorter than 380 nm is not visible to the eye, but as the wavelength starts to increase we begin to perceive shades of violet; from around 450 nm we begin to see blue, from around 500 green, from 570 yellow, from 590 orange shades, and then once the wavelength increases above 620 we see red, all the way up to somewhere below 750 nm, where our sensitivity stops and infrared light starts.

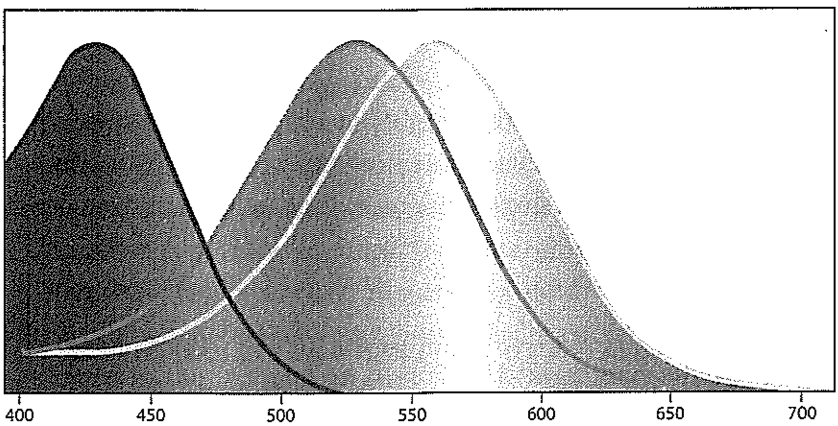
A "pure" light of uniform wavelength (rather than a combination of light sources in different wavelengths) is called monochromatic. It is natural to assume that whenever a source of light looks yellow to us, this is because it consists only of wavelengths around 580 nm, like the monochromatic yellow light of the rainbow. And it is equally natural to assume that when an object appears yellow to us, this must mean that it reflects light only of wavelengths around 580 nm and absorbs light in all other wavelengths. But both of these assumptions are entirely wrong. In fact, color vision is an illusion played on us by the nervous system and the brain. We do not need any light at wavelength 580 nm to perceive yellow. We can get an identical "yellow" sensation if pure red light at 620 nm and pure green light at 540 nm are superimposed in equal measures. In other words, our eyes cannot tell the difference between monochromatic yellow light and a combination of monochromatic red and green lights. Indeed, television screens manage to trick us to perceive any shade of the spectrum by using different combinations of just three monochromatic lights—red, green, and blue. Finally, objects that appear yellow to us very rarely reflect only light around 580 nm and more usually reflect green, red, and orange light as well as yellow. How can all this be explained?

Until the nineteenth century, scientists tried to understand this phenomenon of "color matching" through some physical properties of light itself. But in 1801 the English physicist Thomas Young suggested in a famous lecture that the explanation lies not in the properties of light but rather in the anatomy of the human eye. Young developed the "trichromatic" theory of vision: he argued that there are only three kinds of receptors in the eye, each particularly sensitive to light in a particular area of the spectrum. Our subjective sensation of continuous color is thus produced when the brain compares the responses from these three different types of receptors. Young's theory was refined in the 1850s by James Clerk Maxwell and in the 1860s by Hermann von Helmholtz and is still the basis for what is known today about the functioning of the retina.

Color vision is based on three kinds of light-absorbing pigment molecules that are contained within cells of the retina called cones. These three types of cells are known as long-wave, middle-wave, and short-wave cones. The cones absorb photons and send on a signal about the number of photons they absorb per unit of time. The short-wave cones have their peak sensitivity around 425 nm—that is, on the border between violet and blue. This does not mean that these cones absorb photons only at 425 nm. As can be seen from the diagram below (and in color in figure 12), the short-wave cones absorb light at a range of wavelengths, from violet to blue and even some parts of green. But their sensitivity to light decreases as the wavelength moves away from the peak at 425 nm. So when monochromatic green light at 520 nm reaches the short-wave cones, a much smaller percentage of the photons are absorbed compared to light at 425 nm.

The second type of receptors, the middle-wave cones, have their peak sensitivity at yellowish green, around 530 nm. And again, they are sensitive (to a decreasing degree) to a range of wavelengths from blue to orange. Finally, the long-wave cones have their peak sensitivity quite close to the middle-wave cones, in greenish yellow, at 565 nm.

The cones themselves do not "know" what wavelength of light they are absorbing. Each cone by itself is color-blind. The only thing the cone registers is the overall intensity of light that it has absorbed. Thus, a short-wave cone cannot tell whether it is absorbing low-intensity violet light (at 440 nm) or high-intensity green light at (500 nm). And the middle-wave cone cannot tell the difference between light at 550 nm and light in the same intensity at 510 nm.



The (normalized) sensitivity of the short-wave, middle-wave, and long-wave cones as a function of wavelength.

The brain works out what color it is seeing by comparing the rates at which photons are absorbed in the three different classes of cones. But there are infinitely many different spectral distributions that could give exactly the same ratios, and we cannot distinguish between them. For example, a monochromatic yellow light at wavelength 580 nm creates exactly the same absorption ratio between the cones as a combination of red light at 620 nm and green light at 540 nm, as mentioned earlier. And there are an infinite number of other such "metameric colors," different spectral distributions that produce the same absorption ratios between the three types of cones and thus look the same to the human eye.

It is important to realize, therefore, that our range of color sensations is determined not directly by the range of monochromatic lights in the spectrum but rather by the range of possibilities of varying the ratios between the three types of cones. Our "color space" is three-dimensional, and it contains sensations that do not correspond to any colors of the rainbow. Our sensation of pink, for example, is created from an absorption ratio that corresponds not to any monochromatic light but rather to a combination of red and blue lights.

As the light fades at night, a different system of vision comes into play. The cones are not sensitive enough to perceive light in very low intensity, but there are other receptors, called rods, that are so sensitive they can register the absorption of even a single photon! The rods are most sensitive to bluish green light at around 500 nm. Our low-light vision, however, is color-blind. This is not because the light itself "forgets" its wavelength at night but simply because there is just one type of rod. As the brain has nothing with which to compare the responses from the single type of rod, no color sensation can be produced.

SENSITIVITY TO DIFFERENT WAVELENGTHS

There are about six million cones in total in the retina, but the three types are not found in nearly equal numbers: there are relatively few short-wave (violet) cones, more than ten times as many middle-wave (green) cones, and even more long-wave cones. The far greater numbers of middle-wave and long-wave cones means that the eye is more efficient in absorbing light at the long-wave half of the spectrum (yellow and red) than at the short-wave half, so it takes lesser intensity of yellow light to be detected by the eye than blue or violet light. In fact, our day vision has a maximum sensitivity to light of 555 nm, at yellow-green. It is this idiosyncrasy of our anatomy that makes yellow appear brighter to us than blue or violet, rather than any inherent properties of the light itself, since blue light is not in itself less intense than yellow light. (In fact, wavelength and energy are inversely related: the long-wave red light has the lowest energy, yellow light has higher energy than red, but green and blue have higher energy than yellow. The invisible ultraviolet light has even higher energy, enough in fact to damage the skin.)

There is also a different type of unevenness in our sensitivity to colors: our ability to discriminate between fine differences in wavelength is not uniform across the spectrum. We are especially sensitive to wavelength differences in the yellow-green area, and the reason again lies in the accidents of our anatomy. Because the middle-wave (green) and long-wave (yellowish green) receptors are very close in their peak sensitivities, even very small variations in wavelength in the yellow-green area translate into significant changes in the ratios of light absorbed by the two neighboring cones. Under optimal conditions, a normal person can discriminate between yellow hues differing in wavelength by just a single nanometer. But in the blue and violet area of the spectrum, our ability to discriminate between different wavelengths is less than a third of that. And with red hues near the edge of the spectrum, we are even less sensitive to wavelength differences than in the blues.

These two types of unevenness in our sensitivity to color—the feeling of varying brightness and the varying ability to discriminate fine differences in wavelength—make our color space asymmetric. And as mentioned in the footnote on page 91, this asymmetry makes certain divisions of the color space better than others in increasing similarity within concepts and decreasing it across concepts.

COLOR BLINDNESS

When one of the three types of cones fails, this reduces color discrimination to two dimensions instead of three, and the condition is thus called dichromacy. The most frequent type of dichromacy is commonly called red-green blindness. It affects about 8 percent of men and 0.45 percent of women, who lack one of the two neighboring types of cones (long-wave or middle-wave). Little is known about the actual color sensations of people with color blindness, because one cannot simply "translate" the sensations of dichromats directly to those of trichromats. A few reports have been collected from the rare people with a red-green defect in one eye and normal vision in the other. Using their normal eye as a reference, such people say that their color-blind eye has the sensation of yellow and blue. But since the neural wiring associated with the normal eye might not be normal in their cases, even the interpretation of such reports is not straightforward.

Other types of color blindness are much rarer. A different type of dichromacy, called tritanopia, or in popular parlance blue-yellow blindness, arises in people who lack the short-wave (blue) cones. This condition affects only about 0.002 percent of the population (two people in a hundred thousand). A more severe defect is the lack of two types of cones. Those affected are called monochromats, as they have only one functioning cone type. An even more extreme case is that of rod monochromats, who lack all three types of cone and rely only on the rods that serve the rest of us for night vision.

THE EVOLUTION OF COLOR VISION

Human color vision evolved independently from that of insects, birds, reptiles, and fish. We share our trichromatic vision with the apes and with Old World monkeys, but not with other mammals, and this implies that our color vision goes back about thirty to forty million years. Most mammals have dichromatic vision: they have only two types of cones, one with peak sensitivity in the blue-violet area and one with peak sensitivity in green (the middle-wave cone). It is thought that the primate trichromatic vision emerged from a dichromatic stage through a mutation that replicated a gene and split the original middle-wave (green) receptor into two adjacent ones, the new one being a little farther toward yellow. The position of the two new receptors was optimal for detecting yellowish fruit against a background of green foliage. Man's color vision seems to have been a coevolution with the development of bright fruits. As one scientist put it, "with only a little exaggeration, one could say that our trichromatic color vision is a device invented by certain fruiting trees in order to propagate themselves." In particular, it seems that our trichromatic color vision evolved together with a certain class of tropical trees that bear fruit too large to be taken by birds and that are yellow or orange when ripe. The tree offers a color signal that is visible to the monkey against the masking foliage of the forest, and in return the monkey either spits out the undamaged seed at a distance or defecates it together with fertilizer. In short, monkeys are to colored fruit what bees are to flowers.

It is not clear to what extent the passage from dichromacy to trichromacy was gradual or abrupt, mainly because it is not clear whether, once the third type of cone emerged, any additional neural apparatus was needed to take advantage of the signals coming from it. However, it is clear that the sensitivity to color could not have evolved continuously along the spectrum from red toward the violet end, as Hugo Magnus argued it did. In fact, if viewed over a time span of hundreds of millions of years, the development went exactly the opposite way. The most ancient type of cone, which goes back to the premammalian period, is the one with peak sensitivity in the blue-violet end of the spectrum and with no sensitivity at all to yellow and red light. The second type of cone to emerge was the one with peak sensitivity in green, thus extending the eye's sensitivity much farther toward the red end of the spectrum. And the youngest type of cone, from some thirty to forty million years ago, had peak sensitivity slightly farther toward the red end, in yellow-green, and so increased the eye's sensitivity to the long-wave end of the spectrum even further.

THE BRAIN'S PHOTOSHOP

All the facts mentioned so far about the cones in the retina are correct to the best of my knowledge. But if you are under the impression that they actually explain our sensation of color, then you have been coned! In fact, the cones are only the very first level in a highly complex and still largely unknown process of normalization, compensation, and stabilization—the brain's equivalent of the "instant fix" function of picture-editing programs.

Have you ever wondered why cheap cameras lie about color all the time? Why is it, for example, that when you use them to take pictures in artificial light indoors, suddenly the colors look all wrong? Why does everything look unnaturally yellow and why do blue objects lose their luster and become gray? Well, it's not the camera that is lying; it's your brain. In the yellowish light of incandescent lamps, objects actually do become more yellow and blues do become grayer—or at least they do to any objective measuring device. The color of an object depends on the distribution of wavelengths that it reflects, but the wavelengths reflected naturally depend on the wavelengths of the light source. When the illumination has a greater proportion of light in a certain wavelength, for instance more yellow light, the objects inevitably reflect a greater proportion of yellow light. If the brain took the signals from the cones at face value, therefore, we would experience the world as a series of pictures from cheap cameras, with the color of objects changing all the time depending on the illumination.

From an evolutionary perspective, it's easy to see why this would not be a very useful state of affairs. If the same fruit on a tree looked one color at noon and a different color in the evening, color would not be a reliable aid in recognition—in fact, it would be a positive hindrance. In practice, therefore, the brain does an enormous amount of compensating and normalizing in order to create for us a relatively stable sensation of color. When the signals from the retina do not correspond to what it wants or expects, the brain normalizes them with its "instant fix" function, which is known as "color constancy." This normalization process, however, is far more sophisticated than the mechanical "white balance" function of digital cameras, because it relies on the brain's general experience of the world and, in particular, on stored memories and habits.

It has been shown, for example, that long-term memory and object recognition play an important role in the perception of color. If the brain remembers that a certain object should be a certain color, it will go out of its way to make sure that you really see this object in this color. A fascinating experiment that demonstrated such effects was conducted in 2006 by a group of scientists from the University of Giessen in Germany. They showed participants a picture on a monitor of some random spots in a particular color, say yellow. The participants had four buttons at their disposal and were asked to adjust the color of the picture by pressing these buttons until the spots appeared entirely gray, with no trace of yellowness or any other prismatic color left. Unsurprisingly, the hue that they ended up on was indeed neutral gray.

The same setup was then repeated, this time not with random spots on the screen but with a picture of a recognizable object such as a banana. The participants were again requested to adjust the hue by pressing buttons until the banana appeared gray. This time, however, the actual hue they ended up on was not pure gray but slightly bluish. In other words, the participants went too far to the other side of neutral gray before the banana really looked gray to them. This means that when the banana was already objectively gray, it still appeared to them slightly yellow! The brain thus relies on its store of past memories of what bananas look like and pushes the sensation of color in this direction.

The involvement of language with the processing of visual color information probably takes place on this level of normalization and compensation. And while it is not clear how this works in practice, it seems plausible to assume that the concepts of color in a language and the habit of differentiating between them contribute to the stored memories that the brain draws on when generating the sensation of color.