The absolute maximal vision

How well can humans see?

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Good vision is important. For some, such as pilots, it is a vital requirement. I have examined air force pilots for many years. In some instances, I have recorded uncorrected monocular visual acuity of 20/10, even with a refractive error. Consequently, I have wondered what the maximum limit of human vision is and how it compares to animals. In this article, I attempt to answer such questions.

A starting point is then to determine what we mean by visual acuity. As shown in **Table 1**, there are several categories of visual acuity. We often label 20/20 as "normal" or "standard" vision, which is the ability to see an ortotype on the Snellen chart that subtends an angle of 5 arc minutes (5') at 6 meters or 20 feet (**Figure 1**).

Table 1. Classification of visual acuity

Type of acuity	Description	Degrees
Minimum resolvable acuity	The resolution of two close objects	0.017
Minimum recognizable acuity	The angular size of the smallest identifying feature	0.017
Minimum visible acuity	The smallest detectable object	0.00014
Minimum discriminable acuity	The angular size of the smallest change in a feature	0.00024

The minimum resolvable acuity is a fundamental boundary of spatial vision (the perception of the relationships of objects in space). This is the finest level of detail where a visual system can still discern two separate points. The prerequisite is that three cones on the row are involved. Under ideal contrast and luminance, two photoreceptors must be excited while the gap between the observed points falls on the intermediate cone. The distance between the centers of side-by-side cones in the fovea is 0.5 arc minutes (0.008 degrees or 30 arc seconds). Thus, the lower limit of minimum resolvable acuity must be twice that, which is one arc minute (0.017 degrees). More light is sampled if the photoreceptors are closely packed. The average peak density of photoreceptors in the foveola is 160,000 cones/mm^2, with considerable variation between individuals (ranging 100,000 to 324,000 cones/mm^2), corresponding to theoretical visual acuities of 20/10.5 and 20/7.1.[1] Resolution diminishes dramatically with eccentricity from the fovea. If not, we would have needed eyes and associated brain regions larger than our heads.[2]

However, on a bright day, humans can spot a wire against the background, which spans only 0.5 arc seconds (0.00014 degrees). That is less than described above. How is that possible? This remarkable minimum visible acuity is best explained by the imperfection of the eye's optics. The optics spread and distribute the image of the thin line, making it much broader on the retina. In this situation, the outfall is beneficial, but otherwise not. In fact, your camera might have superior optical quality compared to your eye. Thus, the visual potential of the eye is worse than retinal anatomy might alone imply. One limitation in this respect is that visual acuity depends on pupil size. Optical aberrations decrease visual acuity when the pupil is large (around 8 mm). However, with a small pupil (1–2 mm), diffraction occurs with the bending and scattering of the light waves after passing through the aperture, causing a reduction of image sharpness. The

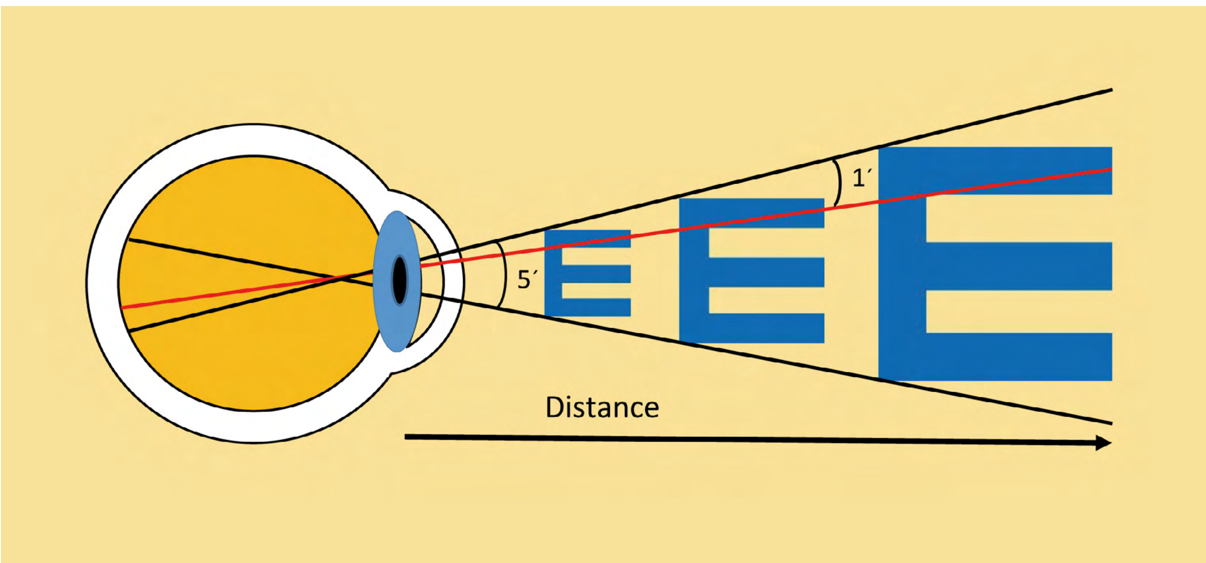

Figure 1. Schematic representation of the visual angle and the Snellen letter E: The visual angle is formed by the imaginary rays from the eye's nodal point to the top and bottom of an object. Arc minute is a unit of angular measure equal to 1/60 of a degree = 0.017 degrees = 1/21600 of a complete circle = 60 arc seconds. Illustration: Atle Østern.

visual acuity is best with a pupil diameter of around 3–4 mm. A measure of the optical performance is the modulation transfer function by testing patterns of sinusoidal gratings (**Figure 2**). The ratio between the contrast of the detected image and the original object defines the quality of the optical system.[2] Contrast sensitivity is hugely important for our visual function. Even when vision is 20/20, poor contrast sensitivity leads to problems in low-light situations, such as driving in darkness or fog.

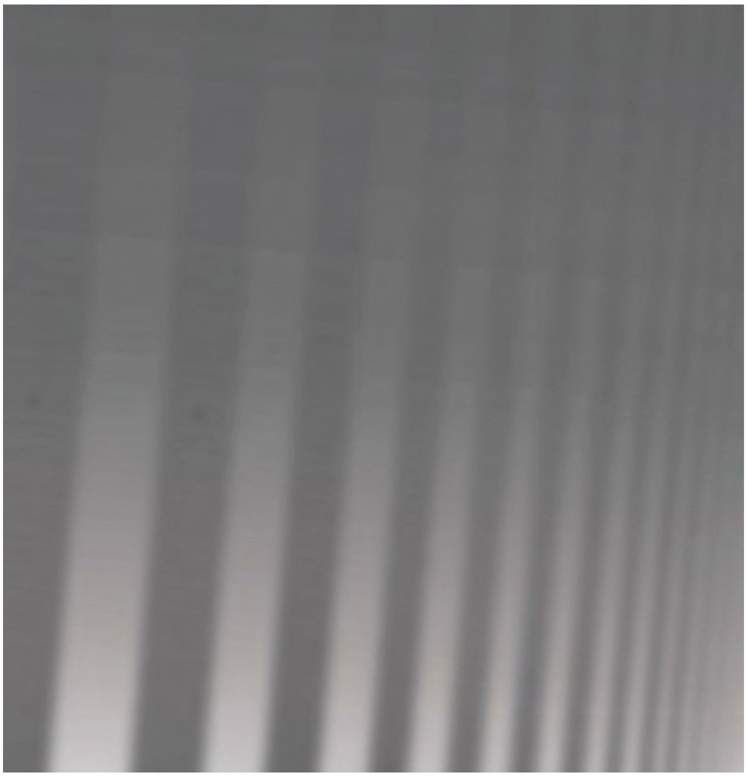

Figure 2. Contrast sensitivity: An image where the luminance varies gradually as a sine wave is called a sinusoidal grating, which can be used to test the optical system concerning the spatial frequency (number of bars, usually specified in cycles per degree), contrast (intensity difference between the dark and light bars), orientation (tilt), and spatial phase (the relative position of a grating). Humans are most sensitive to frequencies of 2–6 cycles per degree. Illustration: Atle Østern.

There is more to vision. Humans have the amazing ability to discriminate a tiny misalignment of two lines that far surpasses the eye's minimum spatial resolution. Consider this: According to Guinness World Records 2005, Dr. Levi, in 1984, "repeatedly identified the relative position of a thin, bright green line within 0.8 seconds of arc (0.00024 deg), which is much less than the smallest foveal cones [and] equivalent to a displacement of some 0.25 inches (6 mm) at a distance of 1 mile (1.6 km)."[2] This fascinating phenomenon is called Vernier acuity, a form of hyperacuity. Hyperacuity refers to the ability of the visual system to recognize the relative location and offset of stimuli (**Figure 3**). The underlying mechanism is not yet fully understood but is an indicator of cortical visual function. Other visual examples include the detection of curvature, line orientation discrimination, and stereoscopic binocular vision.[3]

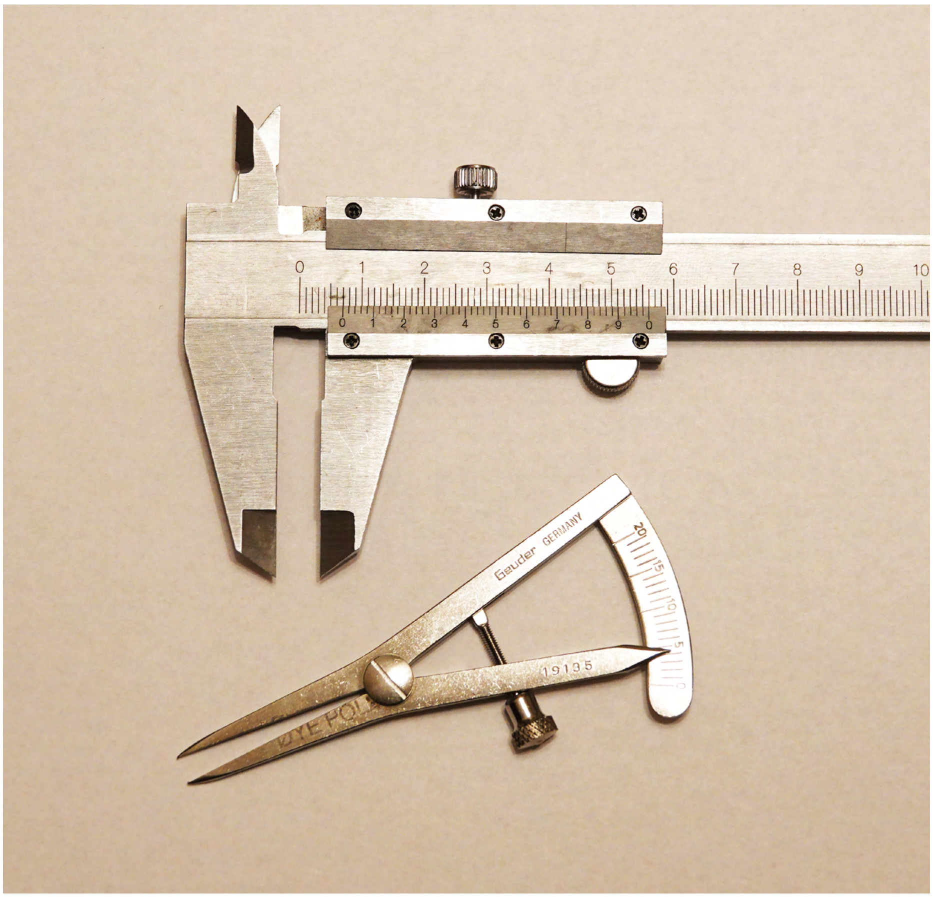

Figure 3. Vernier acuity is applied when detecting the slight misalignments of vertical lines between two adjacent scales, allowing for highly accurate measurements. That is the principle behind calipers. Calipers have long been used in many areas when high precision is needed, such as hand tools and in ophthalmology. Photo: Atle Østern

It gets more complex. As pointed out, the quality of the human optical apparatus and retinal anatomy is crucial for resolution acuity. However, recently published research suggests new compelling aspects of how visual signals are modulated beyond that. For example, scientists have demonstrated that the power-producing mitochondria in the photoreceptors can function like optical microlenses that channel light to the outer segments.[4] Furthermore, continuous unnoticeable microsaccades, accompanied by simultaneously brief periods of blindness, are critical contributors to normal visual acuity. They allow people to read at least two more lines on the Snellen chart compared to an immobilized gaze, which is essential knowledge when evaluating vision in patients with eye motion disturbances such as dyslexia and Parkinson's disease.[5,6] Moreover, how well people see relatively can be predicted based on unique individual differences in the extent of V1 surface area in the visual cortex, generating variable contrast sensitivity among people.[7]

To summarize, the best-corrected vision of two healthy individuals may not be the

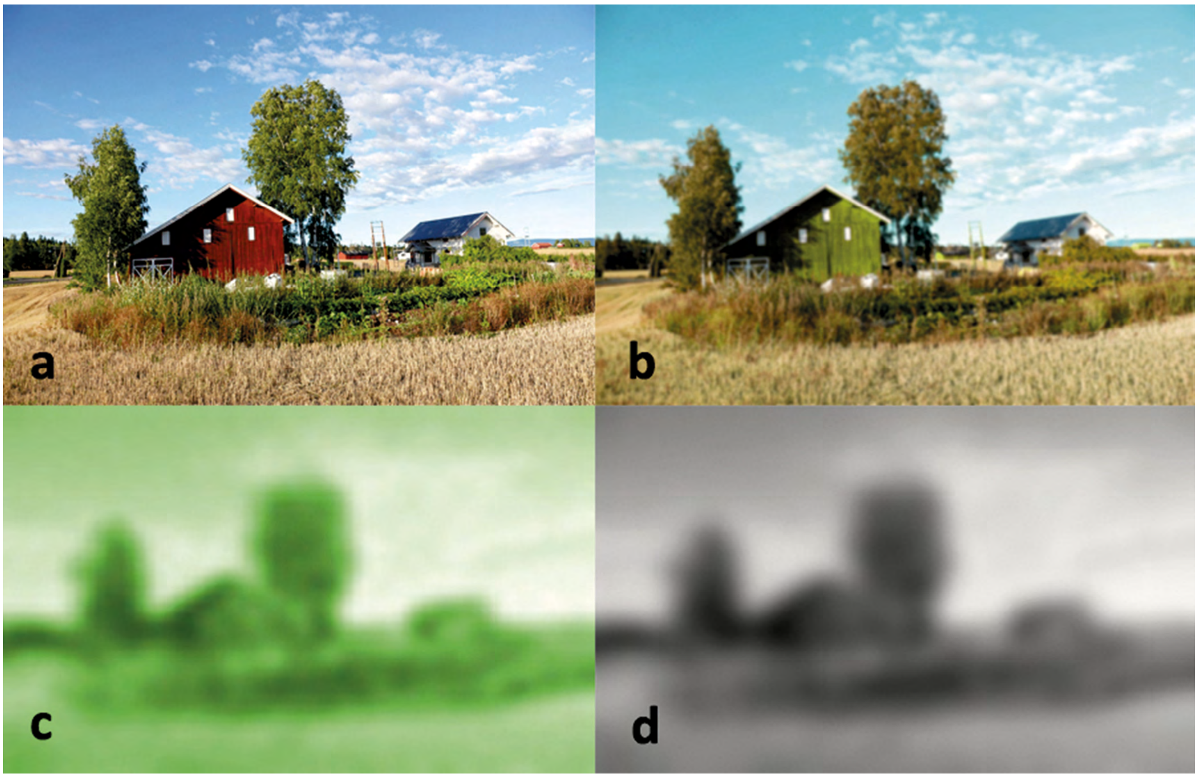

Figure 4. Vision in humans and some animals: The difference is 10,000 times between the worst and best visual acuity. What colors animals perceive varies. The simulated vision is of a human (a), cat (b), fly (c) and snail (d). Image: Atle Østern.

same for many reasons. In young humans, the average visual acuity is 20/16 to 20/12.5. Some claim that about 1% of the population achieves 20/10 vision, while others believe it is much rarer. However, one unvalidated report stated that an Australian Aboriginal person had 20/5 vision. But how do humans cope in a virtual world championship of vision among all living creatures (**Figure 4**)? Pretty well, actually.[8] The winners are some birds of prey, likely having a visual acuity of around 20/4 (**Figure 5**). However, we might compete for the silver medal. Our close extinct relatives (and partly ancestors), the Neanderthals, had even larger orbitas and eyeballs than us, perhaps as an adaptation to see better in dim light while hunting.

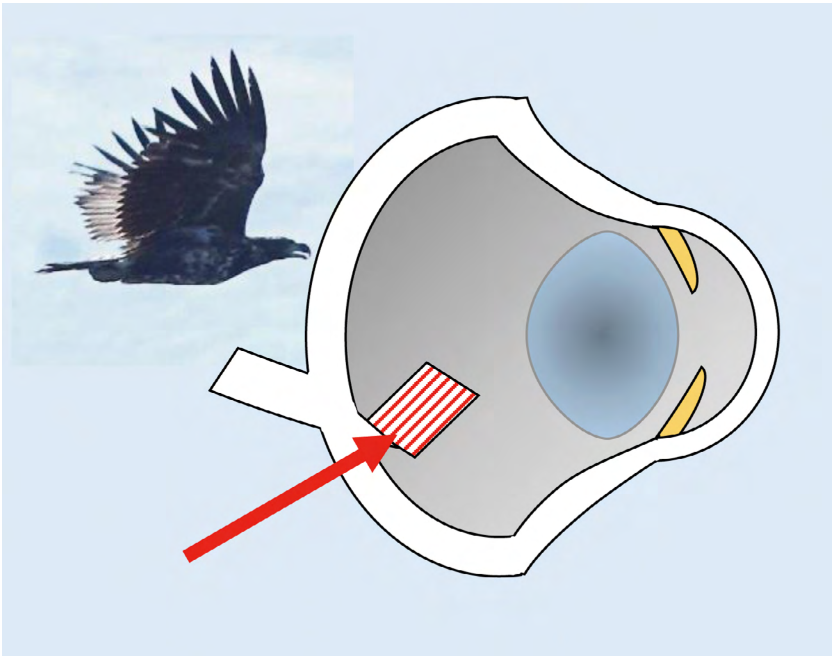

Figure 5. The unique shape of the eagle eye: The number of cones is much higher than in the human eye, and there is a second fovea. To accommodate better, the shape of the cornea is adjustable. The arrow points to the pecten, a pigmented comb-like part of the choroidea projecting into the vitreous, which provides nourishment for the retina. Photo and illustration: Atle Østern.

Even if we can never hope to see the world as keenly as an eagle, refractive surgery and corrective lenses can generate good visual outcomes. However, they come with a cost and risks. Then, perhaps brain training could be an alternative. Studies have shown promising results. Repeated practice can improve the contrast sensitivity and interpretation of visual information.[9] Exercise can delay the symptoms of presbyopia and enhance Vernier acuity.

Finally, to move from cerebral to celestial affairs, one piece of advice: don't go to Mars if you want to maintain your visual capabilities! You see, a study showed that astronauts, who are often former air force pilots, have poorer vision after returning from space, even years later.[10]

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