1

The Perception of Lightness and Color

Content

Determining the origin of lightness and color
Determining the physiological input stage
    The eye
    The retina
    The photoreceptors in general...
    …and the cone receptors in particular
First processing stage: Categorization of information
Second processing stage: Conversion of signals into opponent color channels
    Like on TV: The reason for the complicated procedure
Third processing stage: Adding a spatial aspect for color
    Approximate color constancy does not mean complete color constancy
Fourth processing stage: Generation of impressions
Red is better than blue: Our preference for warm colors
Not yet answered: The question of why

Determining the origin of lightness and color

It took several hundred million years for our eyes to develop from the first sensory cells, which only served to distinguish between light and dark. In parallel, about 500 million years ago, the development of a physiological apparatus capable of distinguishing individual wavelength ranges of the spectrum began. A milestone in this process was the ability to separate three different wavelength ranges about 35 million years ago, which laid the foundation for our color vision today.

The advantages of color perception quickly become clear if we pick up the thread that the first volume in this series began to spin: seeing is information gathering. Those who know more can orient themselves better in a complex environment, can react better and faster, and survive longer. In this sense, the distinction between light and dark is good and useful, but it does not yet allow us to experience the world in all its wealth of information. However, this is essential, for example, to procure food efficiently or to reliably detect predators. Even if the ability to see color were merely a coincidence, it would have quickly given the individuals or species it affected superiority and would therefore have prevailed on a broad front in evolutionary terms.

As the physiological development of living beings progressed, their social interactions also became increasingly complex, and colors gained increasing importance in relation to sexuality, the rearing of offspring, and response to disease. And our long artistic tradition, from the first rock and cave drawings to the more elaborate production of textiles to modern painting, is merely the logical continuation of this line of development.

At the current stage of evolution, colors seem so natural to us that we rarely consider their origins. Most of us would likely assume that color is an inherent property of the objects we perceive, wouldn’t we? However, science has revealed otherwise, so let’s first challenge our comfortable assumptions and awaken our curiosity. Let’s examine an experiment.

The experimental setup by physiologist A. Gelb in 1929 was as follows: He presented a pane of glass to his subjects, who described it as extremely dark, nearly black, in a dimly lit room with black walls. At the start of the experiment, Gelb illuminated only the pane of glass with a lamp hidden from the observers. Remarkably, all participants then perceived the pane as white. When he introduced a piece of white paper alongside the still-illuminated glass pane, this new stimulus caused the pane to appear black again in the subjects’ perception.

The same object thus appears to multiple normally sighted people as either black or white, depending on the context in which it is presented. In the first example, when the object produces the brightest stimulus relative to its surroundings, it appears white. Conversely, in the second case, introducing an even brighter stimulus for direct comparison causes it to appear black. Only a sleight of hand could explain this phenomenon if color were solely an attribute of the object. However, Gelb was a reputable scientist, so we can rule out any trickery. This leaves only the initially unsettling realization that color and brightness are not independent properties that we merely detect. Instead, our visual system constructs both according to specific rules based on the intensity and spectral quality of what we perceive as light.

A spectrophotometer splits the light reflected from a colored surface to produce a **reflectance curve (R-curve)**, which shows the intensity of light for each wavelength. For example, an object that we perceive as green may produce the R-curve shown in Figure 2 (Remission Curve). This curve has a clear predominance in the medium-wavelength region of the spectrum (the so-called dominant wavelength) but also contains, to a lesser extent, components from the rest of the visible spectrum. Interestingly, our eyes do not perceive this wavelength mixture as yellowish-green or greenish-red, just as we do not perceive two different tones played simultaneously as distinct. Instead, we process the stimulus as a single, integrated color. We can learn a great deal about our visual system through the compositions of such mixtures.

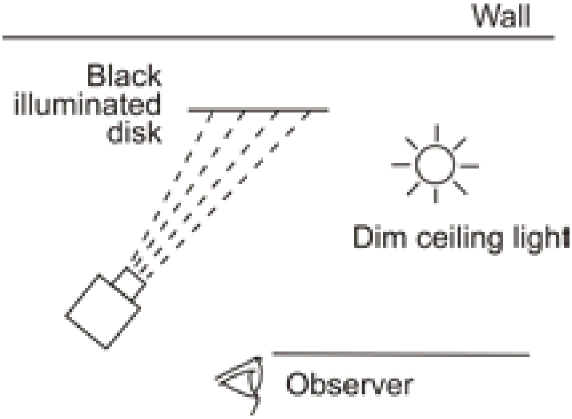

Figure 1: Experimental setup for brightness perception according to A. Gelb

Remission curve:

The curve obtained by plotting the remission (combined absorption and reflection) of a body for each wavelength range.

Intensity distribution curve:

The curve that results when the intensities contained in the spectrum of a light source are plotted on a graph for each wavelength range.

Transfer curve:

The curve that results when we plot on a graph the range of the spectrum transmitted or absorbed by a filter.

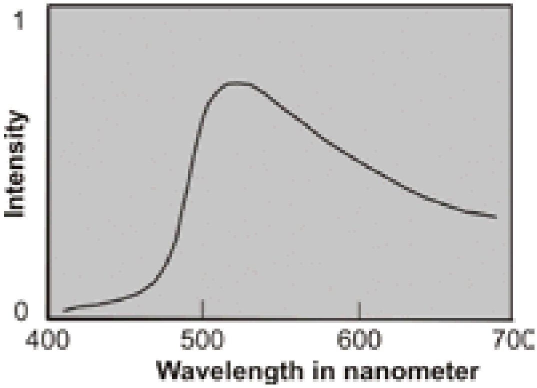

Figure 2: Remission curve
The curve shows the light intensities reflected from a green color sample under white illumination at each visible wavelength.

Let's mix lights with known intensity distribution curves (I-curves) and known color impressions. For example, a red light (650 nm) and a green light (530 nm), with their I-curves shown in Figure 3 A and B (Intensity distribution curves). What color impression will the mixture of these two lights produce? The result of combining the two curves is shown in Figure 3 C, which can be described as quite broad without a prominent wavelength range. The flat peak region of the combined curve is at 570 nm. By superimposing the two curves alone, we cannot predict the color impression, but if we were to perform the experiment, the visual result would be a yellow color impression.

Monochromatic light is spectrally pure and has only a single wavelength, whereas polychromatic light is a mixture of several wavelengths.

This is quite surprising, as monochromatic yellow has an I-curve as shown in Figure 3 D and does not otherwise suggest the presence of red or green components. We can only explain the perception of the same color through our visual system's ability to interpret completely different spectra as identical. We refer to two colors that appear identical to us, despite having distinct intensity distribution curves, as metamers. This term is of further interest because metamerism enables us to reproduce color impressions with reasonable technical effort.

So now we know that color perceptions must be based on different wavelength stimuli. The question remains how we capture and process them. To answer this question, let us look into our eyes.

Determining the physiological input stage

The eye

The physical reactions of living beings to light are approximately 1.5 billion years old. These early responses likely helped organisms switch their activity from night to day, and light-sensitive cells on the skin that serve this purpose can still be observed in primitive single-celled organisms today. In a second phase, photoreceptors were positioned in small pits to shield them from stray light, enhancing the detection of moving shadows and potential dangers. To protect these early eye pits from external objects, translucent membranes gradually formed over them, thickening at the center and laying the groundwork for the development of a primitive lens. These initial lenses likely functioned only to amplify light, and it took several million years for them to produce truly useful images. It was not until about 800 million years ago that eyes evolved, enabling organisms with various receptors to see during both day and night. Today, eyes are essential to our vision because they enable the brain to capture visual information. While the eyes resemble a camera in some ways, they do more than just transmit a highly focused image to the brain; they also perform the initial stage of complex data processing.

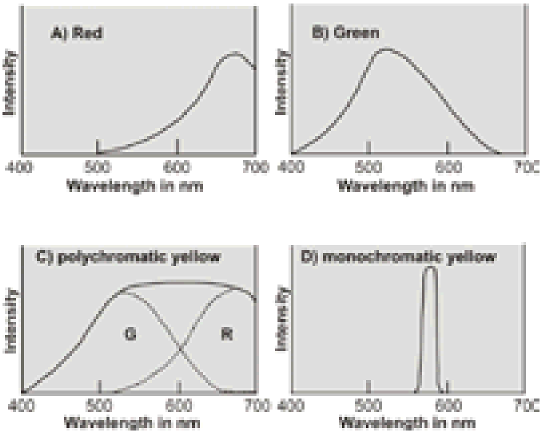

Figure 3: Intensity distribution curves
A shows the I-curve of a light perceived as red. B shows the I-curve of a green light. C shows the mixture of A and B, i.e. yellow. D shows the I-curve of monochromatic yellow light.

The human eye, as we know it today, is a roughly spherical structure approximately 2.5 cm in diameter. The dense tissue of the sclera protects it externally, allowing light to enter only through the small, transparent cornea. The gelatinous vitreous humor occupies most of the eye's interior, maintaining its shape and protecting its sensitive components. The conjunctiva covers the sclera, while the cornea, the eye's outermost functional unit, refracts incident light most strongly and, in combination with the lens, produces a sharp image. The next structure inward is a small chamber filled with aqueous humor, which contains the iris. The iris consists of thin connective tissue with pigmented cells that give the eyes their various colors. However, its primary function is to be completely lightproof, except for the pupil (also known as the iris diaphragm) at its center. The retina, located at the back of the eye and responsible for capturing the visual image, adapts slowly to changes in luminance, so the iris acts as a protective diaphragm that adjusts rapidly. It regulates pupil size between 2 and 8 millimeters, controlling the amount of incident light by approximately two logarithmic units. Only after the iris makes an immediate adjustment do

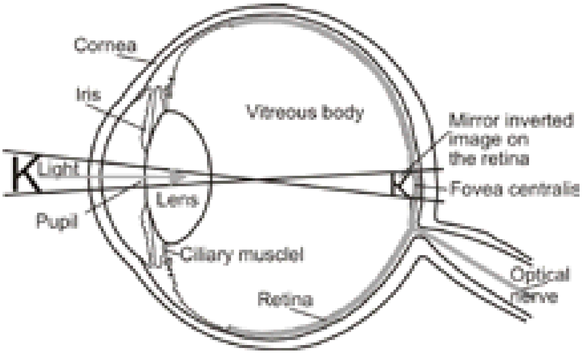

Figure 4: Cross section of the human eye

the sensory cells in the retina gradually adapt to the new luminance. In addition to regulating light, the iris diaphragm, similar to a camera aperture, improves depth of field during near vision by constricting.

A fundus camera is required to look through the pupil into the eye, as the observer's head constantly casts a shadow. However, when photographing with a flash, we can often unintentionally glimpse inside the eye. If the flash is too close to the lens's optical axis and the pupil is dilated due to dim ambient lighting, the retina, richly supplied with blood, appears as a red reflection in the image. Flash units can mitigate this by either constricting the pupil with a series of pre-flashes that reduce reflected light or by triggering the flash offset from the optical axis.The lens, located immediately behind the iris, is responsible for the eye's accommodation to various object distances. The ciliary muscle, located on either side of the eye, contracts or relaxes, and this movement is transmitted to the lens via the zonular fibers, altering its curvature. When the object to be focused on is more than 6 meters away, light rays arrive nearly parallel to the retina, producing a sharp image. As the object moves closer, the image plane shifts behind the retina, and the rays are no longer parallel. For near vision, the ciliary muscle contracts, surprisingly relaxing the zonular fibers, which causes the lens to become more curved. This increased curvature refracts light more strongly, shifting the image plane forward so that a sharp image falls on the retina. This process, known as accommodation, prevents muscle vibrations from affecting the ocular system. The lens, structured like an onion, consists of layers that grow over time as new cells form on its outer surface. Unfortunately, this growth eventually restricts nutrient supply to older inner cells, causing them to lose elasticity. With age, the lens becomes less capable of accommodating varying distances, necessitating glasses or contact lenses to compensate.The interplay of the cornea, iris, pupil, and lens creates a sharp, small, inverted image of the environment on the retina lining the inner eye, analogous to a camera obscura. For a long time, it was believed that the brain interpreted the retinal image as a whole using a kind of "inner eye." However, modern research has shown that visual perception is far more complex.