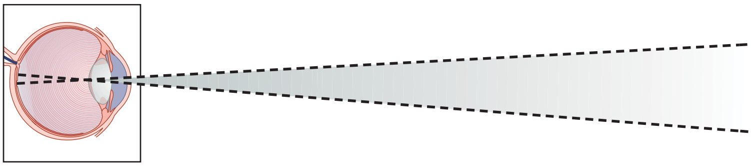

7

Spatial Vision

Spatial vision, as we will use the term, is concerned with variations in luminance across space. Our discussion will concentrate on the visual system's ability to detect and resolve luminance-defined stimuli of various sizes and contrasts.

Clinical assessment of spatial vision is of fundamental importance in routine eye care. Virtually all patient visits include the determination of spatial resolution (visual acuity), a highly sensitive measure of visual function.

SINE WAVE GRATINGS

How do we study the exceedingly complex processes of spatial vision? The key is to choose simple stimuli that can serve as building blocks to construct more complex stimuli. Sine wave gratings serve this purpose.

A sine wave grating is given in Fig. 7–1 along with its luminance profile. The grating consists of alternating bright and dark bars. Note that the peak of the luminance profile corresponds to a bright bar of the grating, whereas the trough of the profile corresponds to a dark bar. The transition from bright to dark bars is a gradual (sinusoidal) transition, not an abrupt transition. To fully describe a sine wave grating, it is necessary to specify its frequency, contrast, phase, and orientation.

Frequency

Compare the two gratings in Fig. 7–2. In the space taken up by the photograph, there are more alterations, or cycles, in the bottom grating. This bottom grating is said to have a high spatial frequency, while the top grating has a comparatively low spatial frequency.

The spatial frequency of a grating can be specified by giving the number of cycles/degree of visual angle (e.g., 30 cycles/degree) or the number of cycles per unit

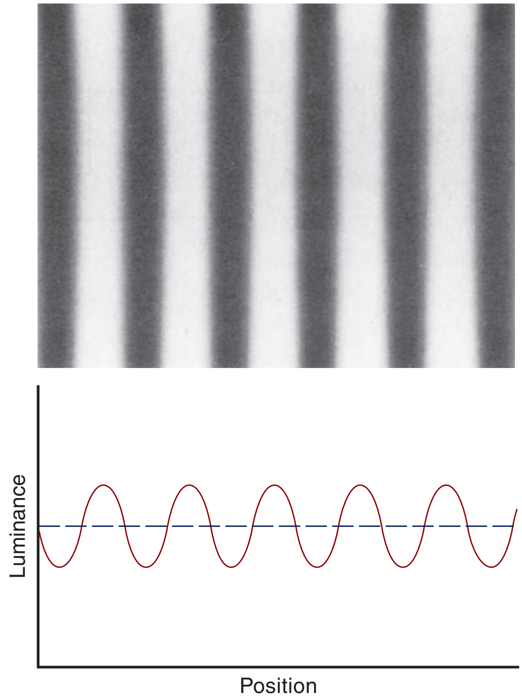

Figure 7–1. A sine wave spatial grating (top) and its luminance profile (bottom).

of space (e.g., 4 cycles/cm). As we shall see, the specification of spatial frequency in terms of cycles per degree offers many practical advantages.

Contrast

The top of Fig. 7–3 shows a grating of low contrast along with its luminance profile. The bottom of this figure shows a grating of the same spatial frequency, but of a higher contrast. The dashed lines across the luminance profiles represent the average luminances of the gratings (the average of the peaks and troughs). While the average luminance (l_{ave}) is the same for both gratings, the bottom one has a larger difference between its peak and the average luminance value, indicative of higher contrast.

Contrast can be defined by following formula:

$$\text{contrast} = \frac{\Delta l}{l_{\text{ave}}} \tag{7.1}$$

where

Δl = the difference between the peak and average luminances

l_{ave} = the average luminance of the grating (the average of the light peaks and dark troughs)

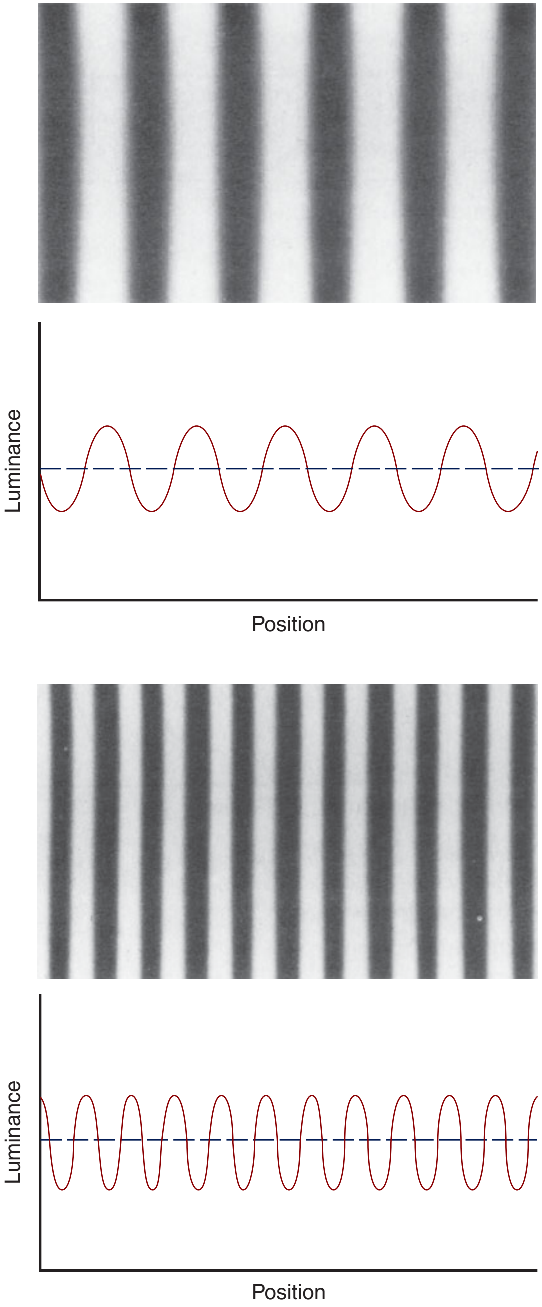

Figure 7–2. A low-frequency spatial grating (top) and a higher-frequency grating (bottom). Both gratings have the same contrast.

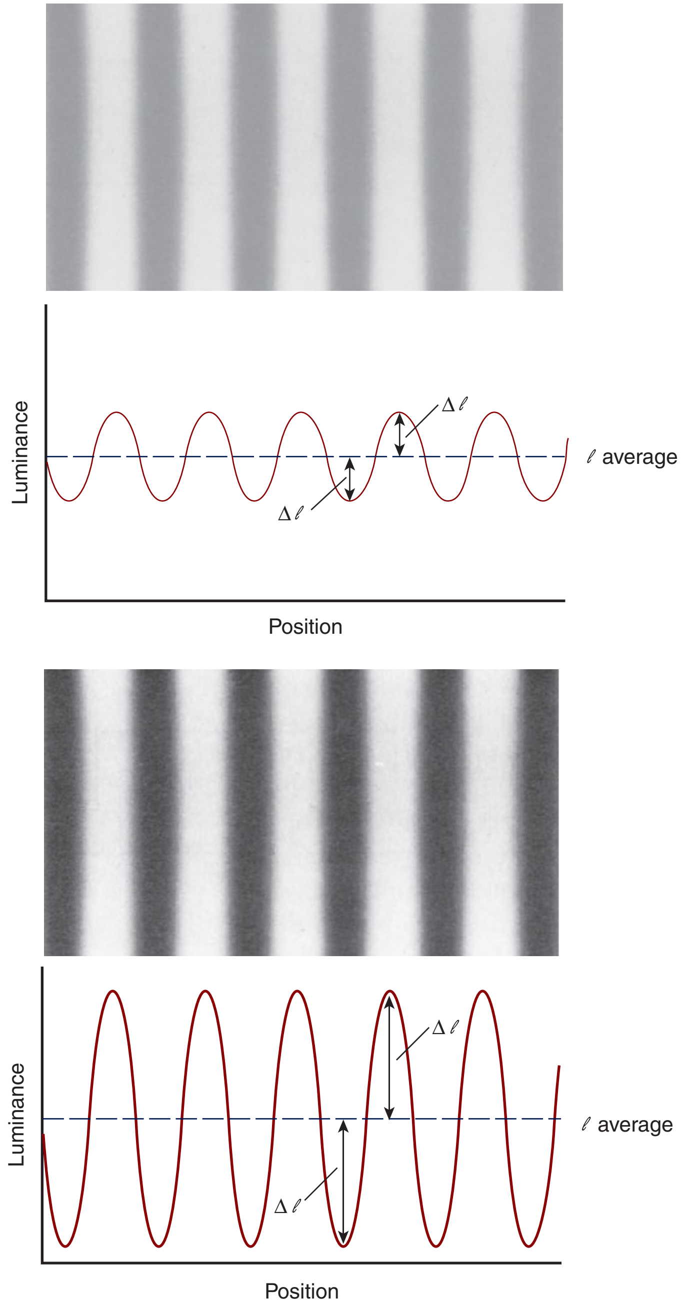

Figure 7–3. A low-contrast spatial grating (top) and a higher-contrast grating (bottom). Both gratings are of the same spatial frequency and average luminance

Although this formula is useful for defining and understanding contrast, it is not very practical for the measurement of contrast. Rather, it is more practicable to measure the maximum luminance (l_{max}) and the minimum luminance (l_{min}) and, from these values, calculate the contrast. The formula used (Michelson equation) is

$$\text{contrast} = \frac{l_{max} - l_{min}}{l_{max} + l_{min}} \tag{7.2}$$

where

$$l_{max} = l_{ave} + \Delta l$$
$$l_{min} = l_{ave} - \Delta l$$

It can be demonstrated that Formula 7.2 provides the same result as Formula 7.1. Substituting for l_{max} and l_{min}, we have

$$\frac{(l_{ave} + \Delta l) - (l_{ave} - \Delta l)}{(l_{ave} + \Delta l) + (l_{ave} - \Delta l)} = \frac{\Delta l}{l_{ave}}$$

Contrast ranges between 0% and 100%. It cannot be greater than 100% because of the physical impossibility of making Δl greater than l_{ave}. (The trough of the luminance profile is at zero luminance when $\Delta l = l_{ave}$. It is not possible to have less than zero luminance.)

Phase and Orientation

Phase refers to the position of a sine wave grating with respect to another sine wave grating. For instance, if two gratings are in phase, the peaks and troughs of their luminance profiles will be in alignment. If two gratings are 180 degrees out-of-phase, the peak of one luminance profile will be aligned with the trough of the other profile.

Orientation describes the angle made by a grating with respect to a reference, such as the horizontal. In this chapter, only examples where all gratings are of the same orientation are presented.

FOURIER ANALYSIS: BASIC INTRODUCTION

Through a mathematical process referred to as **Fourier** (or **linear system**) **analysis**, sine waves of the proper frequency, contrast, phase, and orientation can be used to construct other more complex spatial stimuli. Although it may not be intuitively obvious, any achromatic scene—a black and white photograph of a house, forest, or face—can be thought of as consisting of sine waves of the appropriate frequency, contrast, phase, and orientation.

Consider the square wave grating in Fig. 7–4. Its luminance profile shows abrupt changes between bright and dark bars, sometimes referred to as “step” changes in

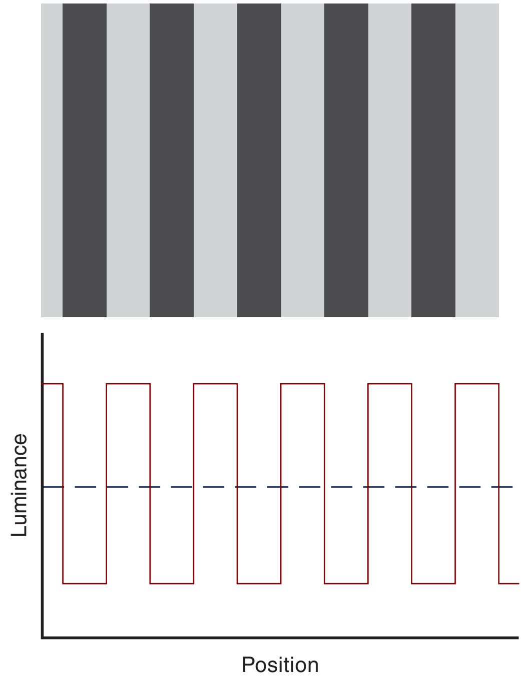

Figure 7–4. A square wave grating and its luminance profile.

luminance. Like any other complex spatial stimuli, a square wave can be constructed by adding together appropriate sine waves. Figure 7–5 shows how this is done. The sine wave that is of the same frequency as the square wave is referred to as the fundamental. The higher frequency sine waves are referred to as harmonics. (The third harmonic has three times the frequency of the fundamental and one-third of its contrast, the fifth harmonic has five times the fundamental frequency and one-fifth of its contrast, and so on.) The addition of the fundamental sine wave and just a couple of odd numbered harmonics (third and fifth) produces a wave that is almost indistinguishable from a square wave. (Adding up the fundamental and all odd numbered harmonics out to infinity would produce an exact square wave.) Constructing a square wave is a far cry from constructing a face. The same principles, however, apply in both cases.

SPATIAL MODULATION TRANSFER FUNCTION OF A LENS

How can we quantify the precision with which an optical lens (or system) transfers information? We start with a grating of a specified spatial frequency and contrast that serves as the object for the lens (Fig. 7–6). The image contrast is measured and

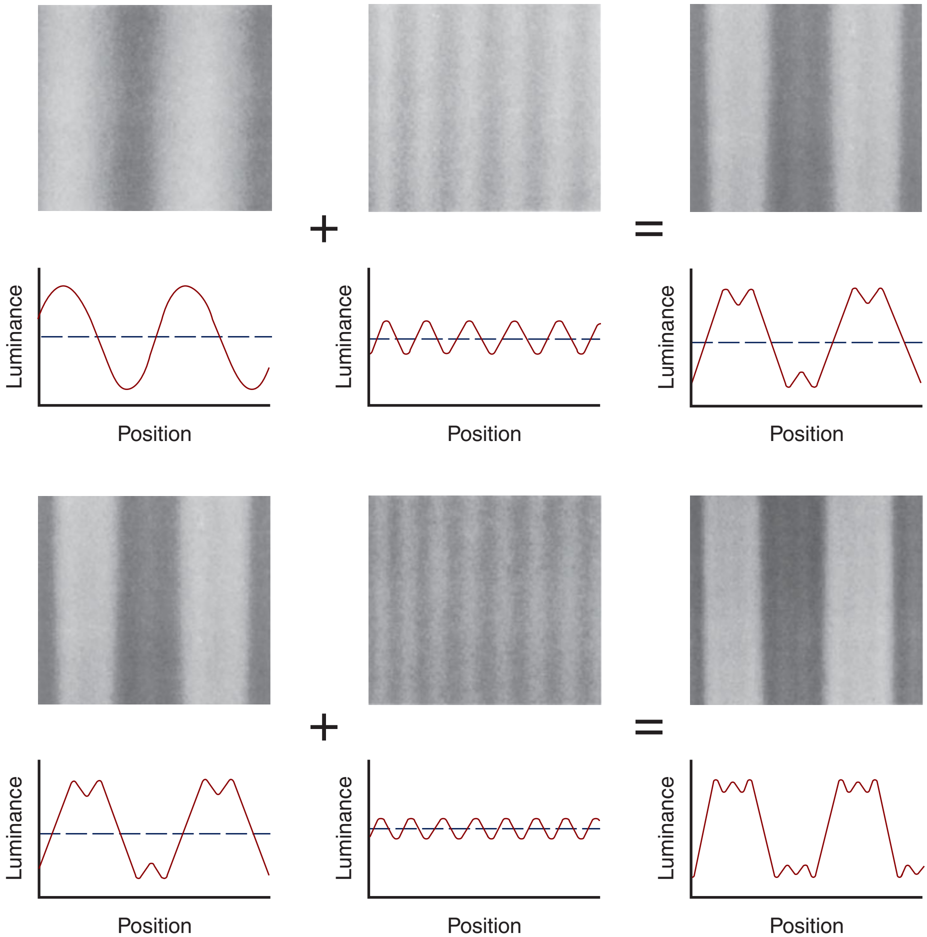

Figure 7–5. A sine wave grating of the fundamental frequency is combined with its 3rd (top rows) and fifth (bottom rows) harmonics to produce a square wave grating (Cornsweet, 1970; Levine and Shefner, 1991).

then divided by the object contrast.[1] This ratio tells us how well the lens transfers the information (i.e., contrast) contained in the object. If the lens were perfect (and no lens is perfect), the image contrast would equal the object contrast. In reality there is some image degradation, even when the lens is in focus, resulting in a reduction in contrast.

This procedure is repeated for a spectrum of spatial frequencies, ranging from low to high. The result is a spatial modulation transfer function (SMTF) that shows the quality of image reproduction as a function of spatial frequency. Figure 7–7 gives

1. For this example, assume the image is in focus.

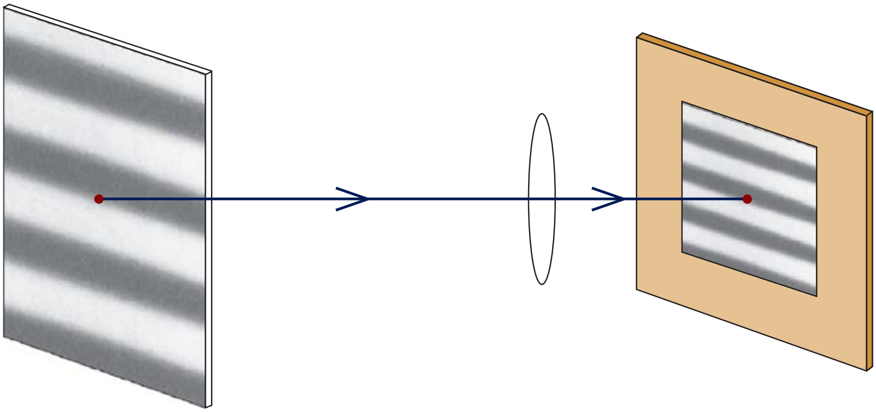

Figure 7–6. A spatial grating is focused by an optical lens to determine the spatial modulation transfer function of the lens.

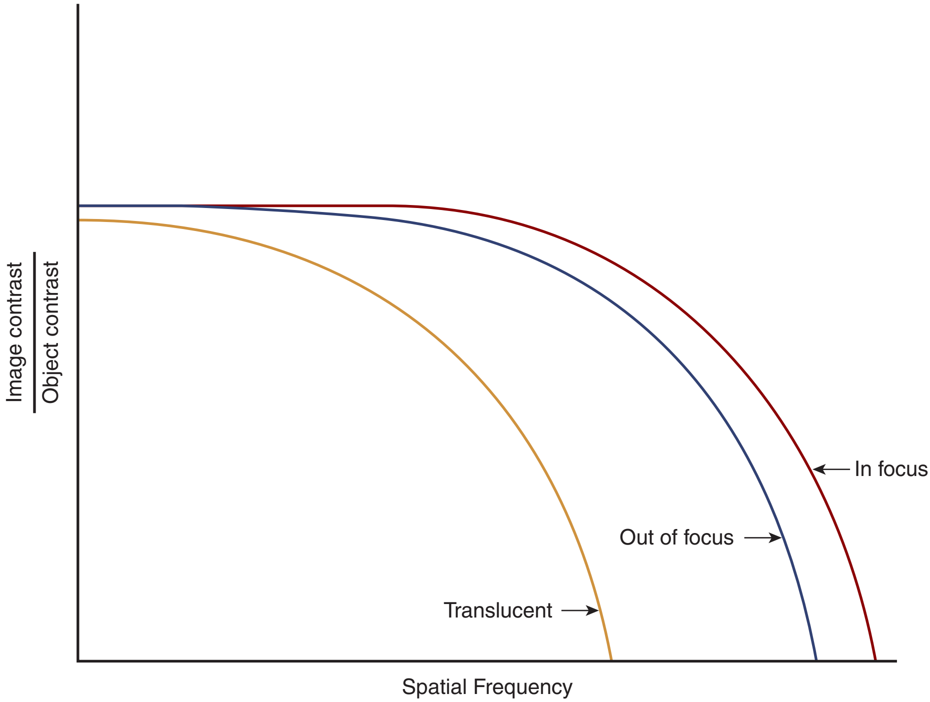

Figure 7–7. Even when an optical lens is in focus, there is a reduction in image quality, particularly at high spatial frequencies. Defocus causes a further reduction in image quality for high spatial frequencies. Painting the lens with clear nail polish or dipping it in melted butter, making it translucent, has a more profound effect, reducing contrast at all frequencies.

the SMTF for an optical lens that is in focus. For low and moderate spatial frequencies, the image is transferred with good fidelity (little image degradation). Because of the aberrations inherent in any optical system, the image becomes more degraded at higher frequencies. These same aberrations have comparatively little effect on optical image quality at low and moderate spatial frequencies.

What is the effect of optical defocus (as would occur if the screen is moved away from the plane of focus) on the SMTF? As can be seen in Fig. 7–7, defocus results in a reduction in image quality primarily at high spatial frequencies, with low and moderate frequencies less affected. As we shall see, this has important clinical implications.

Suppose we paint a spectacle lens with clear nail polish so that it is translucent, as is occasionally done when treating amblyopia. The image formed by this lens is much degraded. Its SMTF reveals an overall reduction in image contrast at all spatial frequencies (Fig. 7–7). This effect, which could also be obtained by roughening the surface of the lens with sandpaper, is due largely to the scattering of light at the lens surface.

THE HUMAN CONTRAST SENSITIVITY FUNCTION

The human SMTF is often referred to as a contrast sensitivity function (CSF) because sensitivity, not image contrast, is measured. A subject is asked to view a monitor that initially displays a spatial grating that is below threshold—it has such low contrast that it is not visible. Instead, a screen with even brightness across its surface is seen. The examiner slowly increases the contrast until a point is reached where the grating is seen (it appears to emerge out of the background). The reciprocal of this threshold contrast is the contrast sensitivity for the grating. Thresholds are determined for a large number of different spatial frequencies, resulting in a graph that shows contrast sensitivity as a function of spatial frequency, a CSF.

A typical adult human CSF is shown in Fig. 7–8. It is a band-pass function, showing peak sensitivity at approximately 4 cycles/degree and decreasing sensitivity on either side of this peak (Campbell and Robson, 1968). Humans detect a grating of about 4 cycles/degree at a contrast lower than that required for the detection of other frequencies. This is further illustrated in Fig. 7–9, which shows, from left to right, gratings of increasing spatial frequency. From bottom to top, the contrast decreases. Note that gratings of moderate frequencies are seen at lower contrast levels (higher on the diagram) than are other frequencies.

CSF HIGH-FREQUENCY CUTOFF

The high-frequency CSF cutoff in sensitivity reflects the visual system's limited ability to resolve detail when the detail is at 100% contrast. As the spatial frequency of a 100% contrast grating is increased, a point is reached where the grating can no longer be resolved. For a young, healthy adult, the high-frequency cutoff can be approximately 60 cycles/degree, indicated by the arrow in Fig. 7–8.

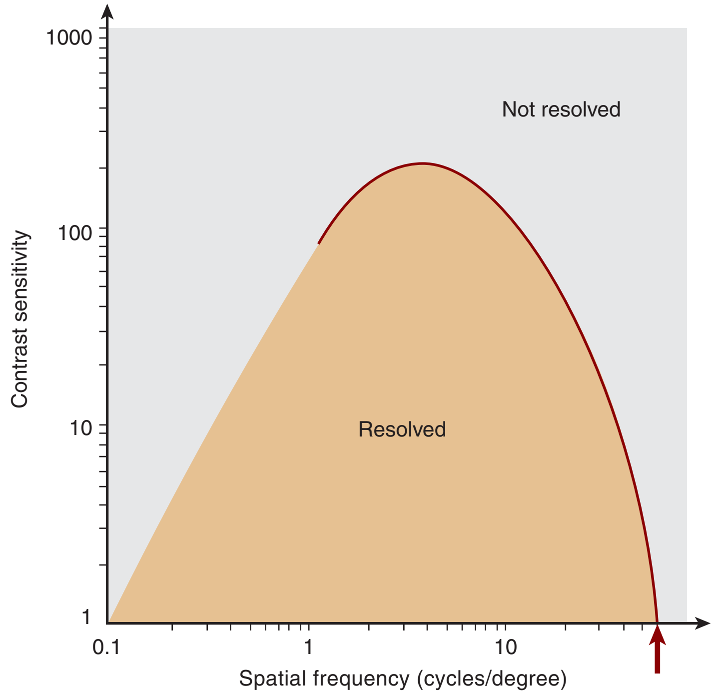

Figure 7–8. Typical human contrast sensitivity function. The arrow points to the high-frequency cutoff. Note that the coordinates are plotted in log units. The abscissa represents 100% contrast. (Contrast sensitivity is the reciprocal of threshold percent contrast.)

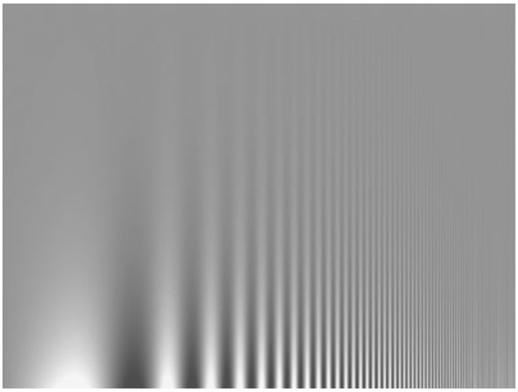

Figure 7–9. A plate that demonstrates the contrast sensitivity function. Contrast increases going from top to bottom, and spatial frequency increases going from left to right. Note that when held at arm's length, moderate spatial frequencies are seen at lower contrasts than low or high spatial frequencies (Campbell and Robson, 1968). Also see Dr. Izumi Ohzawa's Web site: http://ohzawa-lab.bpe.es.osaka-u.ac.jp/ohzawa-lab/izumi/CSF/A_JG_RobsonCSFchart.html.

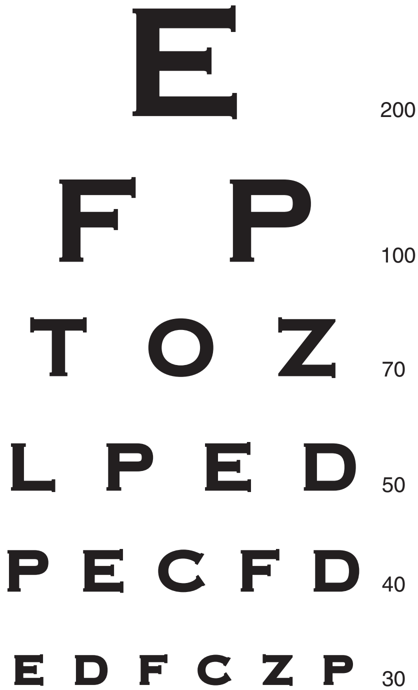

Figure 7–10. Snellen acuity chart. Each line is designated by its foot-size, which is the distance at which each of its optotypes subtends an angle of 5-minute arc.

Let us compare this to visual acuity,[2] which is determined by requiring a patient to resolve the details of visual symbols, called **optotypes,**[3] selected or designed for this purpose (Fig. 7–10). The optotypes are typically of very high contrast. As the patient reads down an eye chart, the optotypes become smaller and their details become finer (i.e., the high spatial frequency content increases). Even at 100% contrast, a point is reached where the details of the optotypes can no longer be resolved. In essence, visual acuity is the high-frequency cutoff determined with optotypes rather than gratings. As we learn later in this chapter, it is straightforward to convert from visual acuity to the high spatial frequency cutoff.

Figure 7–11 further illustrates the relationship between visual acuity and the CSF. The optotypes on the bottom row are at 100% contrast, typical of those used in a standard visual acuity test. The smallest *high-contrast* optotype that falls under the CSF curve represents threshold acuity. As the optotypes vertically approach the envelope of the CSF, they diminish in contrast. The ability to resolve these lower contrast optotypes is usually not assessed in routine clinical care, even though much

2. As we learn later in this chapter, there are several forms of visual acuity. The form of acuity measured with a standard eye chart is referred to as recognition acuity.
3. Optotypes often take the form of letters, such as those on a standard Snellen visual acuity chart.

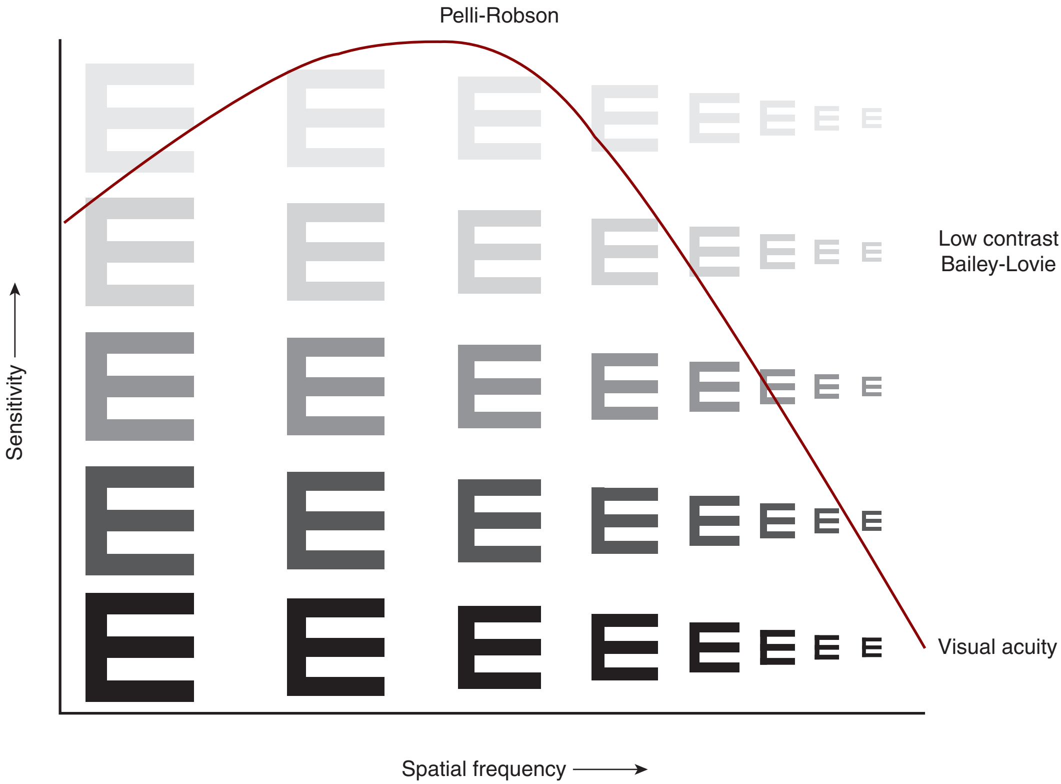

Figure 7–11. The contrast sensitivity function (CSF) forms an envelope for optotypes of various contrast and size. The bottom row of optotypes, which would be used in a standard visual acuity test, is at 100% contrast. Contrast decreases as the envelope of the CSF is approached vertically. A low-contrast Bailey–Lovie chart consists of low-contrast optotypes of diminishing size. The Pelli–Robson chart is constituted of optotypes all of the same size, but of diminishing contrast (Adams, 1993).

of the visual world is not at 100% contrast. This is a critical point that cannot be overemphasized—the typical clinical acuity measurement only tests a very limited aspect of the patient's spatial vision, the high spatial frequency cutoff.

Why does the visual system show a reduction in sensitivity for high frequencies? We have already discussed one reason—optical limitations. Any optical system, including the eye, manifests a high-frequency limitation because of optical aberrations. This is the case even when the eye is in focus.[4]

Another factor that plays a role in the high spatial frequency cutoff is the packing density of retinal photoreceptors. Consider the schematic illustrations of

4. The correction of the eye's optical aberrations can lead to visual acuity beyond the typical 20/20 or 20/15, a condition referred to as supernormal vision (Schwartz, 2002). Although it is possible to create supernormal vision in the laboratory, its clinical attainment with custom contact lenses or laser refractive procedures (e.g., LASIK) has not been fully explored.

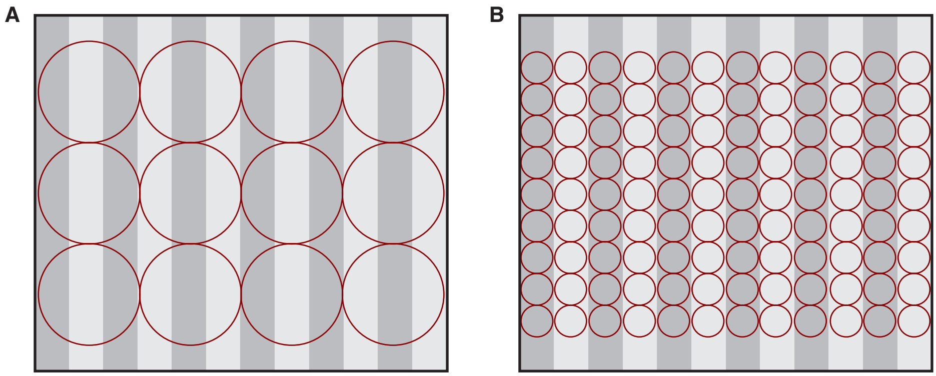

Figure 7–12. A spatial frequency grating projected on a **(A)** coarse photoreceptor matrix and on a **(B)** finer photoreceptor matrix. The finer matrix would enable resolution of the grating because the bright bars of the grating fall on every other row of photoreceptors. (Note that photoreceptors in the fovea actually form a hexagonal mosaic.)

photoreceptors packed at low and high densities in Fig. 7–12. A grating is superimposed on each of these matrices. If it is assumed that each photoreceptor sums up all the light that falls on it, it is hard to imagine how the coarse matrix on the left could resolve this grating. The finer matrix could, however, resolve this grating because the photoreceptors are packed sufficiently densely to allow bright bars to fall on alternate rows of photoreceptors. When stated more formally, this is referred to as the Nyquist theorem (Williams, 1986).

Foveal cones subtend a visual angle of approximately 0.5-minute arc (Curcio et al., 1990). If a grating is constituted of bars of this width so that it appears as in Fig. 7–12B, each cycle would subtend 1-minute arc. Such a grating has a spatial frequency of 60 cycles/degree, which is the high-frequency cutoff for the CSF. As we will learn later in this chapter, 60 cycles/degree corresponds to Snellen acuity of 20/10.

CSF in Uncorrected Refractive Errors

What happens to the high-frequency cutoff if the eye is out-of-focus, such as in uncorrected myopia? The solid curve in Fig. 7–13 shows the CSF for a patient with myopia who is fully corrected, and the dashed curve shows the CSF for the same patient without correction. As with an ophthalmic lens that is out-of-focus (see Fig. 7–7), there is a reduction in the high-frequency cutoff. The patient manifests decreased visual acuity.

Clinical Highlight

We previously pointed out that typical visual acuity charts measure only a limited aspect of a patient's vision. While this is true, the routine measurement of visual acuity provides many clinical advantages. It is exquisitely sensitive to disruption of the foveal photoreceptor matrix, as often occurs in disease that affects the fovea, as well as to refractive errors.

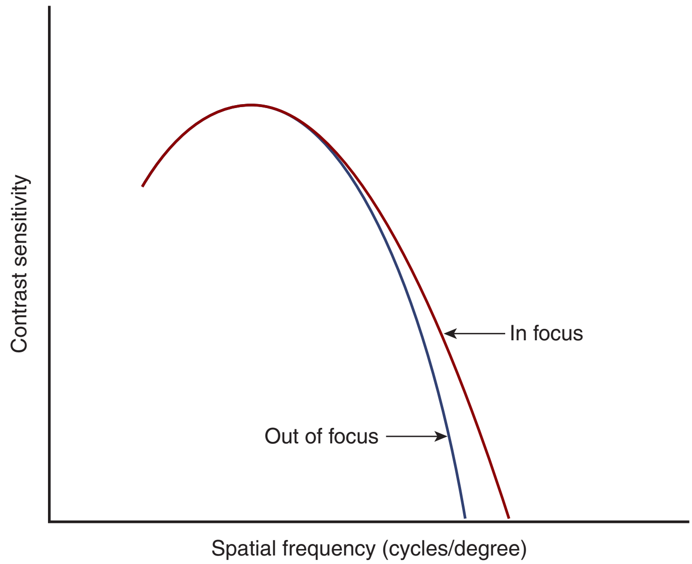

Figure 7–13. Contrast sensitivity functions for an eye that is focused and an eye that is out-of-focus, such as in myopia.

CSF LOW-FREQUENCY DROP-OFF

Consider the response of a ganglion cell to light that falls on its receptive field, the area in space that influences its activity.[5] A typical ganglion cell receptive field consists of a center region that responds to illumination with either excitation or inhibition and a surround region that responds with the opposite sign. The result is spatial antagonism, which is also called lateral inhibition. For the receptive field in Fig. 7–14, light falling on the center causes excitation, while light falling on the surround causes inhibition.[6] This cell will be strongly activated when a bright bar falls on the center of its receptive field and a dark bar on its surround, as depicted in Fig. 7–14A. A lower spatial frequency—where the bright bar falls on both the receptive field's center and surround, thereby causing lateral inhibition—results in a smaller response, accounting for the CSFs low-frequency drop-off (see Fig. 7–14B).[7]

5. See Chapter 12 for a more complete description of receptive fields.
6. For a ganglion cell, excitation is defined as an increase in the frequency of action potentials (indicated by plus signs) and inhibition as a decrease in the frequency (indicated by minus signs).
7. As discussed in more detail in Chapter 12, when light falls on both the center and surround, the excitatory center response is offset by the inhibitory surround response. When dark bars fall on the surround, they block light that would otherwise fall on it, causing the inhibitory response of the surround to be minimized.

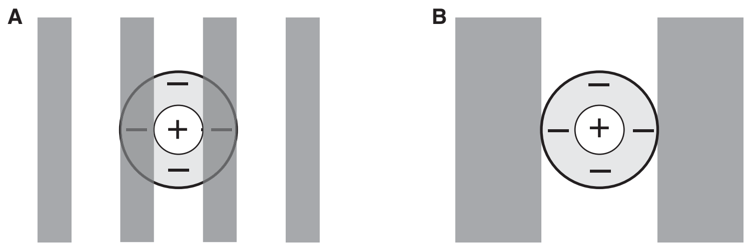

Figure 7–14. The spatial frequency grating on the left is a more optimal stimulus for this ganglion cell than the lower spatial frequency grating on the right. This is because the large bright bar of the low-frequency grating falls both on the receptive field's center and surround. This results in lateral inhibition, which reduces the neuron's response.

THE VISUAL SYSTEM AS A FOURIER ANALYZER

In one view of visual information processing, the visual system is considered to be a Fourier analyzer. That is, the visual system is thought to deconstruct the retinal image into its spatial frequency components.[8]

This view assumes the existence of independent spatial frequency channels within the visual system, as illustrated in Fig. 7–15. Rather than consisting of a single channel that is maximally sensitive to 4 cycles/degree, we can think of the CSF as forming an envelope that encompasses several narrower channels. Each of these channels is presumably independent.

The effect of prior adaptation to a spatial frequency grating supports this model (Blakemore and Campbell, 1969). Suppose a subject's CSF is determined and he or she then views an adapting grating (which is sinusoidal) for about a minute prior to the redetermination of the CSF.[9] The results of this experiment are given in Fig. 7–16A. Note that there is a discrete reduction in sensitivity at the specific frequency to which the observer was adapted. This is the result predicted by the multiple-channel hypothesis.

What would we expect if there was only a single channel? In this case, there would be an overall reduction in the CSF across all frequencies. Moreover, if there was only a single channel, adaptation to any spatial frequency would have the same effect—it would produce a reduction in sensitivity for all frequencies.[10]

Further support for the notion that the visual system performs Fourier analysis comes from an ingenious experiment in which the observer adapts to a square wave grating rather than a sine wave grating (Blakemore and Campbell, 1969). Figure 7–16B shows the results when an observer adapts to a square wave grating of 6 cycles/degree. As

8. This is also referred to as linear system analysis.
9. The adapting grating drifts across the computer screen to prevent the formation of a retinal afterimage.
10. The same principle holds true for a photopigment. Bleaching rhodopsin with 507 nm does not cause a discrete reduction in sensitivity at 507 nm, but a reduction in sensitivity for all wavelengths. Furthermore, any wavelength that is absorbed by rhodopsin could cause this same overall reduction.

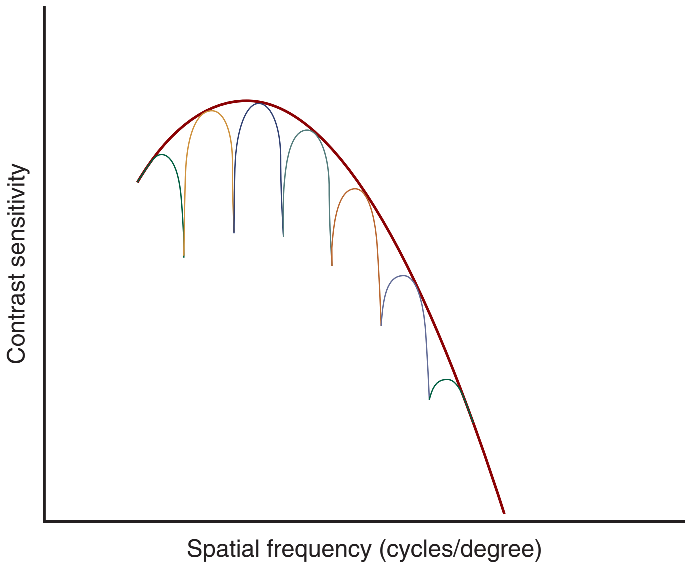

Figure 7–15. The contrast sensitivity function can be thought of as an envelope for a number of independent narrower spatial frequency channels.

expected, there is a reduction in sensitivity at the fundamental frequency of the square wave, 6 cycles/degree; however, note that there is a secondary reduction in sensitivity at 18 cycles/degree. We can account for this reduction by recalling that a square wave is composed of a fundamental sine wave of the same frequency and harmonic sine waves of odd multiples of this fundamental frequency. The secondary reduction in sensitivity represents adaptation to the third harmonic, which has a frequency of 18 cycles/degree.[11] It appears that a complex stimulus, the square wave, is broken down by the visual system into its components (a fundamental and its harmonics). This has been interpreted to indicate a form of Fourier analysis.

Mach bands demonstrate the usefulness of considering the visual system as a Fourier analyzer. As indicated by the luminance profile, the transition between the bright and dark regions in Fig. 7–17A is gradual. It is not, however, usually perceived as such. Instead, observers typically report bright and dark bands at the junctions of the bright and dark regions. These perceived bands, which do not actually exist, are referred to as Mach bands.

This illusion can be explained by assuming that the visual system performs a Fourier analysis of the stimulus. The gradual transition between the bright and dark regions consists of low spatial frequencies. Since the CSF manifests reduced sensitivity to these frequencies,[12] there is a relative enhancement of high spatial frequencies, resulting in the perception of enhanced boundaries (Mach bands).

11. Reductions in sensitivity to the fifth, seventh, and other odd harmonics are not noted because of the low contrast of these harmonics.
12. Recall that this reduced sensitivity to low frequencies is because of lateral inhibition within the retina.

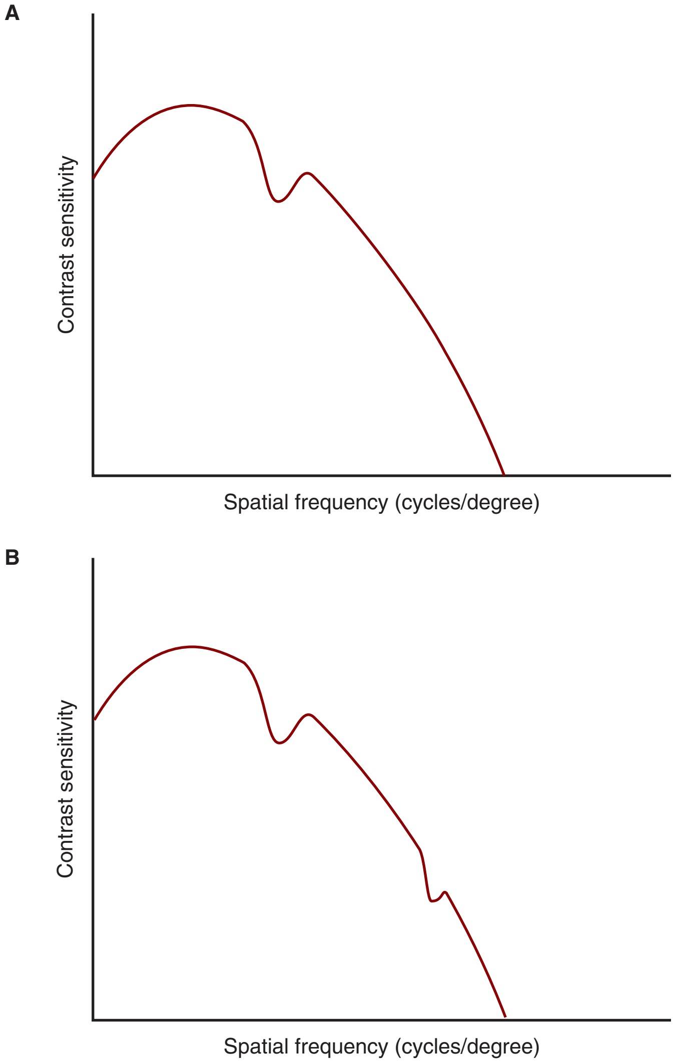

Figure 7–16. A. Prior adaptation to a sine wave grating of 6 cycles/degree results in reduced sensitivity at this frequency. **B.** Prior adaptation to a square wave grating of 6 cycles/degree produces a reduction in sensitivity at both the fundamental frequency (6 cycles/degree) and the third harmonic (18 cycles/degree).

Single-unit electrophysiological data from the primate visual cortex are consistent with the notion that the visual system could act as a Fourier analyzer.[13] Neurons in striate cortex appear to be finely tuned to specific spatial frequencies (DeValois et al., 1982). A collection of such neurons could form the physiological basis for the spatial frequency channels we discussed.

13. See Chapter 14 for a discussion of the receptive fields of cortical neurons.

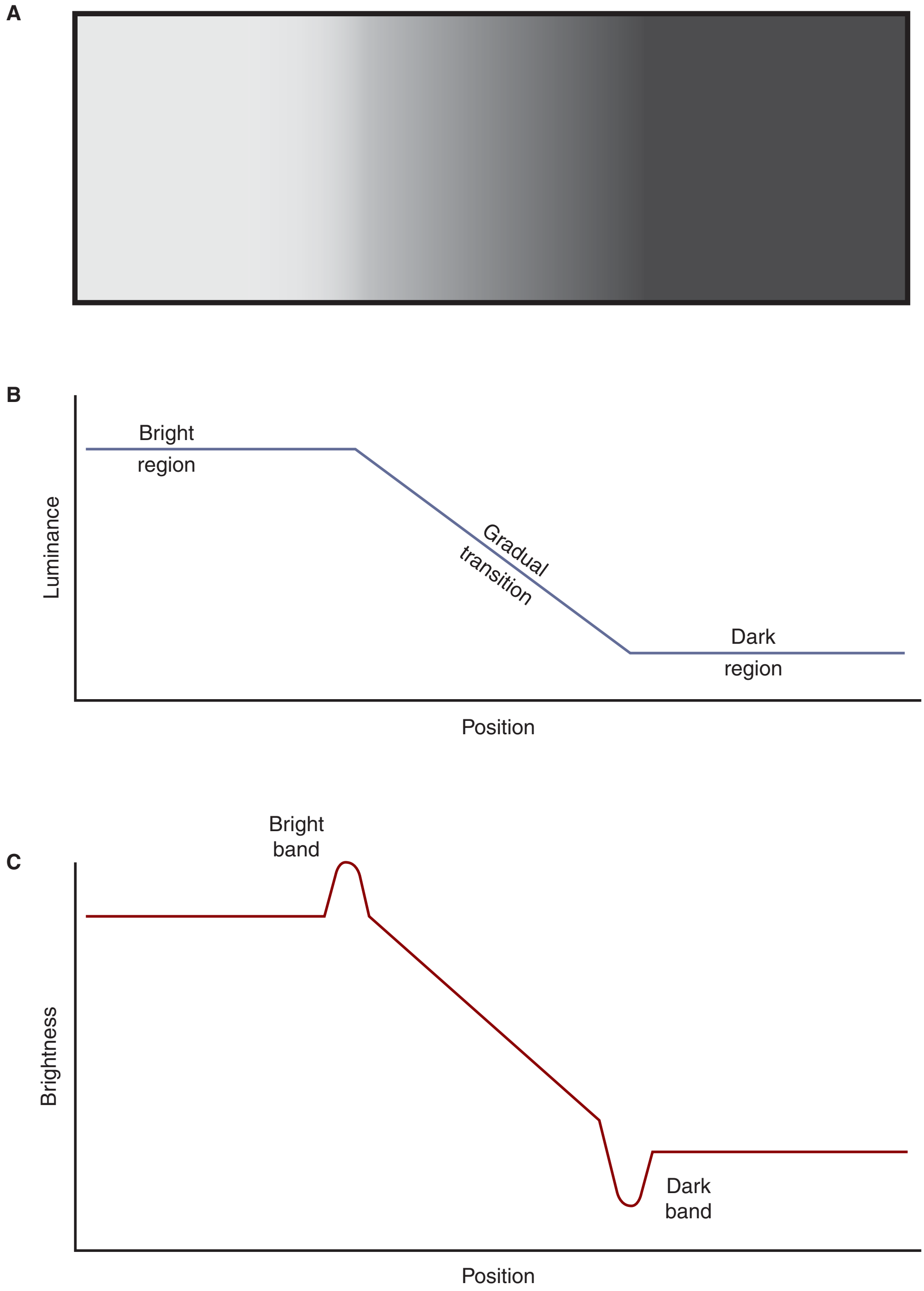

Figure 7–17. A. Although the decrease in luminance from left to right is gradual, bright and dark bands are observed. (The bright band is seen about one-third of the distance from the left edge of the diagram and the dark band at about one-third of the distance from the right edge of the diagram.) These bands, which are not physically present, are referred to as Mach bands. They represent a perceptual enhancement of borders. That the bands are not physically present is best seen by covering the image with white paper and then slowly moving the paper to the left. The bright band becomes apparent only after at least a portion of the gradual transition is uncovered. **B.** Luminance profile for the pattern in A. Note the gradual transition between the bright and dark regions of the pattern. **C.** Brightness of the pattern as perceived by a typical observer. The bright and dark bands, which are not physically present, are Mach bands.

Does the visual system actually act as a Fourier analyzer? The jury is still out on this question. Although the preceding experimental evidence is consistent with this model, it does not prove that it is correct. Nonetheless, the CSF is a useful and important tool for understanding how the visual system processes spatial information.

RELATIONSHIP OF CSF TO SNELLEN ACUITY

As we learned, visual acuity, as determined with optotypes, is equivalent to the CSF high-frequency cutoff. A typical optotype is designed such that its overall size is five times that of its detail (Fig. 7–18). The legs of the optotype **E** can be thought of as bars of a spatial grating (Fig. 7–19). To read the **E,** the patient must resolve its detail (e.g., bars and gaps). The angle that *just resolvable* bars (or gaps) make with the eye is called the **minimum angle of resolution (MAR).**

Visual acuity is commonly recorded in the form of the **Snellen fraction.** The numerator is the distance at which the measurement is taken, for example, 20 ft. The denominator is the **foot-size** of the smallest optotype that the patient can resolve. Foot-size is defined as the distance at which an optotype subtends 5-minute arc. At this same distance, the optotype detail subtends one-fifth of this

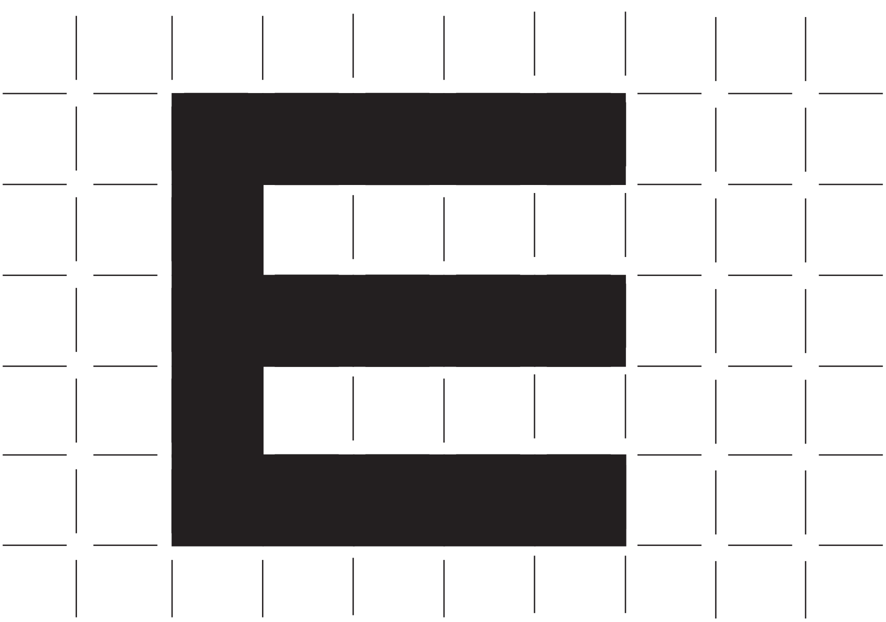

Figure 7–18. Construction of the optotype **E.** The detail (a bar or a gap) is one-fifth of the overall size of the optotype.

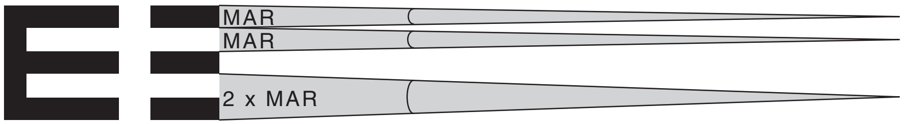

Figure 7–19. The optotype **E** may be thought of as consisting of the bright and dark bars of a grating. The smallest resolvable bar (or gap) subtends the minimum angle of resolution (MAR) at the eye. The combination of the bar and a gap, which is equivalent to one complete cycle of a grating, is twice the MAR.

value (1-minute arc). Each line on a Snellen chart is designated by the foot-size of its optotypes (see Fig. 7–10).

An important advantage of the Snellen fraction is that it allows easy calculation of the patient's MAR, which is simply the reciprocal of the Snellen fraction. What information does a Snellen fraction of 20/40 provide? It tells us that the measurement was taken at 20 ft; the smallest optotype the patient can read subtends 5-minute arc, overall, at 40 ft (i.e., it has a foot-size of 40 ft); the detail of this optotype subtends 1-minute arc at 40 ft; and the patient's MAR is 2-minute arc.[14]

What is the expected high-frequency cutoff of a patient with 20/40 acuity? Referring back to Fig. 7–19, note that the combination of a bar and a gap corresponds to a cycle of a spatial grating. A patient with 20/40 acuity can just barely resolve a grating whose bars (or gaps) subtend 2-minute arc; therefore, a just resolvable grating subtends 4-minute arc.[15] Since spatial frequency is typically given in cycles/degree , we must make the following conversion:

$$\left(\frac{1\,\text{cycle}}{4'\,\text{arc}}\right)\left(\frac{60'\,\text{arc}}{1\,\text{degree}}\right) = 15\,\text{cycles/degree}$$

This tells us that Snellen acuity of 20/40 is equivalent to a high-frequency CSF cutoff of 15 cycles/degree.

We can also do the reverse calculation and determine the patient's visual acuity when the high-frequency cutoff is known. For a high spatial frequency cutoff of 60 cycles/degree, each cycle of the grating (a light and dark bar) subtends 1/60th of a degree. An individual bar, which is the grating's detail and represents the patient's MAR, subtends 0.5/60 of a degree. We can convert this to minutes as follows:

$$\left(\frac{0.5\text{ degree}}{60}\right)\left(\frac{60'\,\text{arc}}{\text{degree}}\right) = 0.5'\,\text{arc}$$

The corresponding visual acuity is 20/10.

14. If this same patient was tested at 10 ft, the expected visual acuity is 10/20. In both cases, the MAR is 2-minute arc.

15. Since the MAR is 2-minute arc, each bar (or gap) of the threshold optotype **E** subtends 2-minute arc at the patient's eye.

Clinical Highlight

In most doctor's offices and eye clinics, visual acuity is determined using the Snellen eye chart (Fig. 7–10). As is sometimes the case in medical care, this procedure is used not because it is the most clinically or scientifically sound one, but because it has a long history of usage (Hussain et al., 2006). It is tradition.

There are significant limitations to the Snellen chart. Note that the optotypes are not evenly spaced, with those on the top of the chart less crowded together than those toward the bottom. As a result, the optotypes on the bottom are more difficult to resolve not only because they are smaller, but also because of the masking effect produced by the closely proximate surrounding contours (see Chapter 8). This so-called crowding phenomenon is especially strong in disorders of central vision, including amblyopia (Flom et al., 1963).

The Bailey–Lovie eye chart was designed to circumvent many of the design flaws of the standard Snellen chart (Bailey and Lovie, 1976). As can be seen in Fig. 7–20,

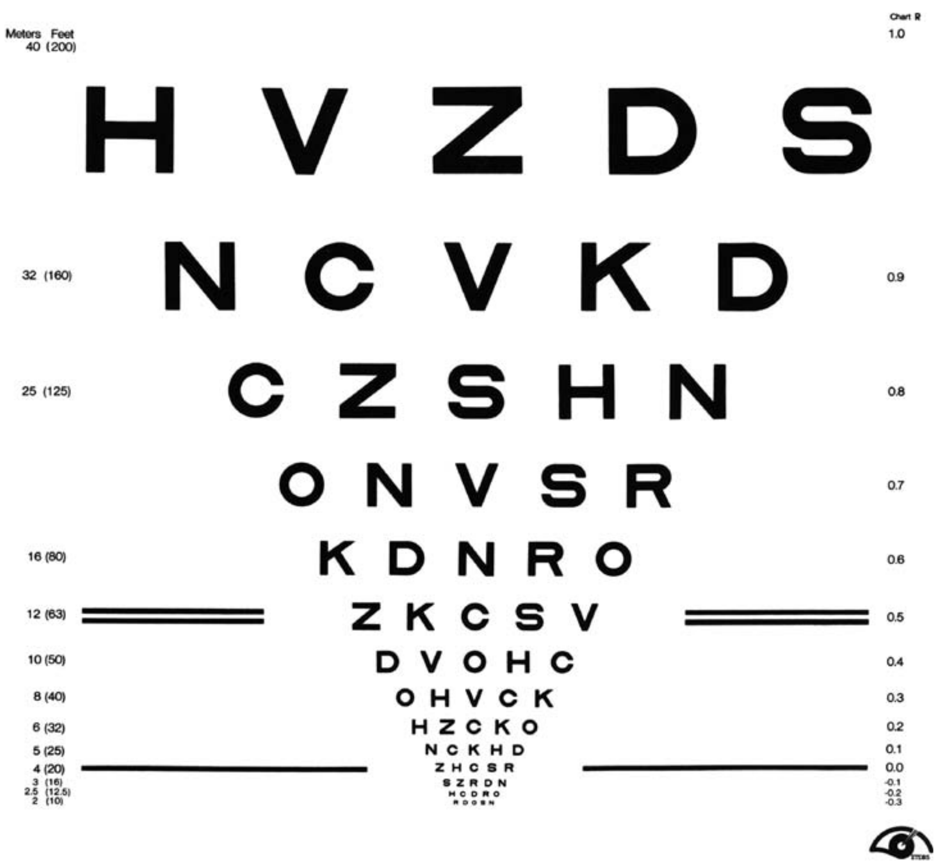

Figure 7–20. Early Treatment of Diabetic Retinopathy Study (EDTRS) eye chart, which is based on Bailey–Lovie design principles. The chart given here has high contrast. Low-contrast versions are also available. (*Source: National Eye Institute, National Institutes of Health.*)

each line has the same number of optotypes. Moreover, the spacing between the optotypes is proportional to the size of the optotypes, making contour interactions approximately the same for each line. Finally, the optotypes were selected to be equally legible.[16] The result is an eye chart where the difficulty of the task is determined primarily by the spatial frequency of the optotypes and not other factors.

The Bailey–Lovie chart was designed with a logarithmic progression from line to line, with each line labeled by the optotypes's foot-size in standard units (e.g., 200 ft) as well as by the logarithm of the detail subtended by the optotypes at 20 ft, which is referred to as the logMAR. For the 200 ft line, the logMAR is log 10 or 1.0. The difference between each line of the chart is 0.1, making it straightforward for the clinician to measure visual acuity at nonstandard testing distances, as may be required with low-vision patients.

Because all optotypes on the Bailey–Lovie chart are equally legible, it is possible to more precisely quantify a patient's visual acuity when the acuity falls between lines (Bailey et al., 1991). For instance, if a patient reads all letters on the 20/40 row of a Snellen chart and three more on row below, the traditional designation would be $20/40^{+3}$. When measured with a Bailey–Lovie chart, each letter can be given a value of 0.02 log units since there are five equally legible letters on a row. Consequently, we can designate the patient's acuity as logMAR $= 0.24$ [e.g., $\log (40/20) - (3)(0.02) = 0.24$].

CLINICAL IMPLICATIONS OF THE CSF

We have spent a considerable amount of time developing the concepts associated with the human CSF. What is the clinical value of this knowledge? Of primary interest is that the optical correction of refractive errors improves only a limited aspect of a patient's spatial vision. Visual acuity is improved, but there is little effect at low frequencies.

In a highly visual society such as ours, high-frequency resolution is critical. Reading road signs, blackboards, computer screens, and books and watching movies and television are all dependent on a high level of visual resolution. Consequently, the demand for the correction of refractive errors is great. It is, however, important to realize that a reduction in acuity, secondary to a refractive error is often well tolerated by patients whose acuity demands are not high. Eye care practitioners are occasionally frustrated by the patient whose acuity can be substantially improved, yet prefers his or her old correction that produces worse visual acuity. These patients illustrate the critical fact that there is more to spatial vision than high-frequency resolution.

Consider the world about you. Certainly many objects are highly detailed and require good acuity to resolve. Yet many objects can be recognized by their moderate frequency content. Consider the tree across the street, the dog in the driveway, or the outline of your spouse's body. These objects may be recognized without high-frequency acuity.

16. For the Snellen chart, certain letters are more legible than others. Letters with serifs can be particularly difficult to resolve.

The novice clinician is sometimes surprised by how well a patient with central (foveal) vision loss (say, 20/200 acuity) performs certain visual tasks. The patient's high-frequency spatial resolution is severely impaired, but he or she retains vision at low frequencies. This patient will have difficulty reading, driving, and inserting a key into a keyhole, but may be capable of performing certain of the essential tasks of life, such as ambulation.

Studies of visual disability suggest that reductions in visual acuity and contrast sensitivity contribute independently to the performance of visually guided activities (West et al., 2002). Consider a patient who has deficits at low and moderate frequencies with only a minimal reduction at high frequencies. He or she may present with complaints of significant visual impairment, but when we perform a standard acuity test, there may be normal or near-normal visual acuity.

Clinical Highlight

A patient with early cataract formation may manifest only minimal reduction in high-contrast visual acuity, but complain of disabling visual loss (Fig. 7–21) (Hess and Woo, 1978). The discrepancy between the severe complaint and the slight reduction in acuity occurs because the cataract acts as a diffuser, reducing image contrast across all frequencies.[17] The patient is impaired not only at high frequencies, but at moderate and low frequencies as well (Fig. 7–22). Consequently, the patient's complaints are disproportionate to the reduction in acuity.

Shining a light into the eye causes light scatter—a so-called **veiling glare**—that can reduce the contrast of the retinal image. This is the basis of the brightness acuity tester (BAT), a clinical instrument that shines diffuse light into the eye as the patient views an eye chart. While the diffuse light has minimal effects on visual acuity in the healthy eye, there can be a marked reduction in acuity if there is a cataract, even an early one, because of light scatter caused by the cataract.[18] A substantial reduction in the patient's visual acuity during BAT testing suggests that extraction of the cataract may be warranted.

Do cataracts and the resultant reduction in contrast sensitivity impair a patient's ability to drive safely? When subjects view driving scenes (e.g., on a video monitor) while wearing diffusing goggles that simulate cataracts, they are slower in detecting traffic hazards (Marrington et al., 2008). Along these lines, it should be noted that patients who have undergone cataract surgery are involved in significantly fewer motor vehicle accidents than cataract patients who have not undergone surgery (Owsley et al., 2002).

Contact lenses can produce corneal edema, with swelling of the corneal stromal layers (or epithelial cells) resulting in increased light scatter similar to that produced

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17. This is similar to the example discussed earlier in this chapter, where an optical lens is coated with clear nail polish.

18. A similar effect can be found by comparing the patient's visual acuity as determined in a dark room with the acuity determined when the lights are turned on. A patient with a cataract is expected to show a more profound reduction in visual acuity with the lights on than a patient who does not have a cataract.

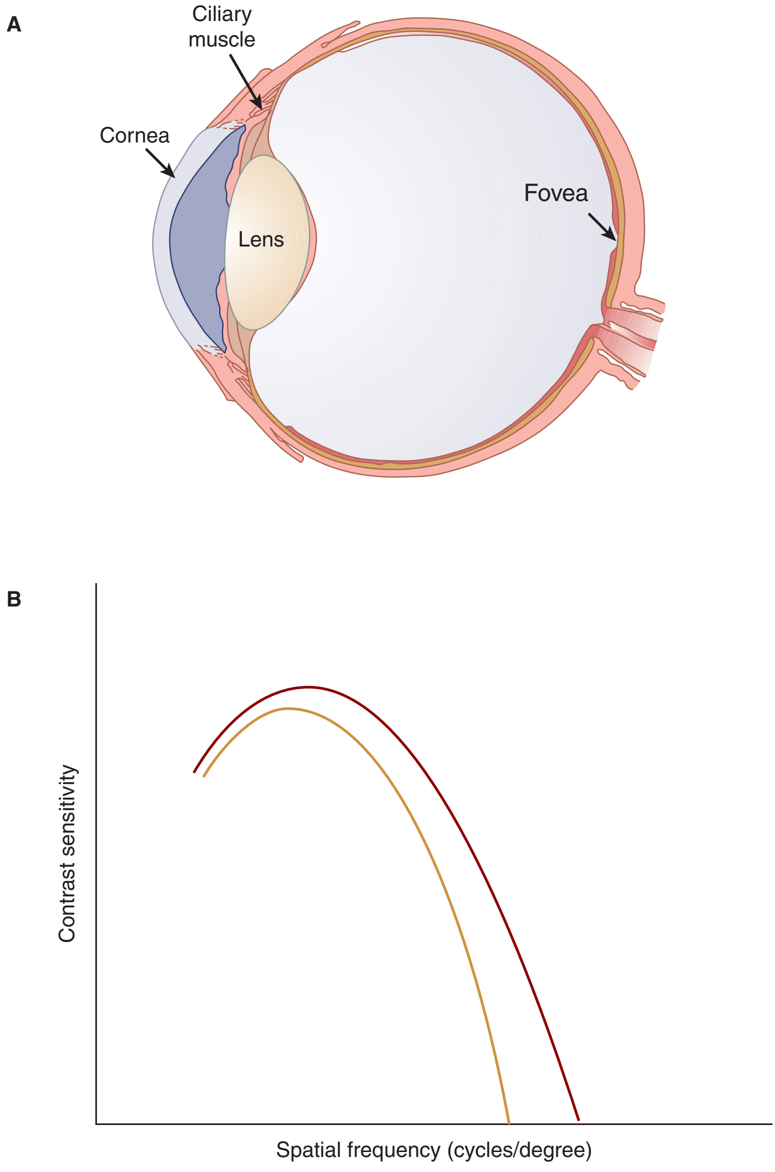

Figure 7–21. **A.** A cataract is an opacity of the crystalline lens. **B.** This opacity scatters light and reduces contrast for all spatial frequencies, resulting in a CSF that is depressed at all frequencies.

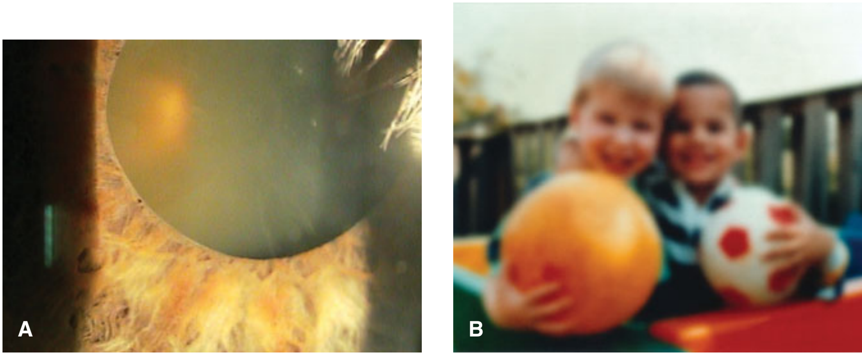

Figure 7–22. **A.** Senile nuclear cataract in an elderly patient. (*Photograph courtesy of Dr. Mitchell Dul*) **B.** Depiction of how the world may appear to a patient with a cataract. (*Source: National Eye Institute, National Institutes of Health.*)

by a cataract (Hess and Carney, 1979; Woo and Hess, 1979). There is a resultant reduction in contrast sensitivity across all frequencies. Not surprisingly, these patients may have normal or near-normal acuity, but complain of poor vision. For example, the patient may have close to 20/20 vision yet complain of substantial blur.

Scarring of the stromal layers secondary to trauma or refractive laser procedures can cause clinically significant light scatter, with a resultant reduction in contrast sensitivity at low and moderate frequencies. Swelling of the stroma, as occurs in Fuchs endothelial dystrophy, can also lead to loss in sensitivity at these frequencies. Again, it is important to keep in mind that patients with reductions in contrast sensitivity at low/moderate frequencies may have only a slight reduction in acuity (e.g., 20/25), yet complain of severe visual impairment.

In summary, we must be aware that Snellen acuity samples only a small portion of the patient's spatial vision. Cataracts, corneal edema, and other conditions commonly reduce contrast sensitivity at spatial frequencies other than those measured in an acuity task (Bodis-Wollner and Camisa, 1980). Consequently, complaints of reduced vision that are not proportionate to the reduction in Snellen acuity warrant careful investigation.

CLINICAL DETERMINATION OF THE CSF

The most accurate clinical methods display gratings on a video monitor that is driven by a microprocessor. Such instruments are typically available only in large eye clinics. More accessible methods employ gratings displayed on a printed chart (VISTECH) or a series of cards (Arden plates). The reliability of the former test has been called into question (Reeves et al., 1991).

Because useful clinical information regarding contrast sensitivity can generally be obtained more efficiently with other procedures, determination of a CSF is not a common clinical procedure. A practical approach is to determine low-contrast visual acuity. A Bailey–Lovie acuity chart constructed with low contrast, rather than high contrast, may be used for this purpose. The concepts associated with this chart are illustrated in Fig. 7–11.

A variation on this theme is the Pelli–Robson approach, which measures threshold contrast using optotypes, not gratings (Pelli et al., 1988). Rather than the optotypes becoming smaller as the patient reads down the chart, they remain the same size and their contrast decreases. The concepts associated with this task are also illustrated in Fig. 7–11. Either a low-contrast Bailey–Lovie or Pelli–Robson chart would be appropriate for the typical eye care office. They are efficient and can alert the clinician to reductions in contrast sensitivity.

Clinical Highlight

The contrast of a Snellen eye chart projected onto the far wall in a dark examination room is greatly affected by room illumination. Why is this so? Consider a chart projected in a dark examination room where the optotypes have a luminance of 5 cd/ft^2 and the bright background has a luminance of 95 cd/ft^2. We can calculate the contrast as

$$\text{contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$\text{contrast} = \frac{95 - 5}{95 + 5}$$

$$\text{contrast} = 0.90, \text{ or } 90\%$$

What happens when we turn on the room lights? The added illumination falls on both the dark and bright portions of the chart, equally increasing the luminance of both. If we assume that the luminance is increases by, say, 50 candelas/ft^2, the contrast is

$$\text{contrast} = \frac{145 - 55}{145 + 55}$$

$$\text{contrast} = 0.45, \text{ or } 45\%$$

By turning the lights on, we reduce the contrast by 50%.

How does this compare with a *printed* chart? Assume that the dark optotypes have a reflectance of 0.05, and the reflectance of the bright background is 0.95. The initial room illumination is 100 lumens/ft^2. Using the formula for Lambert surfaces from Chapter 4, we calculate the optotype and background luminances as follows:

$$L = rE$$

For the dark optotype

$$L = (0.05)(100 \text{ lumens/ft}^2)$$
$$L = 5.0 \text{ cd/ft}^2$$

For the background

$$L = (0.95)(100 \text{ lumens/ft}^2)$$
$$L = 95.0 \text{ cd/ft}^2$$

Therefore, the contrast is

$$\text{contrast} = \frac{95 - 5}{95 + 5}$$
$$\text{contrast} = 0.90, \text{ or } 90\%$$

Next, we turn on the lights, and increase the room illumination by 50 lumens. What happens to the chart contrast? For the dark optotype

$$L = (0.05)(150 \text{ lumens/ft}^2)$$
$$L = 7.5 \text{ cd/ft}^2$$

For the background

$$L = (0.95)(150 \text{ lumens/ft}^2)$$
$$L = 142.5 \text{ cd/ft}^2$$

Therefore, the contrast is

$$\text{contrast} = \frac{142.5 - 7.5}{142.5 + 7.5}$$
$$\text{contrast} = 0.90, \text{ or } 90\%$$

In the case of the printed chart, room illumination has little, if any, effect on contrast. Keep in mind, however, that visual performance will be reduced at low light levels where Weber's law is not followed.

OTHER FORMS OF VISUAL ACUITY

Our discussion of visual acuity has centered on resolution and recognition acuity, which are by far the most commonly utilized clinical measures, primarily because of their utility in the diagnosis of foveal disease and the detection and correction of refractive errors. A r**esolution acuity** task may require a patient to distinguish a grating from a uniform patch of light of equal luminance, the so-called **grating acuity** (see Fig. 17–13). The CSF high-frequency cutoff, which is from 40 to 60 cycles/degree (MAR of 0.75–0.50 minutes of arc) in a young, healthy adult, is an example of grating acuity.

Recognition acuity requires the patient to not only resolve an optotype, but to also label it. In Snellen acuity, for example, the patient is required to correctly read

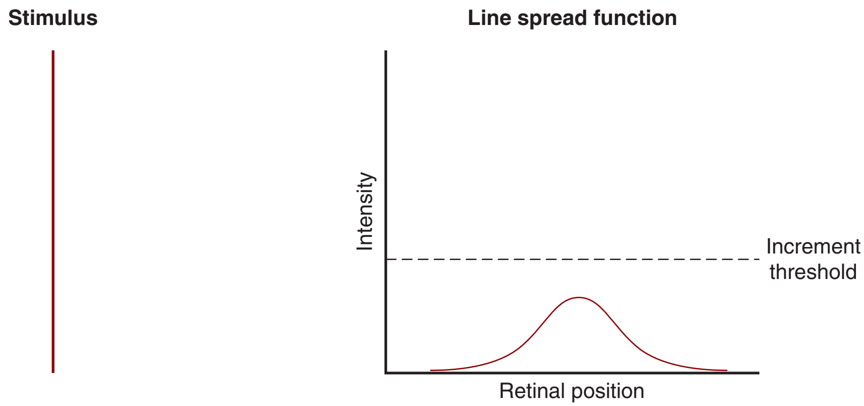

Figure 7–23. Minimum detectable acuity is determined by making a line progressively thinner, until it is no longer visible. A line-spread function (LSF), with a maximum height that diminishes as the line becomes thinner, is formed on the retina. Viewed in this manner, minimum detectable acuity can be considered to be an increment threshold task. In the example illustrated, the line would not be detectable because the LSF's peak retinal intensity falls below the increment threshold.

a letter, which requires familiarity with the alphabet. Young, healthy adults typically manifest Snellen acuities of 20/15 to 20/10 (MAR of 0.75–0.50 minutes of arc).

The determination of resolution acuity in toddlers who cannot yet read requires specially designed optotypes and charts. Alternatives to Snellen acuity include the Tumbling E, Landolt C, Cardiff, Broken Wheel, LEA, Patti Pics, and HOTV tests (Duckman, 2006). If the test requires the child to point out which direction a Tumbling E or Landolt C is oriented or to identify which optotype in a group of optotypes is different than the others, it requires only resolution, not recognition.[19]

Other forms of visual acuity also provide useful information regarding the limitations of spatial vision. **Minimum detectable acuity** refers to the smallest object that can be seen. Imagine a thin wire against a blue sky. How thin could this wire be and still be visible? (In this task, the subject does not need to resolve or recognize the object, only to detect it.) Figure 7–23 illustrates how we can approach this question. Minimum detectable acuity can be considered to be equivalent to an increment threshold.[20] Because of optical imperfections of the eye, the wire is not in perfect focus on the retina; its image takes the form of a **line-spread function.** In order for the line to be detected, the height of the line-spread function must be of a critical value. It turns out that this critical value is the same as ΔI in an increment threshold experiment.

19. Gratings may not be the best choice for identifying refractive errors in preliterate toddlers because of the phenomenon of spurious resolution in which defocus causes a phase shift in a grating, thereby making it look different than a uniform patch of equal luminance (Smith, 1982).
20. See Chapters 3 and 11.

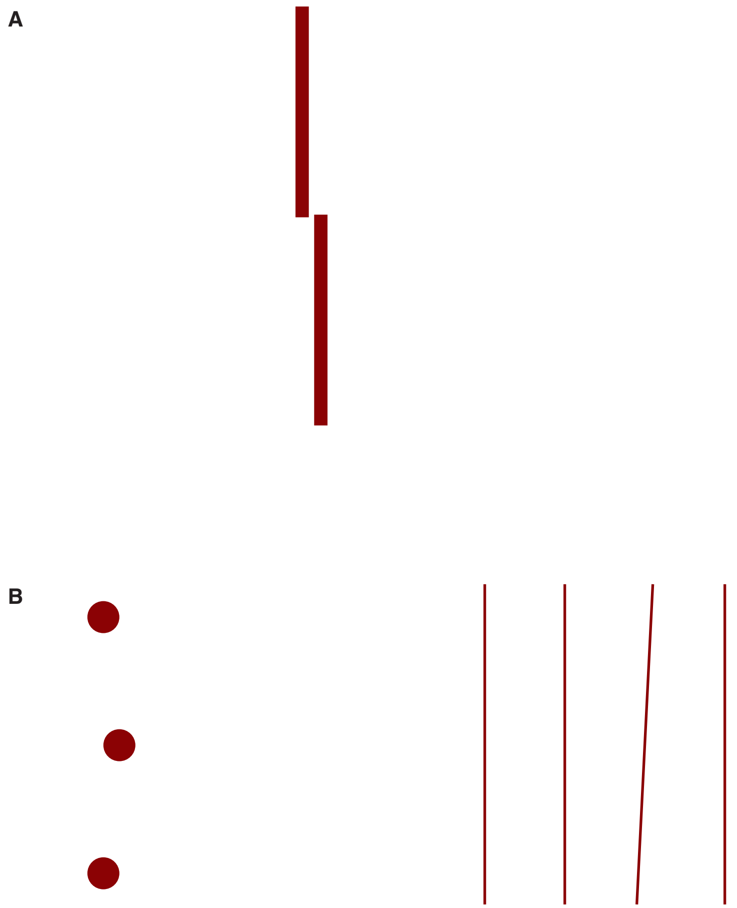

Figure 7–24. A. Stimulus used to measure vernier acuity, a form of hyperacuity. **B.** Other stimuli that measure hyperacuity. For the stimulus on the left, the task is to determine which circle is out of alignment. For the stimulus on the right, the task is to determine which line is tilted.

Minimum detectable acuity is limited by how thin a line (or small a dot) can be made and still emit sufficient light so that the increment threshold is reached. This has been determined to be approximately 1 second of arc (Westheimer, 1979). Note that this value is considerably smaller than that for resolution acuity.

Optical defocus, such as caused by an uncorrected refractive error, will result in diminished height of the line-spread function, with a resultant reduction in minimum detectable acuity. This reduction, however, is not as marked as with resolution acuity.

The final type of acuity that we discuss is **hyperacuity,** so named because of the exquisite sensitivity manifested in this form of acuity. Several different hyperacuity tasks are given in Fig. 7–24. Because of humans' excellent abilities at detecting tilt,

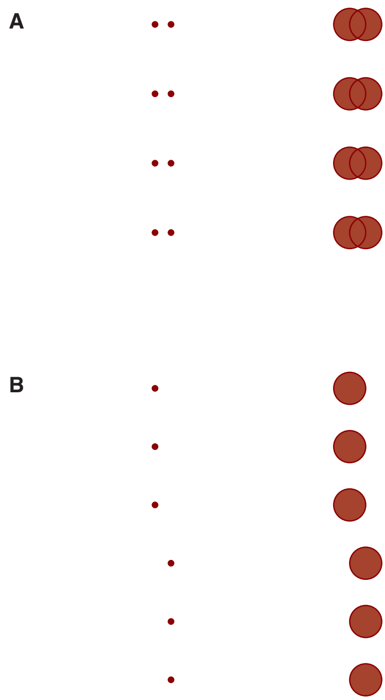

Figure 7–25. A. Each line can be considered as constituted of points. Defocus leads to overlapping blur circles, thereby reducing resolution acuity. **B.** In spite of optical blur, the luminance profiles of the blurred lines of a vernier target provide sufficient information to distinguish their positions.

a form of hyperacuity, it can be very difficult to align a picture on a wall so that it appears perfectly level.

Hyperacuity apparently depends on the visual system's ability to sense direction. Consider the **vernier acuity** task in Fig. 7–24A. Each bar is located at a different horizontal position in the visual field. When these two bars represent sufficiently different directions, a threshold for this hyperacuity task is reached.

Thresholds for hyperacuity are very low, on the order of 3 seconds of arc (Westheimer, 1979). These low thresholds are presumably related to the visual system's ability to average luminance information across space to arrive at a sense of direction. These processes occurs at postreceptoral levels, including the retina and, perhaps, the visual cortex (Levi et al., 1985).

Hyperacuity is very resilient to optical defocus. Whereas refractive errors greatly reduce resolution acuity, they have minimal effects on hyperacuity. Figure 7–25 provides a possible explanation for this. Optical defocus causes the blur circles to overlap, thereby interfering with the resolution of the two lines. In comparison, optical defocus does not interfere with the averaging of information across the retina that enables the positions of the two lines to be determined. The peaks of the luminance profiles are in different positions, and this leads to the perception of a different location for each line.

There is evidence that performance on vernier acuity tasks is adversely affected in glaucoma (McKendrick et al., 2002). The disease may result in damage to retinal circuits involved with the processing of position information.

SUMMARY

CSFs provide a powerful tool for characterizing spatial vision capabilities. The common clinical measurement of visual acuity assesses only a limited aspect of a patient's spatial vision. Reductions at high spatial frequencies, however, prompt the most visual complaints, and if optical in nature, are amenable to correction. Nonetheless, it should be kept in mind that reductions at frequencies other than the highest frequencies do occur and are of clinical importance.

Q Self-Assessment Questions

1. Determine the predicted high-frequency contrast sensitivity function cutoff, in cycles/degree, for the following visual acuities: **A.** 20/15. **B.** 20/80. **C.** 20/150.
2. Visual acuity is to be measured at 20 ft with a Snellen chart. Calculate the expected Snellen fractions for patients with the following high spatial frequency cutoffs: **A.** 5 cycles/degree. **B.** 20 cycles/degree. **C.** 60 cycles/degree.
3. A patient's visual acuity is 20/100. **A.** What is the overall physical size, in millimeter, of the smallest letter the patient can read on a Snellen chart at a distance of 20 ft? **B.** What is the size of the detail, in millimeter, of this letter?
4. A patient has a Snellen fraction of 20/80. What would you predict the Snellen fraction to be when acuity is measured at 10 ft?
5. A patient shows a high-frequency contrast sensitivity function (CSF) cutoff of 30 cycles/degree when tested at 20 ft. **A.** What is the expected high-frequency CSF cutoff, in cycles/degree, when the procedure is repeated at 10 ft? **B.** What is the width of a single bar of the threshold grating, in mm, when the test is performed at 20 ft? **C.** What is the width of a single bar of the threshold grating when the test is performed at 10 ft?
6. You measure a patient's visual acuity with a projected Snellen chart. In a dark room, the acuity is 20/20. **A.** What happens to the measured visual acuity when you turn on the overhead room lights? **B.** Why?