

1 Visual sharpness

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Visual sharpness

Positioning: What is visual sharpness?

We can measure the brightness of a light stimulus in cd/m^2 and determine its chromaticity by its wavelength structure, but sharpness is a purely perceived property of a visual scene that we cannot measure directly. It exists only in the eye of the beholder. Generally, we characterize a visual impression as sharp when we can clearly distinguish objects from one another. Unlike taste or smell, visual sharpness is a perceptual measure that assesses the clarity or distinctness of object edges. Detecting these edges is of great interest to the visual system because, as discussed in volume 2 of this series about Visuality, Depth, and Size (Second Step – Beginning of Information Processing), it organizes object perception around them: objects in a scene are not merely detected but are individually constructed based on their perceived edges. This process is complex, and its exact sequence remains controversial among scientists.

Visual acuity is a byproduct of the process by which the visual system realizes object perception.

Without the registration of object boundaries, visual perception could not arise. The following experiment illustrates the truth of this statement.

Imagine, for example, a red square with a smaller green square in its center. If you artificially stabilize the border between the two areas on your retina, you will first lose perception of the green square, leaving only the red background. After about one second without any movement relative to the retina, this impression also fades, and you see nothing. This occurs because photoreceptors only report potential differences, not absolute potential levels, which enhances efficiency. To ensure that perception is not lost when the gaze lingers on one point for too long, the eyes perform unconscious, random movements several times per second, known as **microsaccades**.

The answer to why our visual system structures and distinguishes objects based on the borders between areas of different color and brightness is simple: economy, effectiveness, and low energy consumption. It is highly efficient and cost-effective for the visual system to process objects based on interruptions in light patterns. This method allows it to encode only the parts of the image that change, rather than the entire image. Edges and boundaries are the critical information that the brain needs to construct the shapes and forms of objects in our environment. It is unnecessary to define brightness and color at every single point of, for example, a solid red object. Instead, it is sufficient to define brightness and color at points where changes occur, such as at an edge or

boundary. This approach significantly reduces the amount of information required for transmission and processing.

We can see the extent of this reduction by comparing two graphics in .tif and .jpeg formats. Assume the image shows a red circle in the center of a green area in a 10x15 cm format. In .tif format, the file size is 1715 KB, while in .jpeg format, it is only 13 KB—132 times smaller. This reduction occurs because .jpeg, much like the visual system, encodes only the pixels where changes occur. The file contains only the boundary positions and the colors on either side. The image processing program automatically fills in the pixels in between.

This reduction in the amount of information is extremely important for the nervous system in general, because energy is needed for a nerve cell to fire, and the body must use this resource as sparingly as possible. Keep in mind that the brain has a particularly high oxygen and energy requirement. It only accounts for about 2% of body mass, but consumes about 20% of the oxygen and more than 25% of the glucose. Therefore, the fewer nerve cells that are active, the better it is for the organism.

To capture as many edges as accurately as possible, the eye and brain must scan the field of view in as much detail as possible and then isolate the

boundaries. This is a complex task, and our visual system accomplishes it in several stages. For precise scanning, it relies on a large number of photoreceptors. Their spacing, along with other factors discussed below, determines the resolving power of the visual system.

To reliably isolate object edges in the resulting image, the visual system has the remarkable ability to process nerve impulses from the photoreceptors, or visual data, in a manner similar to a computer. It employs a specific type of ganglion cell, physiologically divided into **center and surround regions**, for this purpose. These cells connect in a way that creates mutual **inhibition**. This structure, known as the center-surround organization, filters out irregularities, such as object boundaries. The sharper the contour and the more abrupt its transition, the greater the output potential of such a center-surround cell, resulting in a heightened perception of the contour's sharpness.

We have now identified two key concepts—**resolving power** (resolution) and **contour sharpness**—that contribute to our perception of sharpness. These concepts will be explored in greater detail in the following sections.

Visual sharpness

The resolving power of the visual system

Resolution refers to the degree to which the visual system scans a scene. It corresponds to the packing density of photoreceptors, which is highest in the fovea centralis (see “The Arrangement of Photoreceptors on the Retina”). The high resolving power in the fovea allows us to capture edges with great precision.



Figure 1: The combination of resolution and edge sharpness determines our visual impression of sharpness

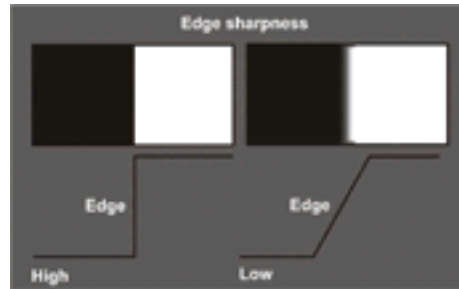


Figure 2: The concept of edge sharpness

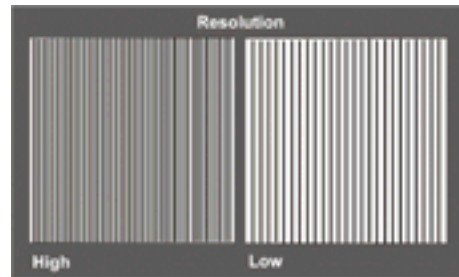


Figure 3: The concept of resolution

Our perception of sharpness in a natural scene or photograph increases with the amount of detail we perceive. The **resolving power** of our visual system determines how much detail we can discern. This can be related to different types of perceptual performance. **Resolution acuity** refers to the minimum distance required between two objects to perceive them as distinct. **Detection acuity** refers to the minimum size of an object needed for recognition. **Minimum detectable acuity** refers to the smallest object size that remains perceptible. **Vernier acuity**, or hyperacuity, refers to the smallest perceptible offset between

two lines. For our photographically oriented discussion, **resolution acuity** is most relevant. It depends on several factors that collectively determine the threshold an image need not exceed to appear sharp. These factors will be examined in detail in the following sections.

Diffraction as a physical limitation

Light waves typically travel in a straight line through space. When light waves encounter an obstacle or pass very close to one, within a few wavelengths, they deviate from their normal straight path. This phenomenon, known as **diffraction**, is an unavoidable physical effect independent of the quality of the optics. The smaller the aperture, the greater the image's impairment due to diffraction.

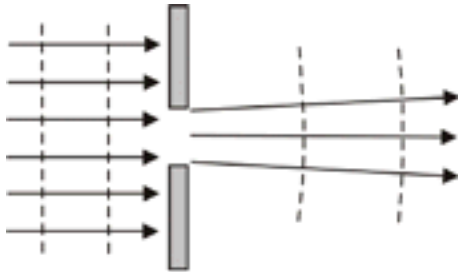
Due to this dispersion in different directions, light waves no longer travel the same distance and partially deviate from their original direction of oscillation. This causes them to overlap and reinforce each other at some points or to partially or completely cancel each other out at others. This superposition, known as **interference**, produces a diffraction pattern with the highest intensity where the waves reinforce and the lowest where they cancel. If we were to measure the intensity along a straight line, the result would resemble the pattern shown in fig. 5.

A perfectly circular aperture, considered ideal, produces a diffraction pattern known as the **Airy disk**, named after its discoverer, the British astronomer Sir George Biddell Airy (1801–1892). To illustrate diffraction in a more practical context, consider a water hose. With sufficient pressure, water exits the hose as a nearly circular jet. However, if the opening is slightly compressed with fingers, the jet spreads into a relatively wide fan.

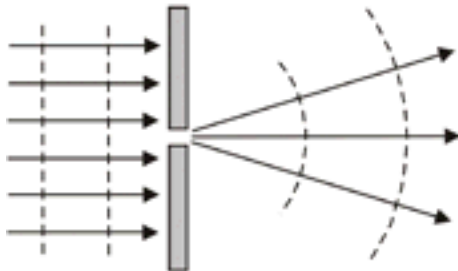
Since we cannot construct infinitely large optics, every optical device, including our eye, is inevitably limited by its **aperture**. Be it by its outer diameter or the size of a built-in aperture. The light is deflected at this bottleneck, and so the optics can never image a distant point light source into a precise point, even if all other aberrations were eliminated. Instead, the image is more or less blurred depending on the aperture size, and the image reflects the general so-called **Fraunhofer diffraction pattern** in the focal plane. In many cases, this effect is so small that it can be neglected, but fundamentally it prevents the imaging of very fine details and thus the magnification of an image beyond a certain degree.

To describe the resolving power of an optical system, we use the **Rayleigh criterion** (CR), named after its discoverer, John William Strutt (1842–1919), the third Lord Rayleigh. It states that two light points are conside-

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Diffraction at a large aperture



Diffraction at a small aperture

Figure 4: Diffraction of light rays at a large opening or a small opening

red resolved if the main maximum of one does not fall within the first minimum of the other.

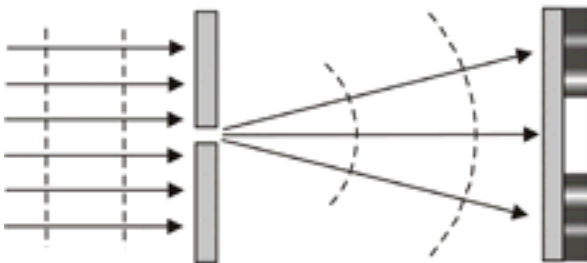
The maximum and minimum of the light sources must therefore be separated by a distance proportional to the ratio of the light's wavelength to the aperture diameter. Thus, a larger aperture can resolve finer details. This relationship is expressed by the formula for a circular aperture:

Formula 1

$$\alpha_{Grenz} = 0,206 \frac{\lambda}{D}$$

α_{Grenz} = Resolution in radian dimension
 λ = Light wavelength
 D = Aperture diameter

For the resolving power of the human eye, the Rayleigh criterion serves as a fundamental benchmark, and with the formula previously introduced, we can calculate the theoretically maximum achievable resolving power. For this purpose, we assume an average pupil diameter for the fully



Diffraction at a small opening with the corresponding diffraction pattern

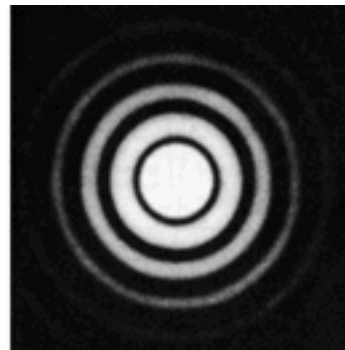


Figure 5: Diffraction of light at a slit and the resulting diffraction pattern

The resolving power of the visual system
Diffraction as a physical limitation

light-adapted eye of $D = 3 \text{ mm}$ and a wavelength of $\lambda = 550 \text{ nm}$, at which the eye's receptor apparatus is most sensitive.

Calculation 1

$$\alpha_{\text{Grenz}} = 0,206 \frac{\lambda}{D}$$

$$\alpha_{\text{Grenz}} = 0,206 \cdot \left(\frac{550}{3} \right)$$

$$\alpha_{\text{Grenz}} = \frac{113,3}{3}$$

$$\alpha_{\text{Grenz}} = 37,7666'' = 0,6294' = 0,0105^\circ$$

Theoretically, in daylight, the human eye can distinguish two points that are approximately 0.6294 arc-minutes apart. In other words, two points must be 1 mm apart to be perceived as separate from a distance of 57 cm.

The radian (unit symbol: rad) is used to indicate the size of a plane angle. It is a derived unit in the SI system of units. The plane angle of 1 radian encloses an arc of length 1 meter on the circumference of a circle of radius 1 meter. The solid angle encompasses 2π radians: 1 solid angle = 2 π rad. (Wikipedia)

The larger the f-number, the larger the diffraction pattern, or Airy disk. This raises the question: At what

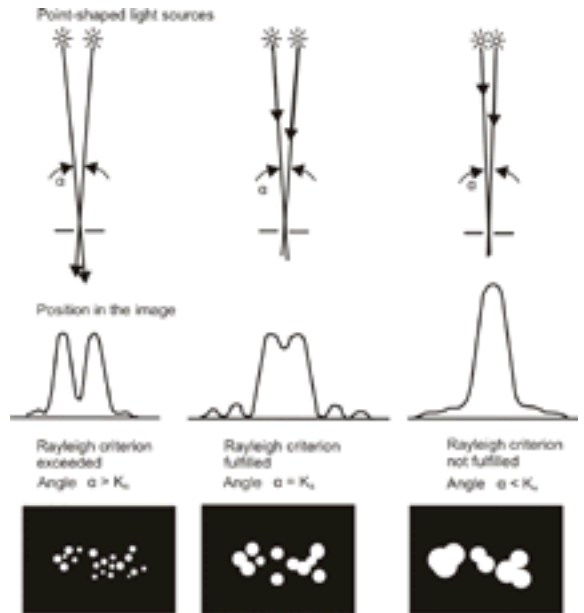


Figure 6: Rayleigh criterion and resolution

point does diffraction become a limiting factor for detail reproduction, i.e., resolution? To address this, we must first determine when the human eye perceives diffraction disks as separate points. Lord Rayleigh conducted and published this investigation in 1879. His findings show that for the eye to perceive two Airy disks as distinct, the intensity in the area between them must drop to 81% of their maximum intensity. This occurs when the maxima of the diffraction disks are separated by a distance equal to the radius of one disk.