1st course

Kazakh National Medical University named after S.D Asfendiyarov

Abstract:

“The Biophysics of Vision: From Photoreceptors to Visual Perception”

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Almaty 2025

Introduction

Vision is perhaps the most complex but essential sense within the human body. It not only allows us to perceive and respond to visual stimuli such as light, color, movement, and shape but also allows us to navigate through space, recognize danger, read facial cues, and decipher social cues. While widely conceived as an ultimately biological process, vision is really rooted in physics—in fact optics, electromagnetism, and signal transduction. These biophysical principles govern the transduction of light energy into the neural impulses that the brain interprets as images.

From the moment when a photon first enters the eye to the later stages of vision processing in the cerebral cortex, vision shows a fascinating intersection of anatomy, molecular biology, and physical law. This abstract outlines the basic biophysical mechanisms of human vision, detailing how photons are responded to by photoreceptors, how signal processing is done in the retina, and how electrical impulses are converted into conscious experience by the brain. We also explain how the principles are brought to medical technologies today.

The Physics of Light and the Eye's Optical System

Light, as a physical phenomenon, is electromagnetic radiation that travels as waves and exhibits wave-like and particle-like behavior. The visible spectrum has a wavelength of approximately 400 to 700 nanometers. Light, on entering the eye, first surfaces over the cornea, a transparent curved body accounting for most of the eye's refracting power. Light passes through the aqueous humor, pupil, lens, and vitreous humor, before being converged onto the retina.

All these elements are responsible for bending of light. The lens is able to alter its shape by contraction of ciliary muscles, altering the focal length in a process referred to as accommodation. This is required to view objects at different distances. The direction of light through these media is governed by Snell's Law:

$$n1\sin\theta1=n2\sin\theta2$$

where n is the refractive index. The refractive and curvatures of the lens and cornea ensure that light is focused at one point on the retina for the highest clarity.

Interestingly, the pupil regulates the quantity of light entering, expanding in poor lighting and closing with bright light. This aperture function is a integral part of the eye's optical system, such as that of a camera shutter.

Photoreceptors and the Phototransduction Cascade

The retina is
a photoreceptor and neural cellcomplex that is layered. Photoreceptors, the rods and the cones, are accountable for photon detection and the trigger of vision. The rods are larger in number and extremely sensitive to
low light levels andare the ones involved in night vision (scotopic vision),
while the cones handledaytime (photopic) vision, color vision, and sharp central vision.

Cones are divided into three classes based on their sensitivity to different wavelengths:

- S-cones respond to short wavelengths (~420 nm, blue),
- M-cones to medium wavelengths (~534 nm, green),
- L-cones to long wavelengths (~564 nm, red).

The phototransduction cascade begins when photons are absorbed by visual pigments within the photoreceptor outer segments. These pigments consist of opsin proteins bound to a light-sensitive molecule called 11-cis-retinal, a derivative of vitamin A. Absorption of light causes photoisomerization of retinal to all-trans-retinal, which activates the opsin.

This initiates a biochemical cascade:

1. Opsin activates transducin, a G-protein.
2. Transducin activates phosphodiesterase (PDE), which hydrolyzes cyclic GMP (cGMP).
3. cGMP levels fall, leading to closure of cGMP-gated Na^+ and Ca^{2+} channels.
4. The photoreceptor cell hyperpolarizes, decreasing neurotransmitter (glutamate) release.
5. This change in neurotransmission is detected by bipolar cells.

This process converts the energy of absorbed photons into a modulated electrical signal—a clear example of physics driving a biological response.

Signal Processing in the Retina

Far from a passive light detector, the retina is a complex neural processor. Between the photoreceptors and the output ganglion cells lies an interposed network of horizontal, bipolar, and amacrine cells that filter, sharpen, and enhance visual information.

A major mechanism is lateral inhibition, which is mediated by horizontal cells. It serves to enhance contrast at edges and is responsible for boundary and shape detection in the visual field. For instance, in the Mach bands illusion, which is the classic example, the retina is exaggerating contrast among neighboring shades of gray by this mechanism.

Amacrine cells play a role in the modulation of temporal aspects of vision, such as motion detection, and bipolar cells convey either ON or OFF signals depending on the receptor type. Lastly, ganglion cells, whose axons form the optic nerve, encode this processed information in the form of action potentials and convey it to the brain.

Visual Perception and the Brain

Visual signals from the retina travel via the optic nerve to the lateral geniculate nucleus (LGN) of the thalamus and then to the primary visual cortex (V1) in the occipital lobe. This pathway, known as the retinogeniculate pathway, is responsible for the conscious perception of sight.

In V1, neurons are arranged into orientation columns, ocular dominance columns, and blobs that respond to edges, angles, and color. Higher-order cortical areas such as V2, V4, and MT integrate visual data to recognize objects, track motion, and interpret spatial relationships.

This hierarchical structure of the visual system allows the brain to reconstruct three-dimensional images, perceive depth (using binocular disparity), and interpret color constancy and perspective. Each layer of the cortex transforms the raw signal into increasingly abstract representations.

Biophysical Applications in Medicine

The biophysics of vision has given rise to powerful diagnostic and therapeutic technologies in medicine:

- Optical Coherence Tomography (OCT): Based on low-coherence interferometry, OCT allows cross-sectional imaging of retinal layers with micrometer resolution. It is widely used in diagnosing glaucoma, macular degeneration, and diabetic retinopathy.
- Electroretinography (ERG): Measures the electrical responses of retinal cells to light stimuli. Used to detect retinal dystrophies, retinitis pigmentosa, and other degenerative diseases.
- Retinal Implants: Devices like the Argus II aim to restore partial vision to patients with photoreceptor loss by electrically stimulating remaining retinal cells.
- Gene therapy and optogenetics are also emerging strategies for restoring vision, particularly in cases of inherited retinal degeneration.

Conclusion

The human visual system is a remarkable integration of physics, chemistry, and biology. From the quantum absorption of a photon to the subjective experience of an image, each step along the way is regulated by precise biophysical laws. To understand these processes not only advances our knowledge of sensory biology but also advances the creation of medical technologies used to diagnose, preserve, or even regain sight. As research in the field evolves, the divide between physics and medicine thins, with evidence showing that seeing is, quite literally, believing in the potential of interdisciplinary science.

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