Atle Einar Østern

The light **we (don't) see**

We depend on light to see. Visible light constitutes a narrow part of the much wider electromagnetic spectrum. Why does the visual system only detect this small fraction? Why not infrared or ultraviolet light? Or radio waves like in Wi-Fi? Do we really experience light in the same way? These basic questions are the focus of this paper.

ATLE EINAR ØSTERN, OVERLEGE PH.D, ØYEAVDELINGEN, OSLO UNIVERSITETSSYKEHUS, HF (ULLEVÅL), 0407 OSLO

In Genesis, it is written: "Let there be light". For billions of years, our planet was mostly illuminated by celestial objects and the sun. Electromagnetic radiation propagates through outer space, carrying energy, by wave-particle duality. Frequency and wavelength of the particles, or photons, define different types of electromagnetic radiation. Photons are either reflected, absorbed or transmitted by atoms as they enter our atmosphere, depending on the wavelengths and corresponding energy levels. Hence, this substantially constricts the frequency bands which are available for any earthbound visual systems to potentially perceive

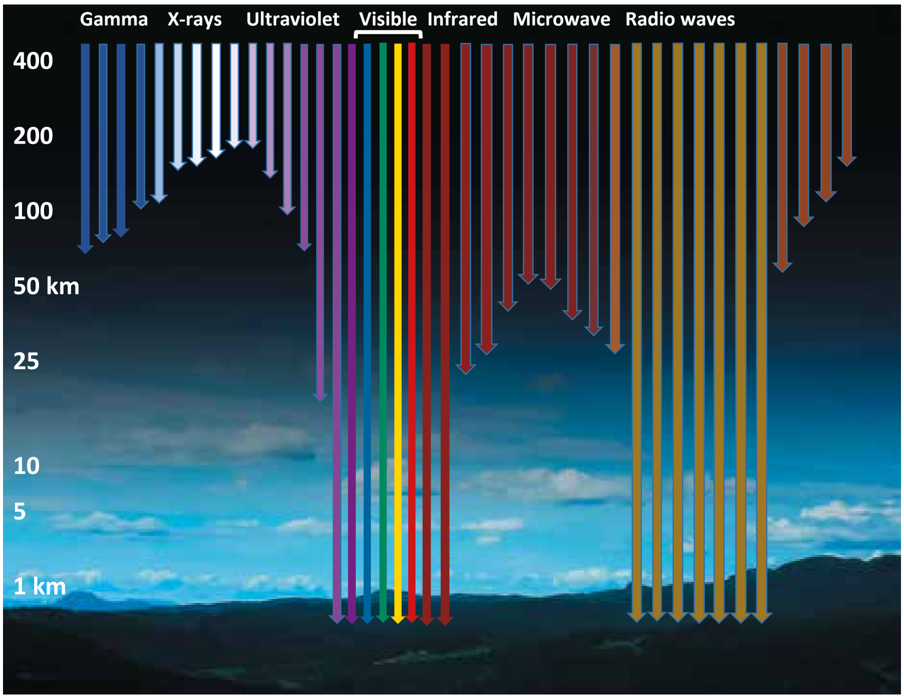

Figure 1: The optic window is composed of the electromagnetic waves which are visible for humans. Photo/illustration: Atle Østern

from above. All other wavelengths will be naturally inaccessible to living organisms. Only ultraviolet (UV) rays, visible light, infrared (IR) radiation and radio waves reach the Earth's surface (Figure 1). So, why don't we see them all?

Radio waves are widely exploited by humans in modern technology, but they will forever be beyond the realm of possibility for us to naturally detect with our eyes. The reason has to do with physics. Their energy is simply too low to trigger any biochemical reactions in cells, including in photoreceptors.

That leaves light around and within the visible spectrum. The visible portion of sunlight has the most intense radiation. This is optimal for electron transitions in pigments to occur. The outcome was that life adapted to utilize this available extraterrestrial energy source. First photosynthesis evolved 3 billion years ago in plants and then, much later, a complex visual sense in animals about 550 million years ago to navigate.

As is well known, the frequency variation in light is distinguished as different colours. Colour vision in animals varies. Birds and reptiles usually have four colour-sensitive cones. Mammalian ancestors converted from a similar cone-dominated to a largely rod-based vision as an adaption to the prolonged period of nocturnal living during the reign of dinosaurs. This era ended less than 66 million years ago when a huge asteroid blasted into the Gulf of Mexico, triggering cataclysmic mass extinctions. Consequently, most contemporary mammals still retain only two cone types; they are dichromatic. Their world is less colourful than ours (Figure 2). On the other hand, some invertebrates have multiple opsins. The mantis shrimp has the record, with 12-16 photoreceptors. It can detect UV, IR and polarized light, as well as move its eyes independently.

The human small (S), medium (M) and long (L) cones are named based on the wavelengths with the corresponding highest spectral sensitivities (Figure 3). Following a duplication of a gene for the longwave opsin in our primate ancestors, the M- and L-receptors arose about 35 million years ago. As a result, the now trichromatic eyes of diurnal monkeys became sensitive to red and green objects. This became important when foraging for ripe fruits and young leaves which were the main food sources. Another potential benefit was the ability to discriminate skin tones of bare-faced members of the same group since social interaction is of great importance to primates and humans. For instance, emotions and conditions are often revealed through reddish colouration, such as when the eye is irritated, skin tissues are inflamed or we blush.

Figure 2: To the left is what humans see, to the right what cats see. Photo: Atle Østern

The combined colour perception, with our ability to differentiate 2-10 million chromaticities, is a result of a complex brain processing. However, there is, in fact, natural variability in human cone density and visual cortex size. Can we then be certain that what appears as red for you is not really what I would describe as blue? In 2015 a video became a viral phenomenon worldwide where people disagreed about the colour of a dress (black and royal blue or gold and white). Other controlled experiments have confirmed stark

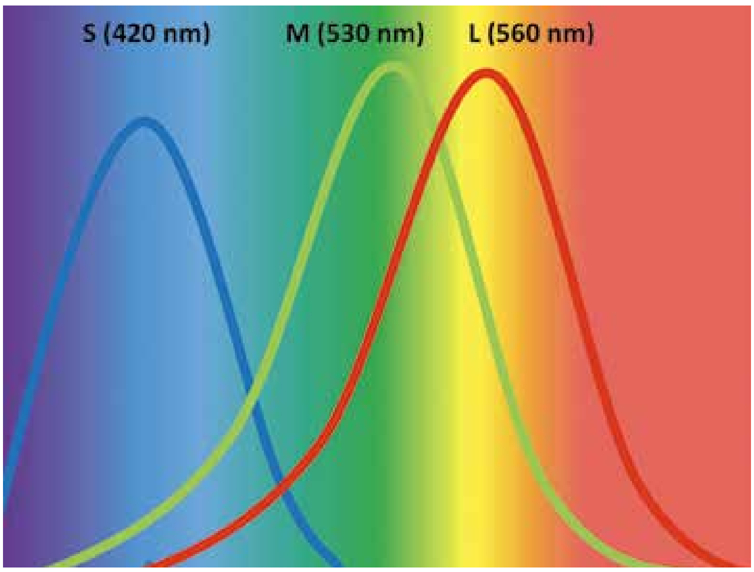

Figure 3: The wavelength sensitivity of the three colour receptors. Figure: Atle Østern

Figure 4: Both the common starling and bees have UV vision according to research. Photos: Atle Østern

differences. The fascinating answer to the question is that colour perception is not always similar, even in the absence of an acquired or congenital colour vision deficiency. Scientists believe that different opinions are due to chromatic adaption and how the brain recognizes colours. The need for colour consistency, the context of illumination and light contrast, influence how we interpret colours as well. Thus, the same objectives can appear darker or lighter depending on the surrounding conditions. We can even be tricked to see colours where there are none. Is this an innate or adaptive feature? Research indicates that whether you are an early or late riser might be part of the explanation in the now-famous dress example above. However, it is also possible that the first time the brain encounters a colour as an infant it is determined how it will be perceived in the future. In addition, studies suggest that language and culture are of importance. For instance, members of the Berinmo tribe in Papua New Guinea categorize and discriminate hues differently from English speaking natives. Blood supply to the eye and the season of the year may also matter. Colour appearance changes as a persistent calibration to greyness in the environment. Colours can even be subtly distinctive in healthy left and right eyes. They are also affected by moods and earlier memories. Light and contrast sensitivity is reduced in depression. Some, usually females, are also tetrachromatic, having a fourth photoreceptor. Consequently, in some cases, they can theoretically discriminate between perhaps 100 million colours. So, to conclude, your world may look different from mine!

The visible frequency range diverges across species. It is influenced by survival strategies and needs. Humans recognize wavelengths from about 400 to 720 nanometers (nm). UV radiation designates wavelengths from about 100 to 400 nm. Many vertebrates possess retinal photoreceptors devoted to the (near) UV, with a multitude of roles in vision (expansion of colour vision, navigation, camouflage, foraging and communication). The capacity to respond to UV is found in many fishes, amphibians, reptiles and birds (with UV reflecting feathers), but previously not in mammals. Recently, UV vision has surprisingly been revealed in reindeer in the Arctic which can identify UV absorbing hair and urine from wolves. Why have humans not preserved this ancestral trait? It has been demonstrated that even humans still have UV sensitive pigments. Research suggests that our primate ancestors switched from originally UV vision to blue light sensitivity through multiple mutations over several million years. The reason is that UV exposure would otherwise cause blurry images due to chromatic aberration and harmful photodamage by the formation of free radicals. While the ozone layer blocks toxic UVC radiation (consisting of wavelengths shorter than 280 nm), cornea absorbs almost all UVB rays (280-315 nm) and the biological lens most of the remaining UVA rays (315-400 nm) in extant humans. The downside is that we have lost the ability to perceive almost otherworldly beautiful flower patterns created by UV-absorbing pigments, which birds and bees can (Figure 4). In other words, this is a trade-off between costs and benefits. However, children, in addition to aphakic patients, can still under some conditions notice near-UV radiation down to 380 nm.

IR light has longer wavelengths (>700 nm) and less energy than that of visible light. It can be reflected off or emitted as heat from objects. IR imaging allows thermal body temperatures to be observed (Figure 5). In nature, this could be potentially beneficial for nocturnal predators. Indeed, many snakes have holes on their faces, called pit organs, which detect IR energy up to a distance of one meter. Nonetheless, these organs are wired up to the somatosensory system and react to heat instead of light. The reason why near-IR vision has been regarded as impossible in vertebrate eyes, albeit exceptions have now been discovered, is that it triggers noise (frequent false alarms)

Figure 5: Infrared thermal image. Photo: Atle Østern

Figure 6: Night vision goggles, where the visual field and objects appear green, is used by Norwegian military pilots on the new NH90 Helicopter. Photo: Atle Østern

in visual pigments. This interferes with light detection. Therefore, according to most textbooks, humans are not able to see IR light. New research suggests that this is not necessarily the case. One study demonstrated that when powerful lasers emitted short IR pulses with a wavelength of 1000 nm, a double absorption of photons in a photoreceptor generated the same amount of energy as a single photon of 500 nm. Individuals perceived this as green light flashes. Interestingly, this implies that under certain conditions the human eye can see beyond the visible spectrum. A possible future application is an ophthalmological instrument to examine and stimulate specific parts of the retina to evaluate functionality.

In dim light our vision changes. It has recently been discovered that some primates (like lemurs) maintain colour vision at night, but in humans, only the rods are of course stimulated in darkness. The rods are sensitive to wavelengths between blue and green light. Dark adaptation increases the light sensibility of the eye up to 100.000 times. Already in 1941, it was established that as few as 5 single photons were enough to trigger an awareness of light. However, in ordinary low light conditions, the visual acuity (VA) is reduced to approximately 20/200, with potentially increased night myopia, weakened depth vision and glare problems. To improve the situation in (near) total darkness a device called "night vision goggles" (NVG) amplifies IR or low light to produce a monochromatic vision. NVG is for instance used by military forces. Yet, they have some limits. NVG produces a VA of 6/12 or less, which creates an illusion of longer distances to terrain obstacles and prevents pilots from seeing power lines. The first Norwegian military helicopter casualty linked to use of NVG occurred in 1995 (Figure 6). In addition to an NVG camera, the new Lockheed Martin F-35 Lightning combat aircraft, which has been bought by Norway and Denmark, also has 6 IR receptors to monitor the surroundings. This enables the pilot to see "through" the floor of the cockpit.

In the permanent absence of daylight, many animals have, besides losing VA or even functional eyes, evolved the ability to create artificial light. This is called bioluminescence. Probably less known is that even humans glimmer with a light intensity 1000 times less than the sensitivity of our eyes. This is due to direct and rhythmic emissions from our bodies of photons within the visible spectrum, related to changes in energy metabolism.

Beyond the use of visual aids, is it possible to extend our predetermined sensitivity to electromagnetic radiation? A new study suggests that this can be achieved by a medical procedure. Mouse eyes were experimentally injected with nanoparticles which adhered to the photoreceptors. The mice gained IR vision in the aftermath, sufficient to sort out shapes. This may lead to new technological breakthroughs in civilian encryption, security and military operations.

Superman has x-ray vision. Perhaps his mother planet Krypton lacked the protecting atmosphere which shaped our visual system? We will never equal his level, but in the coming decades, we may perhaps be liberated from our biological restrictions and expand our light-sensitive capabilities in unknown ways. Only time will tell if there will be a "bright" future.

Sources:

Changizi et al: Bare skin, blood and the evolution of primate colour vision. Biology letters 2006

Cronin and Bok: Review: Photoreception and vision in the ultraviolet. Journal of Experimental Biology 2016, 219: 2790-2801.

Jordan et al: The dimensionality of color vision in carriers of anomalous trichromacy. Journal of Vision July 2010, Vol.10.

Kobayashi et al: Imaging of Ultraweak Spontaneous Photon Emission from Human Body Displaying Diurnal Rhythm. Plos One. 2009.

Ma et al: Mammalian Near-Infrared Image Vision through Injectable and Self-Powered Retinal Nanoantennae. Cell, 2019

Manusco et al: Gene therapy for red–green colour blindness in adult primates. Nature vol. 461, s. 784–787, 2009

Palczewska et al: Human infrared vision is triggered by two-photon chromophore isomerization. Proceedings of the National Academy of Sciences, 2014

Webster: Individual Differences in Color Vision. Handbook of Color Psychology. Cambridge University Press, s. 197-215, 2015

Yokoyama et al: Epistatic Adaptive Evolution of Human Color Vision. PLOS One. 2014.