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4

VISUAL ACUITY AND HYPERACUITY

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4.1 GLOSSARY

Airy disk. Point-spread function in the image of a diffraction-limited optical instrument with a circular pupil.

Diffraction limit. Minimum dissipation of spatial information in the imaging of an optical system, due to the aperture restriction in the propagation of electromagnetic energy.

Fovea. Region in the center of the retina where receptor elements are most closely packed and resolution highest.

Hyperacuity. Performance in task where thresholds are substantially lower than the grain of the receiving layer.

Light. Visually evaluated radiant energy. In this chapter radiant and luminous energy terms are used interchangeably.

Optical-transfer function. Modulation in the transmitted images of spatial sinusoids, as a function of their spatial frequency; it is complex, that is, has amplitude and phase terms.

Psychophysics. Procedure for studying an observer's performance by relating the variables of physical stimuli to measurements of associated responses.

Point-spread function. Spatial distribution of energy in the image of a point object.

Snellen letters. Alphanumeric characters of defined size and shape used in standard clinical testing of visual acuity.

Spatial frequency. Number of cycles of a sinusoidal grating target per unit distance. Commonly cycles/degree visual angle.

Superresolution. Ability to garner knowledge of spatial details in an optical image based on previous available information, either by extrapolation or averaging.

Vernier acuity. Performance limit in the alignment of two abutting line segment; it is the prime example of hyperacuity.

Visual acuity. Performance limit in distinguishing spatial details in visual object.

Visual angle. Angle subtended by an object at the center of the eye's entrance pupil; it is a measure of distance in the retinal image.

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Equation (1). Point-spread function of a purely diffraction-limited optical imaging system with a round pupil.

θ	angular subtense of radius of Airy's disk
λ	wavelength of radiation
a	diameter of aperture

Equation (2). Specification of contrast in the spatial distribution.

L_{max}, L_{min} Luminance of maximum, minimum, respectively

4.2 INTRODUCTION

Visual acuity—literally sharpness—refers to the limit of the ability to discriminate spatial partitioning in the eye's object space. As a psychophysical measure, its analysis encompasses

- The physics—in this case optics—of the stimulus situation
- The anatomical and physiological apparatus within the organism that processes the external stimulus
- The operations leading to the generation of a response

Measurement of visual acuity involves the organism as a whole, even though it is possible to identify the performance limits of only a segment of the full operation, for example, the eyeball as purely an optical instrument, or the grain of the receptor layer of the retina, or neural activity in the visual cortex. But the term acuity is reserved for the behavioral essay and therefore necessarily includes the function of all components of the arc reaching from physical object space to some indicator of the response of the whole organism. It is a psychophysical operation. The fact that it includes a component that usually involves an observer's awareness does not preclude it from being studied with any desired degree of rigor.

4.3 STIMULUS SPECIFICATIONS

Specification of the stimulus is an indispensable preliminary. For this purpose, an Euclidean object space containing visual targets is best defined by a coordinate system with its origin at the center of the eye's entrance pupil and its three axes coinciding with those of the eye. The observer is usually placed to make the vertical (y) axis that of gravity, and the horizontal (x) axis orthogonal and passing through equivalent points in the two eyes; distances from the observer are measured along the z axis. When an optical device is associated with the eye, its principal axes should accord, either by positioning the device or the observer. On occasions when both eyes of an observer are involved, the origin of the coordinate system is located at the midpoint of the line joining the two eyes. More details of possible coordinate systems have been described elsewhere.[1]

The ocular structure most relevant to the spatial dissection of an observer's object world is the retina, and the inquiry begins with the quest for the most instructive way of relating the *distal* and *proximal* stimuli, that is, the actual objects and their retinal images. Here it is achieved by using the center of the entrance pupil of the eye as the origin of the coordinate system which has at least two advantages. First, while associated with the eye's imagery, it belongs to object space and hence is objectively determinable by noninvasive means. In a typical human eye, the entrance pupil is located about 3 mm behind the corneal vertex and is not far from round. Its center is therefore an operationally definable point. The second reason for choosing it as a reference point involves the nature of the eye's image-forming apparatus. As seen in Fig. 1, the bundle of rays from a point source converging toward the retina is centered on the ray emerging from the center of the eye's exit pupil, which is the optical conjugate of the center of the entrance pupil. Regardless of the position

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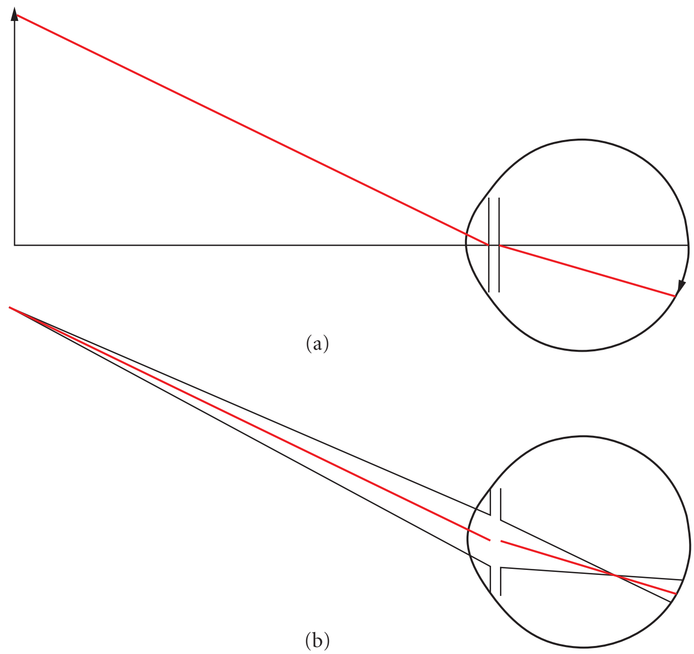

FIGURE 1 Schematic diagram of imaging in human eye. (*a*) The retinal image size of a target is represented by the angle it subtends at the eye's entrance pupil. (*b*) The position of the image of a point is most effectively demarcated by the intercept of the image-sided chief ray, which is the center of the light distribution even if the eye is out of focus.

of the geometrical image with respect to the retina, that is, regardless of the state of defocus, the center of the retinal image patch, blurred or sharp, will be defined by the intersection of that ray, called *chief ray,* with the retina. When two object points are presented to the eye, the retinal distance corresponding to their separation is given by the intercept of the chief rays from these objects. In this manner, the three-dimensional object space of the eye has been collapsed into the two-dimensional one of the retinal surface. What has been lost, and needs to be specified separately, is the object's distance from the eye along the chief ray. But all objects, in or out of focus, anywhere along a given chief ray share a single retinal location, or, to rephrase it, the coordinates on the retinal surface are homologous to angular coordinates within the object-sided sheaf of rays converging on the center of the eye's entrance pupil.

Hence in the specification of retinal distances it suffices to identify corresponding angles in the eye's object space, objectively determinable measures. Units of measurement are the radian, or, degrees or minutes of arc. At a distance of 57 cm, a 1-cm object subtends 1 deg, a 0.16-mm object 1 arcmin. At the standard eye-chart distance of 6 m (20 ft) the limb of a 20/20 letter is just under 2 mm wide.

The next specification to be considered is that of the luminous intensity impinging on the eye. One starts with the most elemental stimulus: the luminous intensity of a point source is given in the internationally agreed-on unit of candela (lumens · steradian^{-1}). This again is object-sided and objectively determinable. Extended sources are measured in terms of luminance (lumens · steradian^{-1} · unit area^{-1}, in practice cd · m^{-2}). Hence the specification of visual acuity targets in the eye's object space requires, apart from their observation distance, their spatial extent in angular measure at the eye's entrance pupil and the luminance of the background from which or against which they are formed. The luminous energy reaching the retina differs in that it depends on the pupil area, the absorption in the eye's

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media, and retinal factors considered elsewhere. Attenuation in the passage through the ocular media will differ from one eye to another and is prominently age dependent (Chap. 1). (Polarization and coherence properties of the incoming luminous energy are generally not relevant, but see special conditions analyzed in Chap. 14). How this luminous energy is distributed on the retinal surface depends on the transfer characteristics of the eye's optics which will now be considered.

4.4 OPTICS OF THE EYE'S RESOLVING CAPACITY

The spatial distribution of energy reaching the retina will differ from that incident on the cornea by being subject to spread produced by the eye's imaging.

Light Spread in the Retinal Image and Limits of Resolution

The two modes of proceeding in this discussion, via the point-spread or the contrast-transfer functions, are equivalent (Fig. 2). So long as one remains in the realm of optics and does not enter that of neural and psychophysical processing where linearity is not guaranteed, it is permissible to transfer back and forth between the two.

Point-Spread Function When the object space is restricted to a single point, the spatial distribution of energy in the image is called the point-spread function and describes the spread introduced by passage through the eye's optics. Even in ideal focus, the spread depends on the eye's aperture and the wavelength of the electromagnetic energy; the object-sided distribution then has θ, that is, angle subtended by the distance from its center to the first zero, given by

$$\theta = \frac{1.22\lambda}{a} \tag{1}$$

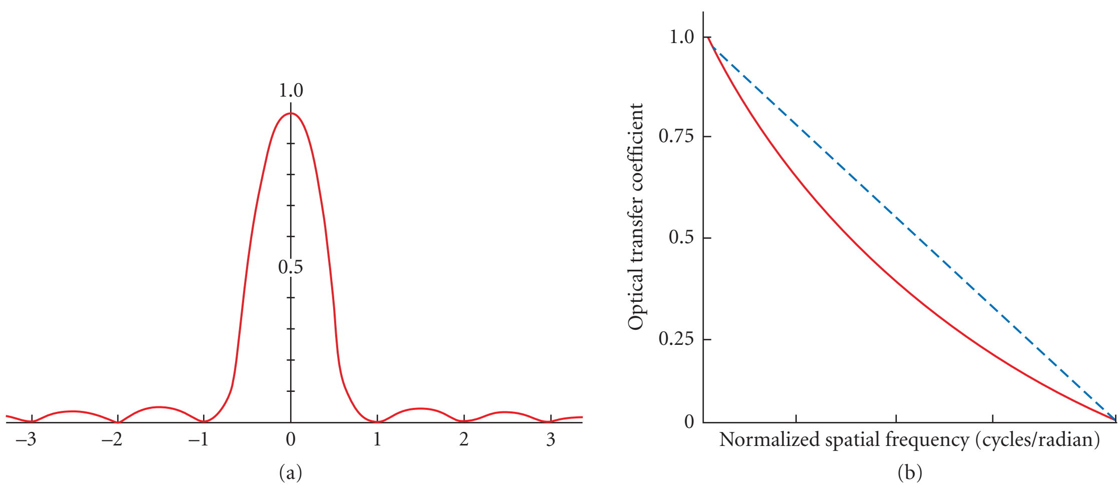

FIGURE 2 Retinal light distribution in an idealized optical system like the eye's. (*a*) Diffraction-limited point-spread function (Airy's disk). Unit distance is given by 1.22 λ/a in radians, where λ is the wavelength of light and a the diameter of the round pupil, both in the same units of length. (*b*) The optical contrast-transfer function for a square pupil (blue dashed line) and a round pupil (red solid line). It descends to zero at a spatial frequency equal to a/λ cycles/radian.

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A point can never be imaged smaller than a patch of such a size; the light distribution for any object is the convolution of that of the points constituting it. In practice there are additional factors due to the aberrations and scattering in each particular eye.

Spatial-Frequency Coordinates and Contrast-Transfer Function A fundamental property of optical imagery in its application to the eye is its linearity. Hence a permissible description of light distributions is in terms of their spatial Fourier spectra, that is, the amplitudes and phases of those spatial sinusoidal intensity distribution in terms of their spatial frequency that, when superimposed, will exactly reconstruct the original distribution. The limit here is the cutoff spatial frequency at which the optical transfer coefficient of the eye reaches zero (Fig. 2*b*).

Either of the two descriptors of the optical transfer between the eye's object and image spaces, the point-spread function, that is, light spread in the image of a point, and the contrast-transfer function, that is, the change in amplitude and phase that the component sinusoids (as a function of spatial frequency in two angular dimensions) experience as they are transferred from the eye's object space to the retinal image, is complete and the transposition between the two descriptors in uncomplicated.

Because resolution relates to the finest detail that can be captured in an image, the interest is in the narrowness of the point-spread function (e.g., width at half-height) or, equivalently, the high-frequency end of the contrast-transfer function. The absolute limit imposed by diffraction gives a bound to these two functions but this is actually achieved only in fully corrected eyes with pupil diameters below about 3 mm, when other dioptric deficits are minimal. Concentrating on light of wavelength 555 nm, for which the visual system during daylight is most sensitive, Fig. 2, taken over directly from diffraction theory, illustrates the best possible performance that may be expected from a normal human eye under ordinary circumstances. The cutoff spatial frequency then is near 90 cycles/degree^{-1} and the diameter of Airy's disk about 1.5 arcmin.

A great deal of effort has gone into the determination of the actual point-spread functions of eyes which include factors such as aberrations. Only under very exceptional circumstances—and nowadays also with the aid of adaptive optics—does one get better imagery than what is shown in Fig. 2. When the pupil diameter is increased, theoretical improvement due to narrowing of the Airy disk is counteracted by aberrations which become more prominent as the outer zones of the pupil are uncovered. The effect of refractive errors on imaging can also be described in theory, but then phase changes in the contrast-transfer function enter because its complex nature (in the mathematical sense) can no longer be ignored (see under "Defocus").

4.5 RETINAL LIMITATIONS—RECEPTOR MOSAIC AND TILING OF NEURONAL RECEPTIVE FIELDS

Also amenable to physical analysis are the limitations imposed on the resolving capacity of the eye by the structure of the retina. All information that is handed on to the neural stages of vision is in the first place partitioned by the elements of the receptor layer, each of which has an indivisible spatial signature. The spacing of the receptors is not uniform across the retina, nor is the individuality of their local sign necessarily retained in further processing. Ultimately, the information transfer to the brain is confined by the number of individual nerve fibers emerging from the retina. Nevertheless it is instructive to inquire into the grain of the retina in the foveal region where there is certainly at least one optic nerve fiber for each receptor.

Figure 3 is a cross section of the layer of a primate retina and shows an approximately hexagonal array of cones, whose average spacing in the center is of the order of 0.6 arcmin. No matter what else is in play, human visual resolution cannot be better than is allowed by this structure. The center of the fovea is only about 0.5 deg in diameter; the further one proceeds into the retinal periphery the coarser the mosaic and the lower the ratio of receptors to optic nerve fibers. This explains the reason for our highly developed oculomotor system with its quick ability to transfer foveal gaze to different eccentric and even moving targets.

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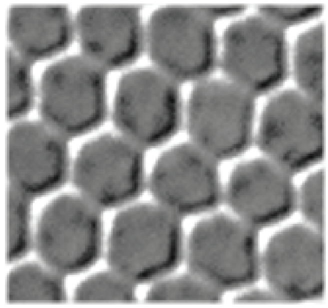

FIGURE 3 Histological cross section of the retinal mosaic in the primate fovea. Each receptor represents an object-sided angle of about 0.6 arcmin.

The neural elements of the retina are not passive transducers but actively rearrange the optical signals that reach the receptors. After transmission to the brain, processing of these neural signals involves interaction from other regions and modification as a result of such factors as attention and memory. As yet the neural circuitry interposed between the optical image on the retina and the individual's acuity response has not reached a level of understanding equivalent to that of the optical and receptor stages.

4.6 DETERMINATION OF VISUAL RESOLUTION THRESHOLDS

Awareness of the limitations imposed by the optics and anatomy of the eye is, of course, of value, but visual acuity is, in the end, a function of the operation of the whole organism: what are the finest spatial differences that can be distinguished? In answering this question, attention has to be paid to the manner of obtaining the measurements.

Since there is scatter in individual determinations, the number of trials will be controlled by the needed precision. The armamentarium of psychophysical procedures allows determination of a threshold with arbitrary precision. The standard optometric visual acuity chart, in use for 150 years, is a textbook case of effective employment of this approach. The ensemble of test symbols, the information content per symbol, the accepted answers, and the scaling of the steps and number of trials (letters in each row) have all been optimized for quick and reliable acuity identification.

A psychophysical threshold is a number along a scale of a variable (e.g., distance between double stars) at which a correct response is made in a predetermined proportion of trials. In a good experiment it is accompanied by a standard error. Thus if in a particular situation the two-star resolution threshold is found to be 0.92 ± 0.09 arcmin and the 50-percent criterion was employed, this means that on 50 percent of occasions when the separation was 0.92 inch the observer would say "yes" (the percentage increasing with increasing separation) and that the scatter of the data and the number of observations were such that if the whole experiment were repeated many times, the value would be expected to be between 0.83 inch and 1.01 inch in 19 out of 20 runs of data.

The distinction is often made between detection and discrimination thresholds. In sophisticated detection procedures, stimulus presentations are alternated randomly with blanks. A count is kept of the number of times the observer gives a "yes" answer when there was no stimulus, the so-called false positives. An elaborate analytical procedure can then be deployed to examine the internal

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"noise" against which the incoming sensory signal has to compete.[2] This methodology is appropriate when there is a blank as one of the alternatives in the test, for example, in the measurement of the high spatial-frequency cutoff for grating resolution. In the bulk of acuity determinations the observer has to discriminate between at least two alternative configurations each presented well above detection threshold, and what has to be safeguarded against are bias errors.

It is the current practice in vision research to observe as many of these niceties of psychophysical methodology as possible (Chap. 3). However, in clinical and screening situations less time and observer engagement is available, with, as a consequence, diminished reliability and repeatability of findings.

4.7 KINDS OF VISUAL ACUITY TESTS

The common denominator of acuity tests is the determination of the finest detectable spatial partitioning, and this can be done in many ways. The closest to the optical concept of resolving power are the two-point or two-line patterns, whose minimum separation is measured at which they are seen as double (Fig. 4*a*). More popular are the two-bar experiments, most effectively implemented in a matrix of 3 × 3 elements, in which either the top and bottom rows, or the right and left columns

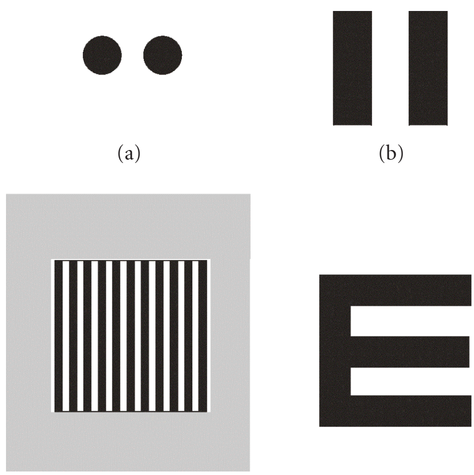

FIGURE 4 Patterns used in visual acuity tests and the associated response criteria: (*a*) Two point resolution. (*b*) Koenig bars in a 3 × 3 matrix. (*c*) Grating resolution. (*d*) Letters, as used in the clinical Snellen chart. Observers respond to these questions: You will be shown either a single or a double star. Was it "one" or "two?" (*a*). You will be shown a two-line pattern. Were the lines vertical or horizontal? (*b*). You will be shown a field that is either blank or contains vertical stripes? Was it "blank" or "striped?" (*c*). You will be shown an alphanumeric character. What letter or digit was it? (*d*).

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have a different contrast than the middle row or column (Fig. 4*b*), the observer's responses being limited to "horizontal" and "vertical." The size of the matrix elements is increased to determine the observer's threshold. Overall size is no clue and the response is based on the detection of the internal image structure.

Some brightness variables are available to the experimenter. In the old days, the lines would be black on a white background whose luminance would be specified. With the advent of oscilloscopic displays this can now be white on black or, more generally, brighter and darker than a uniform background. Contrast is then a further variable, usually defined by the Michelson formula

$$\frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min})} \tag{2}$$

With the advent of the Fourier approach to optics, grating targets have become popular. For the purposes of acuity, the highest spatial-frequency grating is determined at which, with 100-percent modulation, the field is just seen as striped rather than uniform (Fig. 4*c*). The phenomenon of spurious resolution, described below, makes this test inadvisable when focus errors may be at play. The role of grating targets in acuity measurements differs from that in modulation sensitivity tests, where gratings with a range of spatial periods are demodulated till they are no longer detectable. This process yields the modulation sensitivity curve, discussed below.

Since they were first introduced in the second half of the 19th century, the standard for clinical visual acuity are the Snellen letters—alphanumerical characters, each drawn within a 5 × 5 matrix, with limb thickness as the parameter (Fig. 4*d*). From the beginning it was accepted that the resolution limit of the human eye is 1 arcmin, and hence the overall size of the Snellen letter for normal acuity is 5 arcmin, or 9.5 mm at a distance of 6 m or 20 ft (optical infinity for practical purposes). When such letters can be read at 20 ft, visual acuity is said to be 20/20. Letters twice this size can normally be read at 40 ft; an observer who can only read such double-sized letters at 20 ft has 20/40 acuity. The charts are usually assembled in lines of about 8 letters for 20/20 and progressively fewer for the lower ratings, with just a single letter for 20/200. Because in acuity determinations the error is proportional to the size of the letters[3] and the sequence of letter sizes in charts is usually logarithmic.[4] Snellen acuity is often converted to a fraction, 20/20 becoming 1.0, 20/40 becoming 0.5, and so on. When some of the letters in a line are missed, say 2 in the 20/20 line, a score of 20/20 − 2 is recorded. For example, if there are 7 letters in the 20/25 (0.8) line of which 3 are missed, and the next line is 20/30 (0.67) a numerical value of 0.74 [0.8 – (3/7) (0.8 – 0.67)] can be entered for statistical purposes.

Snellen charts have been made available in many alphabets, but letters may not have equal legibility, even in English. Hence a stripped-down version of letter acuity is often used. A single letter E can be shown in four or even eight orientations and the observer asked to respond, perhaps by pointing a hand with outstretched fingers. The detection of the location of a gap in an annulus, that is, the distinction between the letter O and an oriented C, called the Landolt C test after its inventor is particularly useful. Both the E and Landolt C tests can be fitted into the tradition of Snellen letters by, for the 20/20 targets, generating them with 1′ line within a 5 × 5′ matrix, with progressive size increases to arrive at a solid numerical acuity value. These two tests make no demands on the subjects' literacy and have the virtue that the effect of guessing is a known quantity. Even here, a minor problem arises because of the "oblique effect," a small performance deficit in oblique orientations over the horizontal and vertical.

The development of the visual system in infants and the early detection of visual anomalies has sparked the design of infant visual acuity tests, usually depending on the observation of eye movements to targets of interest whose size can be progressively diminished.[5] Apart from this "preferential looking" technique, optokinetic nystagmus, that is, the involuntary eye tracking of large moving fields, can be effectively utilized to measure acuity by progressively diminishing the size of details until tracking fails.

As outlined so far, all the tests have in common the need for the subject to be aware and cooperative, though not necessary literate. When these conditions are absent, other procedures have to be adopted, for example, recording the signals from the eye into the central nervous system from the scalp. These are not further described here.

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4.8 FACTORS AFFECTING VISUAL ACUITY

Visual acuity performance will be diminished whenever any of the contributing functions have not been optimized. Initial analysis concentrates on optical and retinal factors; not enough is known about the subsequent central neural stages to differentiate all the possible ways in which their operation can be encumbered or rendered inefficient. Such factors as attention, training, and task familiarity are clearly relevant. A treatment of the subject from the clinical point of view is available in textbooks.[6,7]

Pupil When the optical line-spread function has been widened for whatever reason, resolution will obviously suffer. This is the case when the pupil is too small—2 mm or less—when diffraction widens it or, in the presence of aberrated wavefronts, when it is very large—usually 6 mm or larger.

Defocus Focus errors are of particular interest, because one of the most ubiquitous applications of visual acuity testing is to ascertain the best refractive state of eyes for purposes of spectacle, contact lens, or surgical correction. Ever since the establishment of the current optometric routines in the late 19th century, rules of thumb have existed for the relationship between refractive error and unaided acuity. One of these is shown in Fig. 5. But this does not take into account a patient's pupil size which governs depth of focus, the possible presence of astigmatism, and higher-order aberrations, nor some complications arising from the nature of out-of-focus imagery. When a spherical wavefront entering the eye's image space does not have its center at the retina, the imagery can be described as having a phase error that increases as the square of the distance from the center of the aperture.[9] The contrast-transfer function, which is the Fourier transform of the complex (i.e., amplitude and phase) pupil aperture function, then does not descend to the cutoff spatial frequency monotonically, but shows oscillatory behavior (Fig. 6); in some regions in the spatial-frequency spectrum it dips below zero and the grating images have their black and white stripes reversed. This so-called spurious resolution means that if one views grating pattern under these conditions and gradually increases spatial frequency, stripes will first be visible, then disappear at the zero-crossing of the transfer function, then reappear with inverted contrast and so on. The seen image of objects like Snellen letters will undergo even more complex changes, with the possibility that "spurious" recognition is achieved with specific states of pupil size and defocus.

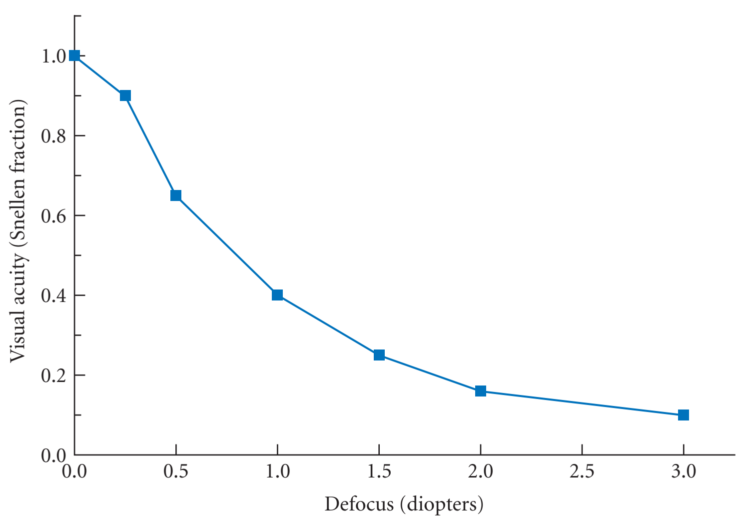

FIGURE 5 Visual acuity in a typical eye as a function of uncorrected spherical refractive error in diopters. (*Adapted from Laurance.*[8])

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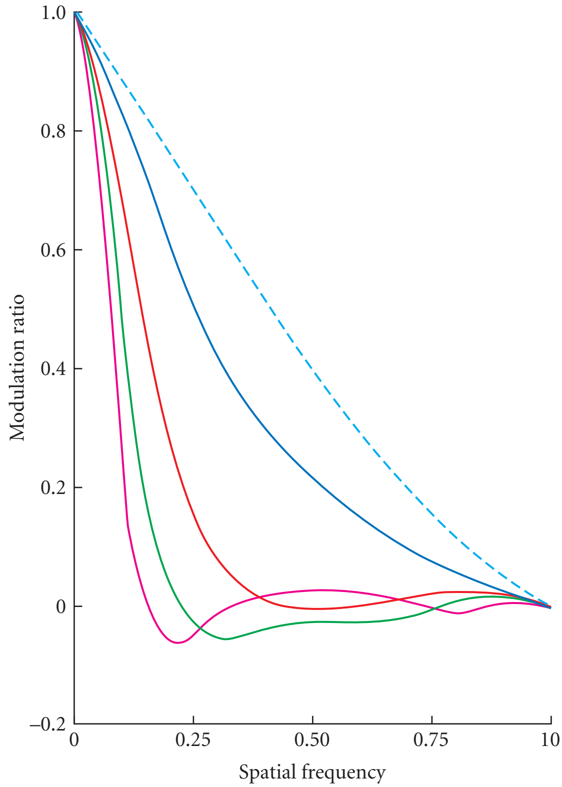

FIGURE 6 Normalized optical-transfer function for various degrees of defocus, showing regions of the spatial-frequency spectrum in which the coefficients are negative and the contrast of grating targets is reversed in the image compared to that in the object. (*Adapted from Hopkins.*[10]) For an eye with a 3-mm round pupil and wavelength 560 nm, the cutoff spatial frequency denoted by the normalized value 1.0 on the axis of abscissas is 1.53 cycles/arcmin and the five curves show the theoretical response for 0, 0.23, 0.31, 0.62, and 1 diopters defocus.

Color The diffraction equations have wavelength as an explicit variable. The width of the point-spread function varies inversely with wavelength. This is, however, only a minor factor where the effect of color on visual acuity is concerned. More immediately involved is the eye's chromatic aberration, giving defocus of about 1 diopter at the extremes of the visual spectrum, where also more energy is needed to compensate for the fact that the luminous efficiency of the eye peaks as 555 nm for the photopic and 500 nm for the scotopic (rod) system. In practice, therefore, each situation will have to be handled individually depending on the wavelength distribution of the particular stimulus.

Retinal Eccentricity Due to the coarsening of the grain of the anatomical connections in the peripheral retina, visual acuity falls off with increasing eccentricity (Fig. 7) and this is more pronounced in the extreme nasal than temporal field of view of each eye. In binocular vision, when

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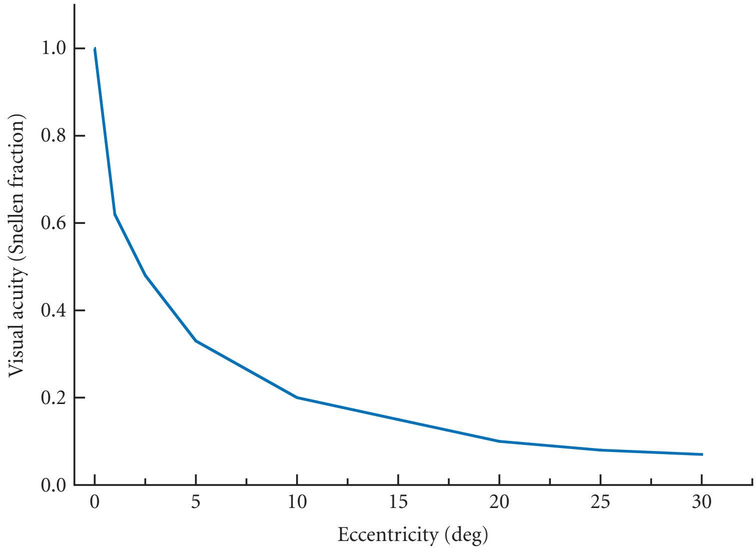

FIGURE 7 Expected visual acuity in various locations in the peripheral visual field. (*Adapted from Wertheim.*[11])

both eyes are in play, acuity is usually better than in monocular vision, not only because the better eye covers any possible deficiency of the other, but also because of probability summation due to the two retinas acting as independent detectors.

Luminance Acuity measured for black symbols against a white background, that is, for 100 percent contrast (Fig. 8) remains constant from about 10 $cd \cdot m^{-2}$ up. Below about 1 $cd \cdot m^{-2}$ the photopic system drops out and rods, which are absent in the fovea, take over. Their luminosity curve peaks at

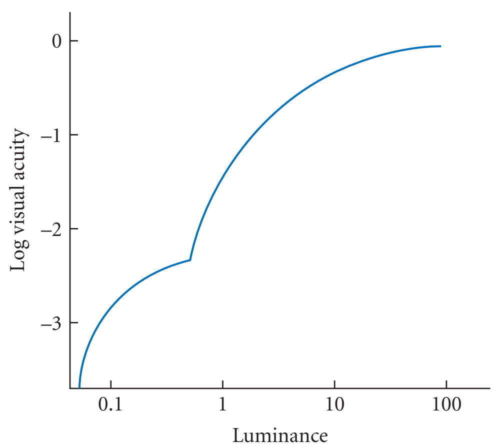

FIGURE 8 Visual acuity for targets as a function of their luminance. (*Adapted from Shlaer.*[12]) The rod-cone break occurs at a light level equivalent to that of a scene lit by full-moon light.

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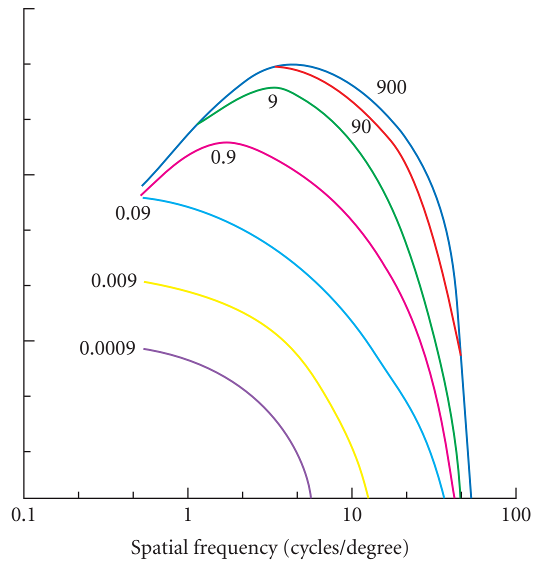

FIGURE 9 Modulation sensitivity (contrast detection) curve of the human visual apparatus as a function of spatial frequency at different light levels. (*From van Nes and Bouman.*[13]) Visual acuity is equivalent to the highest spatial frequency at which a response can still be obtained (intersection with the x axis) and the data here map well on those in Fig. 8.

about 500 nm. Also, they are color blind, and subject to considerable spatial summation and adaptation, that is, become more sensitive with increased time in the dark, up to as much as 30 to 45 min.

Contrast Most clearly shown with the use of grating stimuli, there is reduction in performance at both the low and high spatial frequency ends of the spectrum (Fig. 9). Because contrast sensitivity is lowered in various ocular abnormalities, particularly scatter of or absorption in the media, it has been found valuable to perform acuity measurements with low-contrast charts.[14,15] Reversing the contrast polarity, that is, presenting bright letters against a dark background, has virtue for eyes with a wide point-spread function and light scatter[16] and indeed improves acuity performance in some older eyes.[17]

Time Time is decidedly a factor in visual acuity. For very short presentations, about 20 ms or less, the eye integrates all the light flux, what matters then is the product of the intensity and the duration, in any combination. But acuity improves with duration in the several hundred millisecond range where light detection no longer depends on duration but only intensity (Fig. 10).

Surround A prominent effect in visual acuity is that of crowding, where the presence of any contour close to the resolution target interferes with performance (Fig. 11).

Practice Effects Surprisingly, in the fovea of normal observers, practice in the task does not confer any further advantage—it seems that optimum performance has been entrained through continuous exercise of the facility in everyday situation. Peripheral acuity can, however, be improved by training.[20,21]

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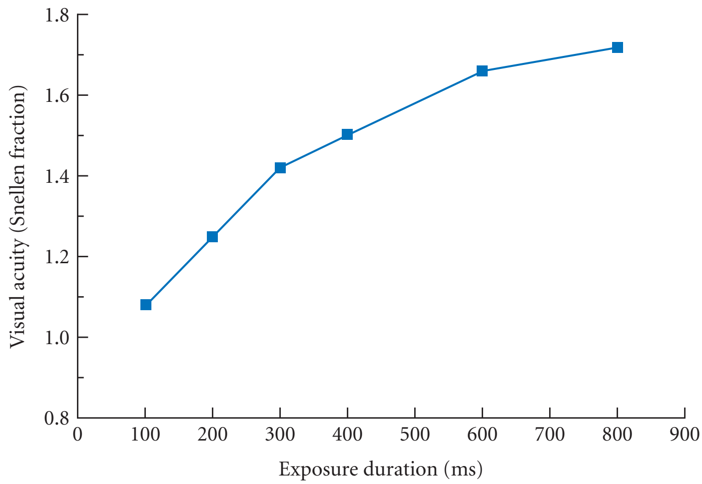

FIGURE 10 Visual acuity as function of exposure duration. (*From Baron and Westheimer.*[18])

Stage of Development and Aging Visual acuity shows a steep increase in the first few months of life and, if a secure measurement can be obtained, is not far from normal at least by the third year.[5] The aging eye is subject to a large number of conditions that impair acuity (Chap. 14); it is their presence or absence that determines any individual patient's status. Consequently age decrements of acuity can rage from none to severe.

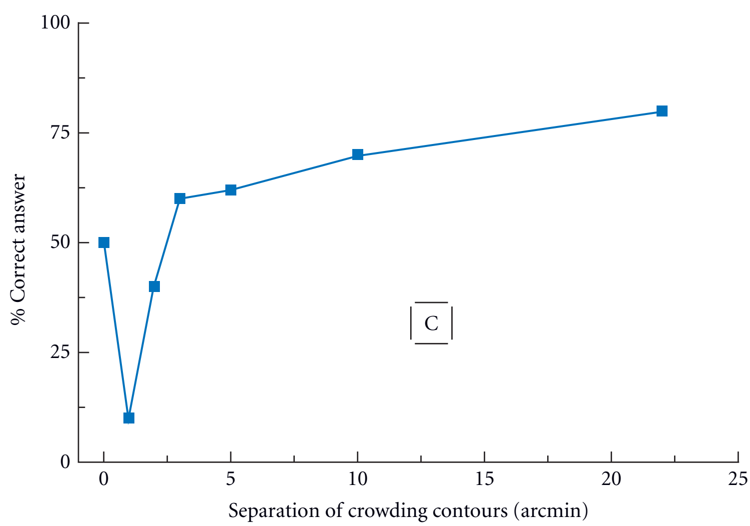

FIGURE 11 Data showing the "crowding" effect in visual acuity. A standard letter is surrounded by bars on all four sides and the performance drops when the bars are separated from the edge of the letter by the thickness of the letter's line-width. (*Adapted from Flom, Weymouth, and Kahneman.*[19])

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4.9 HYPERACUITY

For a long time human spatial discriminations have been known where thresholds are markedly lower than the resolution limit. For vernier acuity, the foveal alignment threshold for two abutting lines is just a few arcsecs, as compared with the 1 arcmin or so of ordinary resolution limit.

Such high precision of localization is shared by many kinds of pattern elements, both in the direction joining them, in their alignment, and in deviations from rectilinearity (Fig. 12). The word hyperacuity is applied to this discrimination of relative position, in recognition that it surpasses by at least an order of magnitude the traditional acuity. Whereas the limitation of the latter are mainly in the resolving capacity of the eye's optics and retinal mosaic, hyperacuity depends on the neural visual system's ability to extract subtle differences within the spatial patterns of the optical image on the retina.

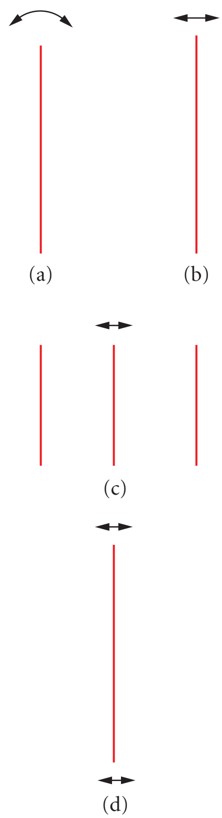

FIGURE 12 Configuration in which location differences can be detected with a precision higher than the resolution limit by up to an order of magnitude. These hyperacuity tasks do not contradict any laws of optics and are the result of sophisticated neural circuits identifying the centroids of light distributions and comparing their location. Thresholds are just a few arcsec in the foveal discrimination of these patterns from their null standards: (*a*) orientation deviation from the vertical of a short line; (*b*) alignment or vernier acuity; (*c*) bisection of a spatial interval; and (*d*) deviation from straightness of a short line.

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Localization discriminations in the hyperacuity range are performed by identification of the centroid of the retinal light distributions[22] of the involved pattern components, for example, abutting lines in the vernier task. The information is available in the image and can be described equally well in the domains of light distribution and its Fourier spectrum. It is testimony of sophisticated neural processing to arrive at the desired decision. Resolution and localization acuity share many attributes, though usually not in the same numerical measure.

Like ordinary visual acuity, hyperacuity is susceptible to crowding and to the oblique effect, but the two classes of spatial discrimination do not share all the other attributes.[23] Specifically, hyperacuity is more robust to reduction in exposure duration and diminishes more steeply with retinal eccentricity. It therefore follows that the neural processing apparatus is different and involves subtly recognition of differences in the excitation state of a neural population. In this respect it is similar to a whole host of fine discriminations, for example, those in the visual domains of color and stereoscopic depth.

4.10 RESOLUTION, SUPERRESOLUTION, AND INFORMATION THEORY

The threshold difference between ordinary visual acuity and hyperacuity raises the question whether any fundamental physical principles are being disobeyed.[24]

Resolution and Superresolution

In the first instance, all of vision must satisfy the laws of physical optics according to which no knowledge can be acquired about an object that is contained in the region beyond the cutoff spatial frequency decreed by diffraction theory. Here the concepts associated with the term *superresolution* (Chaps. 3 and 4 in Vol. I) are relevant; they have been expanded since first formulated as involving an extrapolation: If the predominant features in which the spatial-frequency spectrum of two objects differ are located beyond the cutoff, but are always accompanied by a characteristic signature within it, then in principle it is possible to make the distinction between the two objects from detailed study of the transmitted spectrum and extrapolate from that to arrive at a correct decision. More recently the word has also been used to describe a procedure by which several samples of noisy transmitted spatial-frequency spectra from what is known to be the same object are superimposed and averaged. In both uses of the word, no diffraction theory limit has been broached; rather, knowledge is secured from detailed analyses of observed energy distributions on the basis of prior information—in the first case that the difference in the spatial-frequency spectrum inside the cutoff limit is always associated with those beyond it, in the second that the several spectra that are averaged arose from the same target.

Resolution and Information

Information theory has been of help in understanding some potentially knotty problems in defining resolution.[25] Traditionally, the resolving power of an ideal optical instrument is regarded to have been reached when two stars are separated by the width of the Airy disk, when the images of the two stars partially overlap and the dip between the two peaks is about 19 percent. This so-called Rayleigh criterion usually allows the receptive apparatus to signal the two peaks and the trough as separable features—provided its spatial grain is fine enough and the intensity difference detectable. It is then possible to decide, without prior knowledge, that there are two stars or that a spectral line is double. But when there is prior knowledge that the source can only be either single or double, and if double, what their relative intensity is, then the decision can be made for smaller separations, because the light distribution resulting from the overlapping images of two adjoining sources differs in predictable fashion from that of a single sources, even when the dip between the peaks is less than at the

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Rayleigh limit and even when there is no dip at all. This specific example highlights how information theory, as first formulated by Shannon, enters the discussion: in quantifying the transmitted information, prior knowledge needs to be factored in.

The diffraction image of a point is an expression of the uncertainty principle: it describes the probability distribution of the location of the source of an absorbed photon. The larger the number of absorbed photons, the more secure the knowledge of the source's location *provided always that it is known that it has remained the same source as the photons are being accumulated.* With sufficient number of absorbed photons, and the assurance that they arose from the same source, it is possible to assign location with arbitrary precision. Hence, from the standpoint of optics, there is nothing mysterious about the precision of locating visual target that is now called hyperacuity. Rather it draws attention to the physiological and perceptual apparatus that enables this precision to be attained.

4.11 SUMMARY

The human visual system's capacity to discriminate spatial details is governed by the eye's optical imagery, by the grain of the retinal receiving layer, by the physiological apparatus of the retina and the central nervous system, and by methodological considerations of recording observers' responses. Overall, under the best conditions of ordinary viewing, the resolution limit is close to that governed by the diffraction theory for the involved optical parameters. Performance is impaired whenever any of the optical, anatomical, physiological, or perceptual components does not operate optimally. There is an additional class of visual threshold based not on resolution of spatial detail but on locating relative object position. Because thresholds then are at least one order of magnitude better, they are called hyperacuity. They do not contravene any laws of optics but are testimony to sophisticated neural processing that can identify the location of the centroid of retinal light distributions with high precision.

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