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Glare and Contrast Sensitivity for Clinicians

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2
An Introduction to Contrast Sensitivity Testing

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Introduction

In the treatment of visual disorders and eye disease, it is obviously useful to assess the patient's visual abilities. In principle, a great number of abilities could be tested (e.g., perception of motion, depth, color, faces, etc.). In practice, however, the first and often the only aspect of vision to be tested is spatial vision in or near the fovea. As used here, the term *spatial vision* refers to the ability to see achromatic, two-dimensional patterns. The most common clinical measures of spatial vision are visual acuity measures. In recent years there has been increasing awareness of the limitations of acuity measures and a corresponding rise in interest in other measures of visual function, in particular, contrast sensitivity.

This chapter briefly discusses acuity measures and then turns to contrast sensitivity. It covers the basic rationale for contrast sensitivity testing, methodological factors that influence the results of such testing, the underlying psychophysics and physiology, the clinical uses of contrast sensitivity testing, and clinical constraints on methodology.

Visual Acuity

When patients read an eye chart, be it a 19th century standard such as the Snellen letters, Landolt *C*'s, tumbling *E*'s, or a newer chart such as the *ETDRS* chart, their visual acuity is being measured. Visual acuity is a measure of the size of the smallest resolvable spatial detail. Ways to assess acuity can generally be grouped into three large categories: detection, resolution, and recognition. In tests of detection, one might determine the smallest stimulus element that the patient can see (Fig. 2.1).* Certain pitfalls have to be avoided. For example, assuming that it is bright enough, a white spot on a dark background can be seen no matter how small the spot. A point light source forms a disk of light on the retina. The optics of the eye ensure that the disk always illuminates several cones. Detection of a white spot, therefore, becomes a matter of absolute visual sensitivity and not of visual acuity. (A star is a good example of a bright spot that is visible even though it subtends a very small angle.) Detection of dark disks on a light background would be a better acuity test (Fig. 2.1). In such a test, 30 seconds of arc is a good estimate of the limits of resolution.[1,2]

Rather than detect a single item, it is possible to measure visual acuity by having patients look for separation between elements in a stimulus. For example, rather than measure the smallest visible disk, we could measure the smallest gap that can be seen between two disks. A particularly useful version of such a resolution test is shown in Figure 2.2. Here acuity would be measured by the finest resolvable grating. Typically, the bar width at the

*To correct for viewing distance, the size of visual stimuli is generally given in degrees of visual angle. The visual angle of any small target may be approximated by the equation:

$$\text{Visual angle} = \arctan\left(\frac{\text{size}}{\text{viewing distance}}\right)$$

Thus a 1.25-cm thumbnail held at a 70-cm arm's length from the eye subtends arctan (1.25/70) = 1.02 degrees of visual angle.

FIGURE 2.1. Detection acuity determines the smallest resolvable item.

limits of acuity is between 40 and 60 seconds.[2,3] Gratings may also be described in terms of the number of cycles per degree of visual angle. If the acuity limit is 60 seconds for a single bar, then a cycle (one white and one black bar) would be 120 seconds (2 minutes). This corresponds to an acuity limit of 30 cycles per degree (cpd).

In conditions such as astigmatism, grating acuity will be dependent on the orientation of the grating, because different gratings of one orientation will be in better focus than gratings of other orientations. However, the impact of the same clinical condition on other measures of acuity is less clear, because those measures (e.g., Snellen) involve stimuli containing a variety of orientations.

Tests like the Snellen letters are examples of recognition measures of acuity; they are the most common measures (see Fig. 2.3). Here the task of the patient is to name the target (a letter or number) or to name the location of some particular element of the target (the gap in a Landolt *C*, the direction of an *E*, etc.). Acuity is determined by the size of the elements making up the target (line width of letters, size of the gap) and is often rendered as a fraction: 20/20 designates an ability to recognize a target whose critical elements subtend 1 minute of arc at 20 feet. Various other systems use 6 meters or 10 feet, or some other standard, yielding 6/6 or 10/10 as "normal acuity." An acuity of 20/40 corresponds to an element size of 2 minutes, 20/80 to 4 minutes, and so on. It is certainly possible to resolve elements of under 1 minute, and 20/20 does not represent a limit on acuity nor, in any real sense, on "normal" acuity. A large portion of the healthy young population (>50% under age 40[4]) can resolve letters at 20/15.

FIGURE 2.3. Recognition acuity determines the smallest recognizable item in some set, here letters.

Methodological Issues in Acuity Measures

Acuity measures vary systematically with factors such as pupil size,[5] luminance,[6] and contrast.[7] Further, the style of testing can have a strong impact on the acuity measures. A tester who simply asks the patient to read as many letters as possible will get a quite different result from one who asks the same patient to "guess" at hard-to-see letters. Similar methodological issues affect contrast sensitivity testing and will be discussed in greater detail later in this chapter. For any measure of this sort, consistency is vitally important if measures are to be compared with each other. If the testing method is changed between a patient's visits, changes in the measured acuity are more difficult to interpret. For similar reasons, it may be difficult to evaluate changes in acuity measures for a patient if those measures come from different doctors or hospitals.

Contrast Sensitivity

The most important limitation on the usefulness of acuity measures is not methodological. Even if the methodology were flawless, acuity measures could not contain all the information needed to describe spatial vision. The heart of the matter is that acuity is a one-dimensional answer to a two-dimensional

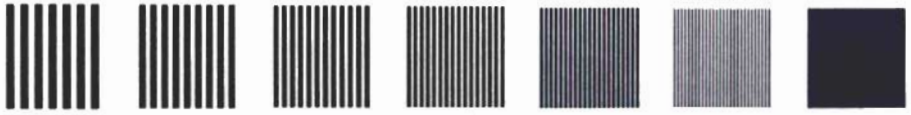


FIGURE 2.2. Grating acuity determines the highest resolvable spatial frequency.

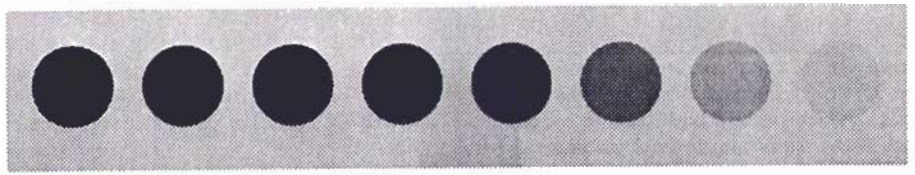


FIGURE 2.4. Contrast sensitivity determines the lowest detectable contrast for stimuli of a fixed size.

problem.* Let us consider one of the black spots in Figure 2.1. It has two salient attributes: size and contrast. In this figure all of the spots are of high contrast (black on white) and visibility is reduced by reducing the size of the spots. Instead of manipulating size, visibility could be reduced by reducing the contrast of a series of spots of equal size (Fig. 2.4). Spatial patterns varying in size and contrast occupy a two-dimensional (size × contrast) space (Fig. 2.5). Acuity tests locate the upper limit in the size dimension: the size below which an item cannot be resolved regardless of its contrast. There must be a similar limit in the contrast dimension: a contrast below which an item cannot be detected regardless of its size (Fig. 2.6). A car looming up in the fog might be an example of an important low-contrast stimulus. Cataract is an example of a clinical disorder that could lower a contrast limit as well as the acuity limit. Figure 2.6 makes the unrealistic assumption that contrast and size limits are independent of each other. In fact, they are not. The minimum visible contrast varies as a function of the size of the item, and so we get a "contrast sensitivity function," or CSF (Fig. 2.7), that partitions the size × contrast space into visible and invisible stimuli. As will be discussed later in this chapter, the normal CSF shows greatest sensitivity to test patterns of intermediate size. Sensitivity decreases gradually as the patterns become smaller, approaching the acuity limit. Sensitivity also decreases as the patterns enlarge. This can be thought of as a relative insensitivity to gradual changes in illumination (e.g., indistinct shadows on the wall). It follows that unless one makes a number of strong assumptions, knowledge of the acuity limit alone is insufficient to specify the

*Three dimensional, if we include luminance as a variable.

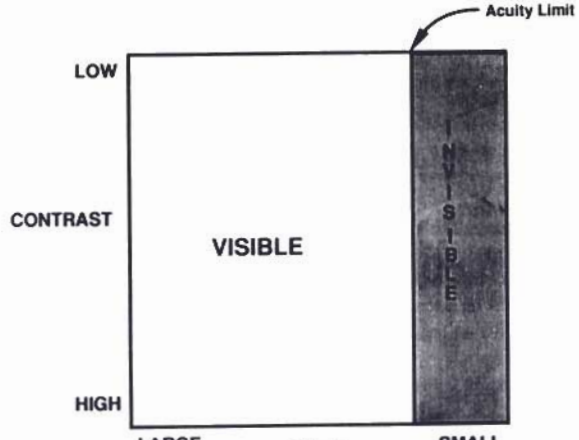


FIGURE 2.5. Alone, acuity determines a size limit on visibility but ignores the dimension of contrast.

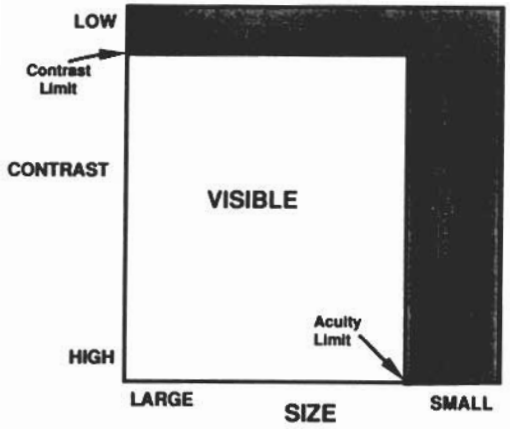


FIGURE 2.6. There must be some contrast below which stimuli are not visible.

entire CSF. It is certainly possible to have "normal" acuity and significantly reduced contrast sensitivity with serious visual consequences.

Stimuli for Measuring Contrast Sensitivity

Just as a variety of stimuli can be used to measure the acuity limit, a variety of stimuli can be used to measure contrast sensitivity. In practice, however, most work in the last 20 years has involved sinusoidal or "sine wave" gratings. A sine wave grating is a pattern of bars whose luminance varies sinusoidally in the direction orthogonal to the orientation of the bars. Such a grating looks like a fuzzy set of parallel lines. The size of a grating is specified in terms of its spatial frequency: the number of sinusoidal cycles per degree of visual space. Contrast of a grating (or, indeed, of any other pattern) is generally given as

$$\frac{\text{Maximum intensity} - \text{minimum intensity}}{\text{Maximum intensity} + \text{minimum intensity}}$$

This quantity varies from 0 to 1 and can be multiplied by 100 to give percent contrast. With sinusoidal gratings, acuity is the highest frequency that can be seen at 100% contrast. As with black and white (or "square wave") gratings, the limit of normal resolution is 30 to 45 cpd. The lower figure, 30 cpd, is equivalent to 20/20 Snellen acuity.*

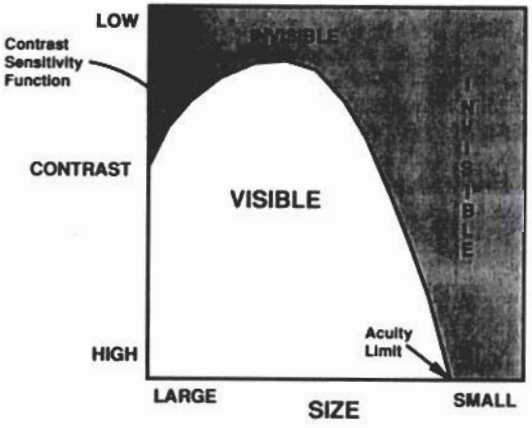


FIGURE 2.7. A more realistic figure shows that visibility depends on both the size (more precisely, the spatial frequency) and the contrast of the stimulus.

Sine waves have properties that make them attractive stimuli for measuring contrast sensitivity. First, Fourier's theorem holds that any complex waveform can be decomposed into a set of sine waves. For example, a black and white square wave (e.g., Fig. 2.2) can be created by taking a sine wave of the same spatial frequency (the "fundamental frequency") and adding to it a sine wave of three times the fundamental frequency at one third the amplitude of the fundamental plus a sine wave of five times the frequency at one fifth the amplitude, and so on for all of the odd harmonics of the fundamental. These gratings must be added in the correct relationship to each other. In this case, for example, the minima of harmonics must be aligned with the maxima of the fundamental so that the harmonics subtract light from the peak of the fundamental, flattening the sinusoid into a square wave. This positional relationship is known as *phase*. If we allow for gratings of different orientation, we can in principle generate any two-dimensional pattern by combining a set of sine waves having the correct frequency, amplitude, phase, and orientation.

For some purposes, the visual system can be treated as a device that adds up sine waves in a linear fashion. Then the system's sensitivity to any arbitrary two-dimensional pattern can be estimated by knowing its sensitivity to sine waves. Moreover, since contrast sensitivity is a smooth, continuous function, it is not necessary to measure the system's response to every spatial frequency. A properly selected set of frequencies allows the overall function to be estimated. For example, we have described how a square wave grating can be created by adding together a series of sinusoidal gratings. Going in reverse, a square wave of 30 cpd can be decomposed into a series of sinusoids – in this case a fundamental sine wave of 30 cpd, a third harmonic of 90 cpd at one third the amplitude of the fundamental, a fifth harmonic at 150 cpd and one fifth the amplitude, and so on through all the odd harmonics of the 30-cpd fundamental. However, we have already noted that the visual system does not respond to sine waves above about 45 cpd. Therefore, all of the harmonics are invisible and the 30-cpd square wave should be and is indistinguishable from a 30-cpd sine wave. More on this "linear systems" or Fourier approach to spatial vision can be found in Cornsweet[9] and Ginsburg.[10]

Sine waves have a second property that is useful in a clinical setting. Defocus reduces the contrast of a sine wave but does not alter its form. A blurred sine wave is still a sine wave, albeit a fainter one, while a blurred *E* on a Snellen chart, for example, changes its appearance as well as its contrast. Other sets of stimuli have the attractive properties of sine wave gratings, but sine waves have become the standard.

Methodology of Contrast Sensitivity Testing

Thresholds and Guessing

In principle, measurement of a contrast sensitivity function is straightforward. For a variety of spatial frequencies, one determines the minimum detectable contrast. Sensitivity is defined as the inverse of the minimum contrast (hence the apparently inverted *y* axis in Figs. 2.5, and 2.6). Sensitivity plotted as a function of spatial frequency gives the contrast sensitivity function.

In practice, a number of methodological issues complicate matters. First is the definition of "minimally detectable." It is incorrect to assume that there is some contrast above which a particular stimulus is visible and below which it is not. Figure 2.8 shows hypothetical results from an experiment where contrast is varied from 0 to 100% and the observer is asked to respond if the stimulus is seen. If, after many repetitions at each contrast level, percent stimuli detected is plotted as a function of contrast, results from almost any experiment of this sort will have the characteristic sigmoid shape shown in Figure 2.8.

There are a number of ways to understand this lack of a sharp criterion. Perhaps the most straight-

* In general, acuity measured in cycles per degree can be converted to Snellen notation by dividing the acuity by 30 cpd and then multiplying by 20/20 or 6/6. Because Snellen and grating acuity may not measure exactly the same thing, there is some doubt about the validity of this transformation (e.g., Thorn and Schwartz[8]).

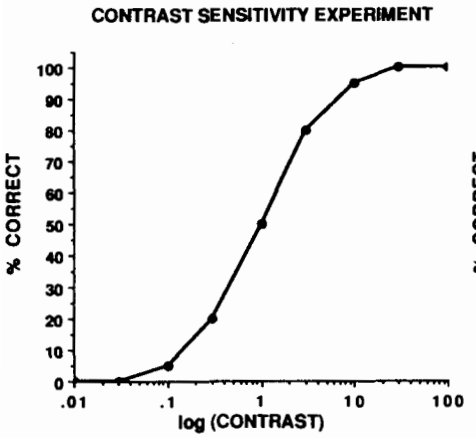


FIGURE 2.8. Contrast sensitivity experiment. As contrast is increased, observers will detect the stimulus with greater and greater accuracy. "Contrast threshold" is an arbitrary point on this smoothly increasing function. There is no sharp division between visible and invisible.

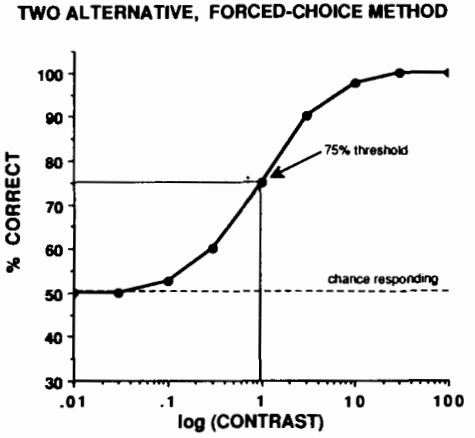


FIGURE 2.9. Two-alternative, forced-choice method to correct for guessing in threshold determination tasks, observers are asked to locate the stimulus in one of two locations in space or time. The contrast threshold is a point (e.g., 75%) on a function that increases from a 50% chance responding level to 100% correct.

forward is to realize that detection of a faint stimulus requires detection of a weak neural event in a system subject to random fluctuations in the background response rate of neurons. Near threshold some signals will be lost in this neural "noise."

This raises a second problem. Some fluctuations in internal noise might be mistaken for the presence of the stimulus by an observer straining to detect a barely visible stimulus. That observer might incorrectly state that the stimulus is visible. In fact, in the experiment just described, the observer could get 100% correct simply by stating that the stimulus was present on each trial. Such a result would be meaningless. Thus, reliable tests of contrast sensitivity (or any other measurement of threshold) require a method to counteract the effects of guessing. More extensive discussion of issues of this sort can be found in Falmagne[11] and in Snodgrass, Levy-Berger, and Haydon.[12]

The experiment just described could be conducted in a slightly different manner. The observer could be presented with two possible stimulus locations and be asked to state which of the two contains the stimulus. On each trial one location would contain a grating of some contrast and the other would contain a blank gray field of the same average luminance. The two locations could be separated in space or in time. The vital aspects of this "two-alternative, forced-choice" (2AFC) method are that the observer (or patient) is forced to make a response and that guessing, which is perfectly permissible in this case, will yield correct answers a predictable 50% of the time. Hypothetical results are shown in Figure 2.9. Again, there is no sharp threshold. However, a fixed criterion level can be picked (e.g., 75%). Since this method incorporates a correction for guessing, more reliable comparisons can be made between observers and between sessions for a single observer.

The problem of guessing can be dealt with in other ways as well. For example, a Snellen chart is, to a first approximation, a 26-alternative test. In this case the effects of guessing are minimal, because the chance of guessing correctly is under 4%. In reality, guessing effects in letter tests are somewhat more complicated because a patient may be able to narrow the field of possible letters by noting the overall shape even if he or she cannot resolve the details (i.e., *G* might be mistaken for *C* or *Q*, not *A* or *L*).

Speed Versus Accuracy

In the 2AFC experiment just described, observers would be tested at several spatial frequencies and at a range of contrasts for each frequency. Curves of the sort shown in Figure 2.9 would be generated for each frequency, the 75% point would be estimated, and the set of 75% points would serve as the CSF. While this test should produce a reliable CSF, it can take a very long time. Suppose ten contrast levels are chosen for each of six frequencies. Further, suppose that 100 trials are run at each contrast level, giving "percent correct" results in 1% steps. This test, for one eye at one orientation, requires $10 \times 6 \times 100$ or 6000 trials. At one trial every 3 seconds (unlikely), the test would take 5 hours. To scientifically establish the existence of the CSF this might be acceptable. However, the test is obviously too arduous for clinical use or, indeed, for most laboratory use.

More efficient methods exist. In general there is a trade-off between accuracy and efficiency, but some small or at least tolerable sacrifices in accuracy can yield substantial savings in time. For example, many of the trials in the 2AFC experiment contain very little information. One-hundred trials at a contrast that can be seen all the time are more than are necessary. If contrast threshold is defined as one point on a function of the sort shown in Figure 2.9, then time and effort should be concentrated at that threshold. Since the threshold is not known in advance, particularly in clinical cases, methods are required to guide the test to the correct contrast levels.

Staircase Methods

One such method was brought into the realm of experimental psychology from work with munitions. One way to determine the amount of force required to explode a bombshell was to carry the shell up, say, ten steps of a ladder and drop it. If it exploded, the next shell was carried up only nine steps. If the first shell did not explode, the next one was carried up 11 steps. This procedure, if repeated many times, will oscillate around the height that causes explosions 50% of the time.

The staircase method can be imported to vision testing very easily. If an observer reports seeing the stimulus in a contrast sensitivity experiment, the contrast is lowered one step. If the observer does not see the stimulus, the contrast is raised one step. This staircase will locate the 50% point on a function such as the one shown in Figure 2.8. This version of a staircase experiment is subject to errors due to guessing. A 2AFC version requires a modification of the staircase rule. The 50% point is the chance response level and is not useful. For the 2AFC case, a better rule is: Decrease contrast if the observer makes *two* correct responses at a given contrast level.[13] Increase contrast if the observer makes *one* incorrect response.

An example of the workings of such a two-down, one-up rule is shown in Figure 2.10. Contrast starts at 100%. It is decreased to 30% after two correct responses, to 10% after two more, and to 3% after two more. At 3% the observer makes an incorrect choice and so the staircase goes back up to 10%, and so on. It can be shown that this staircase estimates the 70.7% point on a 2AFC function such as is shown in Figure 2.9.[14]

The threshold estimate is obtained by averaging the peaks and troughs of the function shown in Figure 2.10. Starting from the right side of the figure, the first trough is at 0.3%; the first peak at 3%, then at 1%, 3%, 0.3%, 3%, and so on. It is important to average an equal number of peaks and troughs to avoid biasing the estimate. It is also important that the contrast steps be equal. Here they are roughly equal on a logarithmic scale. If we take the six values listed here and average their logarithms, we get an estimate of 1.2% for the contrast that is detectable 70.7% of the time.

Figure 2.10 shows an estimate of threshold obtained in 60 trials. That is a great savings over the 900 trials (100 trials at nine contrasts) required to obtain the data in Figure 2.9. These 60 trials can be further reduced. A staircase is usually run for a fixed number of peaks and troughs (reversals). The accuracy of the threshold estimate improves with the number of reversals, but the 18 reversals shown in Figure 2.10 are probably more than are needed. Using ten reversals would require 33 trials in this example. The number of trials required for a fixed number of reversals will vary with the reliability of the observer, fewer trials being required for a careful, reliable observer. Figure 2.10 would represent data from a "good" observer.

The 2AFC staircase procedure is by no means the only reliable method of obtaining a contrast sensitivity function (e.g., Tyrell and Owens[15]). However, the issues addressed by this method

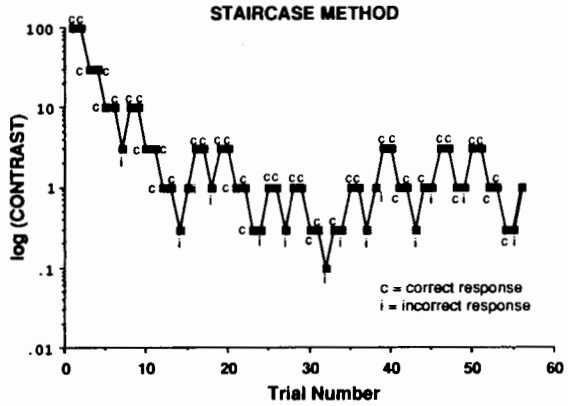


FIGURE 2.10. "Staircase" method. The time required to determine a contrast threshold may be shortened by using a "staircase" method. If the observer can see the stimulus, contrast is decreased; if not, it is increased. The staircase comes to oscillate around the threshold. See text for details.

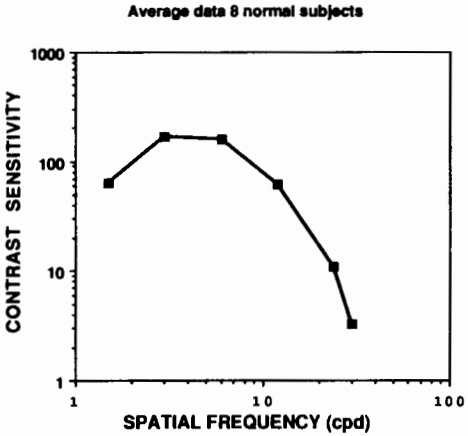


FIGURE 2.11. Average contrast sensitivity for eight young, healthy observers. Sensitivity is the reciprocal of threshold contrast. Both spatial frequency (cycles per degree, cpd) and sensitivity are plotted on logarithmic scales.

Figure 2.11 shows actual data from an experiment of this sort. Average monocular sensitivity for eight young subjects is plotted as a function of spatial frequency on logarithmic axes.* These data were obtained with a three-alternative, forced-choice method (stimuli could be vertical, tilted 15 degrees left, or tilted right). Fourteen reversals of the two-down, one-up staircase were used. Mean luminance was 85 candela (cd)/m² and the stimuli subtended 1.9 × 1.7 degrees at the 10-foot viewing distance. Stimuli appeared gradually over the course of 0.5 second, remained at full contrast for 1 second, and faded over 0.5 second. Under these conditions, sensitivity was maximal at 3 to 6 cpd, corresponding to correct identification of gratings of less than 1% contrast. Acuity can be estimated by extending the high-frequency limb of the function to the x axis. This yields an estimate of between 30 and 40 cpd (20/20–20/15). These results with a peak at 3 to 6 cpd and sensitivity falling off at both high and low frequencies are a fair representation of a normal CSF.

(e.g., the probabilistic nature of "thresholds," guessing, speed-accuracy trade-offs, etc.) are issues that any method should address. At a minimum, those using a method should understand the effects of these factors. In some cases, particularly in some clinical settings, further methodological shortcuts may be justified. This point will be discussed later in this chapter.

Stimulus Variables

Virtually all of the variables that might affect contrast sensitivity do affect contrast sensitivity. If measurements are to be comparable one to another it is important that these stimulus variables be held constant. Contrast sensitivity improves as mean luminance increases[16] and as the size of the stimulus increases.[17,18] Thus, if grating stimuli are used, it will be easier to detect six cycles of a 3-cpd grating than to detect two cycles of that grating. Retinal location is important, since acuity and contrast sensitivity for medium and high frequencies decline rapidly from the fovea to the periphery.[19] Acuity and contrast sensitivity vary with the orientation of stimuli even in nonastigmatic observers.[20,21] In general, Caucasians show decreased sensitivity to oblique orientations (oblique effect). This effect may be reduced or absent in other groups[22,23] and may be altered by extensive practice.[24]

Temporal factors may also influence the CSF.[25] Of particular interest in clinical settings, contrast sensitivity at low frequency is likely to be enhanced by abrupt stimulus onset. If desired, this effect can be minimized by having the stimuli appear and disappear slowly (e.g., contrast increases for 0.5 second, is steady for 1 second, and fades over 0.5 second). In general, comparisons between observers or between multiple tests of a single observer will be valid only if these stimulus factors are held constant or if the stimulus variations are taken into consideration in the comparison. More detailed discussion of these factors can be found in Olzak and Thomas.[26]

Refractive state and pupil size affect the quality of the retinal image and therefore affect contrast sensitivity. Defocus has predictable effects on all frequencies, not merely on visual acuity.[27-29] It is important to consider changes in refractive state as possible causes for changes in the shape of the CSF. Refractive error can even produce "notches" in the CSF.[30] Pupil size has two primary effects. Retinal light level varies with pupil size and large pupils introduce larger optical aberrations. Intermediate pupil size (2–5 mm) provides the best acuity and contrast sensitivity.[5,31]

Observer/Procedural Variables

Differences in testing protocol can make surprisingly large differences in results of acuity and contrast sensitivity measures. Naive observers (by which we mean individuals who do not know the purpose of a test and do not have extensive experience with it; e.g., patients) tend to be unwilling to be conservative when reporting on faint, near-threshold stimuli. That is, returning to Figure 2.8, they might claim to be unable to see stimuli that fall below the 90% point on their underlying sensitivity function. Just as they correct for guessing, 2AFC procedures can correct for this conservative tendency. However, the forced-choice must be a true-false choice. Observers cannot be allowed to use the third choice of "I don't know." This need for true forced-choice holds in others tests. For example, an observer who is asked to locate the smallest visible line on a Snellen chart is likely to yield a poorer acuity measure than an observer who is asked to make a real 26-alternative, forced-choice "guess" at the letters on subsequent lines.

Consistent use of forced-choice methods also makes comparison between observers more trustworthy. Without forced choice, a difference in sensitivity or acuity measures could be attributed either to a "real" difference in vision or to a difference in response criteria. (Forced-choice measures are often called *criterion-free methods*). Further, some observers are less reliable than others and will make careless errors. The results obtained by criterion-free methods are less vulnerable to distortion by errors.

Underlying Mechanisms of Contrast Sensitivity Testing

The shape of the CSF is a product of optical, retinal, and neural factors. There is a basic scientific interest in explaining the CSF. Moreover, our interpretation of deviations from the "normal" CSF are based on our understanding of the processes that give rise to that normal function.

Optics and Photoreceptors

Over the past 20 years, a host of psychophysical and physiological experiments have provided a fairly clear picture of the underlying mechanisms that give the normal contrast sensitivity function its characteristic shape. Optical and photoreceptor characteristics provide the primary limitations for visual acuity (and thus for high spatial frequencies). The optics of the eye act to reduce the contrast of spatial frequencies above about 5 cpd. The reduction increases with spatial frequency and becomes complete at about 60 cpd.[9,19,27] Under

*Logarithmic axes are used here because they better reflect perceptual reality. For example, the difference between 3 and 6 cpd is much more salient than the difference between 33 and 36 cpd.

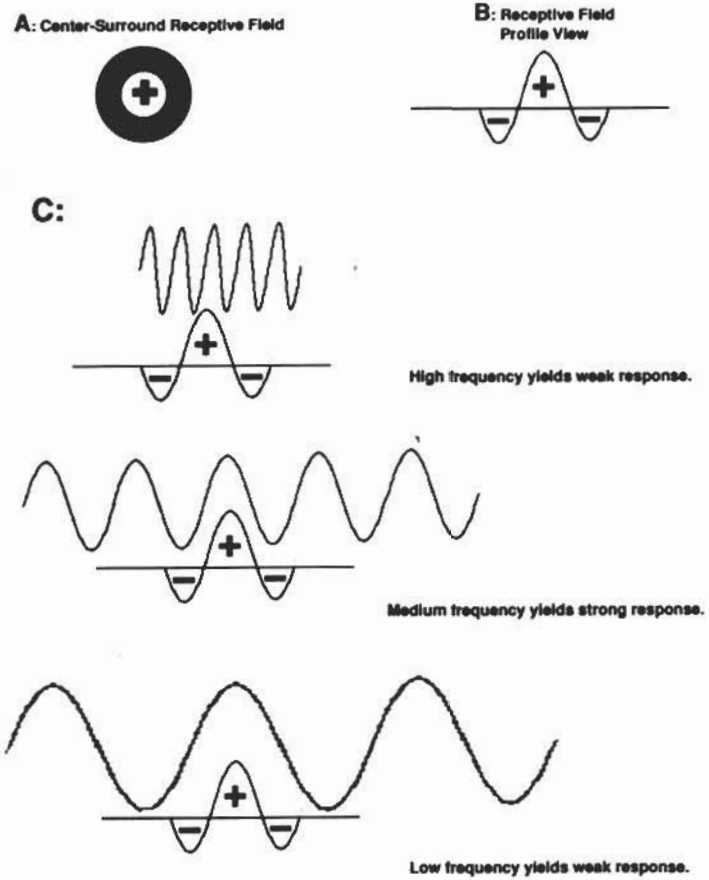
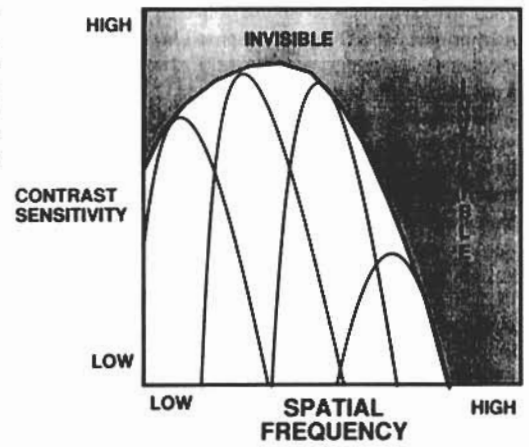


FIGURE 2.12. Individual cells in the retina and central visual pathways have receptive fields that render them more responsive to some spatial frequencies than to others.

normal viewing conditions, spatial frequencies above 60 cpd are not imaged on the retina, so it is no surprise that they are not detected. It is possible, using interference patterns, to form higher frequency gratings directly on the retinal surface. However, even when the optics of the eye are bypassed in this manner, acuity does not improve.[31] Given an image on the retina, the limitation becomes the density of the foveal photoreceptors. Roughly speaking, to see a grating an observer needs photoreceptors packed so that at least one photoreceptor is stimulated by each light bar and one by each dark bar. Not surprisingly, the density of photoreceptors roughly matches the optical limits of the eye.*

*With interference patterns it is possible to see higher spatial frequencies. Imagine that the light from three bright bars and two dark bars of a very fine grating stimulates one photoreceptor while the light from two bright bars and three dark bars stimulates a neighboring photoreceptor. Under these circumstances a pattern might be detected, though it would have an apparent spatial frequency lower than its physical frequency. This interesting phenomenon, known as *aliasing*,[32] does not have important consequences for normal contrast sensitivity or acuity measures.

FIGURE 2.13. Individual cells measured physiologically, or "channels" measured psychophysically, will have contrast sensitivity functions that, when summed together, yield the contrast sensitivity function (CSF) for the organism as a whole. Here, for illustrative purposes, four hypothetical channels are shown underlying the CSF.



Ganglion Cells

The axons of the retinal ganglion cells form the optic nerve. By means of quite complicated neuronal circuitry in the retina,[33,34] these ganglion cells act to pool responses from a patch of photoreceptors. That patch of retina or, equivalently, the portion of visual space that forms an image over that set of photoreceptors, is known as the *receptive field of the cell*. Ganglion cell receptive fields have a characteristic "center-surround" organization, as shown in Figure 2.12A. Stimulation of the photoreceptors in the center causes an increase in the cell's response. Stimulation of the surround causes a decrease. Another useful representation of the receptive field's response properties is shown in Figure 2.12B. Here the response of the cell is shown for a one-dimensional slice through the receptive field center. Again, stimulation of the center excites the cell. Stimulation of the surround inhibits the cell. It is possible to have the arrangement reversed so that the cell is activated by an absence of light in the center. More information about ganglion cell receptive field properties can be found in Dowling[33] and Bishop.[35] Stimulation by a large patch of light will activate both center and surround and, because of the inhibitory action of the surround, will produce relatively little activation of the ganglion cell.

A ganglion cell with the response profile shown in Figure 2.12B will have a contrast sensitivity function associated with it. This can be understood by comparing the response profile of the cell with the luminance profile of a grating stimulus (Fig. 2.12C). The response of the ganglion cell will be greatest when the response profile matches the periodicity of the luminance profile. Put another way, the response of the cell will be greatest when a bright bar falls on the center of the receptive field while flanking dark bars fall on the inhibitory surround regions. Thus, for the receptive field shown in Figure 2.12B, there will be an optimal spatial frequency with response falling off as the frequency becomes higher or lower than the optimal.

Ganglion cells can have receptive fields of different sizes. As Figure 2.13 indicates, a set of such cells with their associated contrast sensitivity functions could, in aggregate, give rise to the contrast sensitivity function of the observer as a whole.

Spatial Frequency Channels

The preceding assertion is somewhat of an oversimplification. The CSF is not determined completely at the level of retinal output. The output goes to the lateral geniculate nucleus of the thalamus and from there to the visual cortex. Rather than being circularly symmetric, the receptive fields of many visual cortical cells have a preferred orientation. Thus, a CSF measured with horizontal gratings would be the product of the output of cortical cells "tuned" for horizontal orientations, whereas a CSF measured with vertical gratings would involve a different set of cortical cells, those

tuned for vertical orientations. Presumably, this orientational selectivity is responsible for the oblique effect already mentioned.[36,37] The matter is not completely clear, however.

We generally assume that the physiology underlying the human CSF is similar to the physiology discussed here, though our data come primarily from monkey and cat. The properties of the human system can be probed only indirectly using psychophysical methods. When discussing human vision, we tend to talk about spatial frequency and/or orientation selective "channels" or "mechanisms," to acknowledge that the experiments do not directly measure the responses of single cells.

Human psychophysical studies of these underlying mechanisms attempt to specify their number, shape, and size. In Figure 2.13, the number of mechanisms would be four. Their shape would be roughly parabolic. Of course, "shape" is used here in a graphic sense and is dependent on the axes used. Normally CSFs are plotted as log sensitivity as a function of log spatial frequency. Finally, the "width" of the mechanism gives an estimate of the range of spatial frequencies to which the mechanism responds. Width is usually defined as the width at half the height of the channel. Thus, if the maximum sensitivity of a channel were 2 log units (=100=1% contrast), width would be defined as the range of spatial frequencies that stimulate the channel at 1 log unit (=10=10% contrast).

Several experimental paradigms provide converging evidence that there are a limited number (perhaps six to eight) of spatial frequency selective channels underlying the human CSF. Four of these methods will be described here: adaptation, discrimination at detection thresholds, subthreshold summation, and masking. The existence of multiple spatial frequency channels is of more than purely scientific interest. Given that multiple mechanisms underly human spatial vision, a simple acuity measure may be inadequate, since it will reflect only activity in the high-frequency channels.

Adaptation

Stimulation of a channel renders that channel less sensitive to subsequent stimulation for some period of time. This is known as adaptation. Adaptation of a psychophysical channel is directly analogous to adaptation of photoreceptors to light. Exposure to light reduces the photoreceptor's ability to respond to light. Sensitivity is reduced until the photoreceptor returns to its unadapted state. In adaptation to spatial frequency, it is assumed that exposure to a spatial pattern either depletes some limited resource (perhaps neurotransmitter) or produces some prolonged inhibition. This is made manifest as a reduction in the observer's sensitivity to the adapting stimulus. Sensitivity recovers as the limited resource is replenished or the inhibition dissipates.

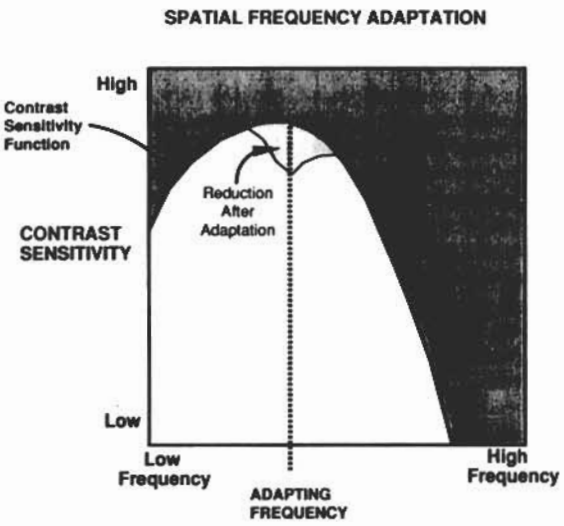
Given that adaptation to a grating reduces sensitivity to that grating, information about the nature of underlying spatial frequency channels can be obtained by adapting to a grating of one spatial frequency and looking for effects of that adaptation at other frequencies. If the CSF reflected the sensitivity of a single underlying channel, then adaptation at one spatial frequency should reduce sensitivity at all visible frequencies. The analogous example from light adaptation would be adaptation of the rod photoreceptors. There is a single type of rod with a single spectral sensitivity function. Adaptation to any wavelength of light decreases sensitivity to all other wavelengths. At the opposite extreme, there could be a distinct, narrowly tuned channel for each spatial frequency such that a single frequency would stimulate one and only one channel while a neighboring frequency would stimulate a different channel. In this case, adaptation at one frequency would reduce sensitivity only to that frequency.

Reality lies between the extremes. Adaptation to a single frequency reduces sensitivity to a range of spatial frequencies surrounding the adapting frequency[38] (see Fig. 2.14). These results provide evidence for multiple spatial frequency selective channels and give an estimate of their tuning (the degree of their selectivity). For a number of reasons, it is not simple to infer the precise tuning of the underlying channels from the results of adaptation studies. For instance, adaptation at one frequency may influence several underlying channels. Therefore, the spread of the elevation in threshold cannot be used to estimate directly the shape of any single channel.

Discrimination at Detection Thresholds

No simple, one-channel model of the CSF could be correct, because a single channel could not provide information about spatial frequency. Two spatial frequencies could produce identical outputs from a

FIGURE 2.14. Spatial frequency adaptation. If an observer views a sinusoidal grating of a particular spatial frequency, sensitivity at that frequency and at its near neighbors will be reduced. Remote frequencies will show no reduction.



single channel and the stimuli would be indiscriminable. This observation can be turned into a method for studying spatial frequency channels. At the detection threshold, a grating is presumed to be detected exclusively by the channel most sensitive to that spatial frequency. If a grating of a neighboring frequency stimulated the same channel at threshold, the two frequencies should be indistinguishable. Each is producing a minimal activation of the same channel. If, however, the second grating is detected by a second channel, the two gratings should be discriminable at threshold. By examining the discriminability of numerous pairs of spatial frequencies it is possible to estimate the number and shape of the underlying spatial frequency selective mechanisms. For example, Watson and Robson[39] used this method to obtain an estimate of seven selective mechanisms (see also Nachmias and Weber,[40] Thomas and Gille,[41] and Thomas, Gille, and Barker[42]).

Subthreshold Summation

Two other methods, subthreshold summation and masking, emerge from the idea that gratings should interact if their spatial frequencies are similar enough to stimulate the same mechanisms. Subthreshold summation is best understood if we consider detection of a simple spot of light. Suppose that 100 units of light are required for detection and suppose that the available stimuli are two 75-unit light sources. Each of these is "subthreshold," but if both shine on the same patch of retina the energy will summate and the resulting 150 units will be detectable. If the two sources shine on separated patches of retina, no summation will occur and no light will be detected.

Similarly, if two sinusoidal gratings are presented to the same patch of retina at subthreshold contrast, they may summate and produce a detectable stimulus if they stimulate the same underlying spatial frequency channel. However, if the two gratings are far enough apart in spatial frequency that they stimulate entirely different channels, no summation and no detection will occur. Experiments of this sort indicate that gratings can show summation if their spatial frequencies differ by less than a 2:1 ratio.[43] Interestingly, frequencies that are much farther apart may inhibit each other.[44]

Masking

The use of masking in the study of spatial frequency channels can also be understood by analogy to detection of a spot of light. We again assume that, in the absence of other light, the threshold for detection is 100 units of light. It is intuitively clear

and factually correct that those 100 units of light will not be detected if they are presented in a location already illuminated by 1000 units of light. The 1000 units *mask* the 100 units. If the 1000 units are presented elsewhere in the visual field, the masking effect will be reduced or eliminated. Switching to spatial frequency, the threshold for a test grating of one spatial frequency will be raised by the presence of a second masking frequency if that masking frequency stimulates the same channels as the test frequency. In masking experiments, gratings mask each other when their spatial frequencies differ by less than a factor of 2. Estimates of the number of underlying mechanisms are similar to those obtained by other methods (e.g., six channels[45]).

While different studies do yield different estimates of the number and shape of spatial frequency channels, an estimate of six to eight channels seems reasonable. The shape of the CSFs for these channels appears to be roughly parabolic plotted on logarithmic coordinates. The width of these channels at half height appears to be about 1 octave (a factor of 2; i.e., a channel that responds maximally to, say, 8 cpd would respond with roughly half that enthusiasm to 6 or 12 cpd). These estimates change as other properties of the stimulus change. For example, if the stimuli are flickering on and off, estimates of the number of channels drop (e.g., from seven to three in Watson and Robson's 1981 study[39]). Spatial frequency channels are tuned for orientation as well as spatial frequency. This means that the channel that detects a vertical 3-cpd grating will be quite insensitive to horizontal gratings of the same frequency. Estimates for the width of the tuning for orientation generally fall in the range of 5 to 20 degrees (see Olzak and Thomas[26]). Methods for determining orientation tuning are similar to those for spatial frequency tuning. For example, detection of a vertical grating would be masked by the presence of another grating oriented near vertical but not masked by a grating oriented at 45 degrees.

As noted previously, a two-dimensional spatial pattern can be decomposed into a set of sinusoids of varying amplitude, phase, frequency, and orientation. The set of spatial frequency channels can be thought of as filters that can selectively attenuate the components of specific frequencies (or orientations). The CSF is the sum of all of those filters. When it is "normal," the world looks normal. Deviations from the normal CSF produce deviations from normal vision that are the natural consequence of a different filter being used to modify visual input. For example, in a reasonably close encounter with a zebra, the highest frequency channels will be activated by the small details: hairs, a small spot, and so on. A loss in the high-frequency end of the CSF would cause a loss in the ability to resolve those fine details. Let us suppose that the stripes on the zebra are of medium spatial frequency. Because they are black and white "square-wave" stripes, they stimulate the medium spatial frequency channels *and* the high-frequency channels. The high-frequency channels are being stimulated by the sharp edge; they would not be stimulated by a sinusoidally striped zebra. If the CSF were depressed in the medium-frequency range, the high-frequency channels might note the edges of the stripes but the stripes would look "washed out" due to a lack of the normal response from the medium-frequency channels. The lowest frequency channels would respond to more substantial chunks of the whole animal: head, limbs, and so forth. A low-frequency loss might cause the animal to appear somehow indistinct while small details remain visible.

Clinical Uses of Contrast Sensitivity Testing

As already noted, the evidence for multiple spatial frequency channels is a strong argument against the use of a single visual acuity test as a measure of spatial vision. A condition that disrupts low-frequency channels may have no influence on acuity. There are numerous reports in the clinical literature of just this situation: clear disruption of spatial vision in spite of Snellen acuity of about 20/20 (e.g., cataract, Hess and Woo[46]; glaucoma, Ross[47]; macular degeneration, Loshin and White[48]; optic neuritis, Fleishman et al.[49]; anterior pathway compressive lesions, Kupersmith, Siegel, and Carr[50,51]). As described in the zebra example, low- or mid-frequency loss with normal acuity can lead to complaints that the visual scene looks washed out or indistinct even though the patient can read small print. These reports are easy enough to understand. Consider a 20/400 *E* on a Snellen chart. The edges of this letter stimulate high spatial frequency channels. The broad areas of black

stimulate medium- and low-frequency channels, while the sharp edges stimulate the high-frequency channels. If the medium- and low-frequency channels are not functioning properly, the edges will be seen normally while the bulk of the letter will provide a weaker than normal signal. A weaker signal is interpreted as reduced contrast, and the letter appears washed out.

There are at least four general uses for contrast sensitivity testing: screening, diagnosis, documentation, and tracking. At the present time, for each category, honest investigators may differ about the value of contrast sensitivity testing.

Screening

Contrast sensitivity testing could be made a part of many routine examinations, replacing or augmenting current acuity measures. For example, early cataract may have significant effects at medium and low spatial frequencies and might not be detected by an acuity measure.[10,46] Like most visual tasks, driving involves use of low and medium frequencies. Therefore, it has been argued that state driver's exams could use CSF and not acuity alone.[52] Screening tests need not be as accurate as tests done under laboratory conditions. Clinical constraints on testing will be discussed below.

Diagnosis

Many of the subsequent chapters in this book will deal with the effects of specific disorders on the CSF. While it is clear that a large number of disorders cause changes in the CSF, it is substantially less clear that the nature of that change is diagnostic of the disorder. Cataract, for example, produces a reduction in contrast sensitivity but the nature of that reduction may not be distinguishable from reductions due to other causes (e.g., diabetic retinopathy, Howes, Caelli, and Mitchell[53]; see discussion in Rubin*).

There are reports that some disorders produce specific "notches" in the CSF resembling those seen after adaptation to a specific spatial frequency (see Fig. 2.14) (e.g., multiple sclerosis, Regan, Silver, and Murray[54]). However, notches do not appear in all cases,[55] and some notches may be due to purely optical causes.[30] That said, CSFs are of some use in locating the source of a visual problem. For example, a loss that is restricted to medium and low spatial frequencies is unlikely to be optical in origin. As a different example, it might be possible to use contrast sensitivity testing in conjunction with acuity testing to detect psychogenic visual defects and/or malingering. An abnormal relationship between the two measures (e.g., 20/200 Snellen acuity with 20-cpd grating resolution) could be an indication of a problem without an organic cause.

Documentation

Cataract is a good example of a disorder that is easily diagnosed without the aid of contrast sensitivity testing. However, measurement of the CSF can serve to document the visual loss that accompanies the cataract. The degree of visual impairment can then be used as a guide to treatment. Similarly for other disorders, reduction in spatial vision can be quantified by comparing the patient's CSF with a standard (e.g., Vistech provides standard ranges for "normal" contrast sensitivity with its equipment). The ability to document loss has led to a desire for criteria for treatment. When is a loss in contrast sensitivity sufficient to warrant, for example, the removal of a cataract? Unfortunately, there is inadequate data on the impact of contrast sensitivity losses on normal visually guided behavior. With an acuity loss, it is possible to state the behavioral consequences fairly precisely. The patient might be unable to read standard newsprint or traffic signs. The behavioral impact of, for example, a 25% loss in overall contrast sensitivity is less clear. For CSFs the situation is further complicated because losses can be restricted to a range of frequencies.

A sensible approach might be to look at the area under the CSF. One can imagine a criterion that recommends removal of a cataract if the area under the CSF has been reduced by X% regardless of the spatial frequency specificity of the loss. At the present time, however, there does not appear to be firm scientific evidence to back any particular criterion.

That said, documentation remains an important use for the CSF. If a patient complains of problems with spatial vision in spite of 20/20 acuity, a CSF

* Rubin GS: Contrast sensitivity and glare testing in the evaluation of anterior segment disease. In press.

can document the presence (or absence) of a visual deficit and can be an argument for treatment or nontreatment, even if firm numerical criteria for treatment do not exist at the time.

Tracking

Tracking (longitudinal testing) is a logical extension of documentation. If a disorder causes a CSF change, the course of the disease and/or the effect of treatment may be tracked by repeated CSF measures. Cataract can be used again as an obvious example. Prior to treatment, the CSF may be tracked to determine when the visual loss warrants lens extraction. After removal of the cataract, recovery can be measured by longitudinal testing of the return of the CSF to normal. In cases of degenerative disease, CSF longitudinal testing can be used to monitor the rate of decline and, of course, the efficacy of treatment. In some cases, longitudinal testing of the CSF can reveal the presence of subtle residual deficits even after an acute condition has resolved (e.g., optic neuritis[49]).

In summary, in conjunction with acuity testing, contrast sensitivity testing provides a more accurate assessment of a patient's spatial vision than does acuity alone. At the present time it appears to be of more use in the quantification of visual loss than in the diagnosis of disorders. A clinician with some familiarity with the test should be able to use it to monitor the visual consequences of disease and of treatment.

Clinical Constraints on Psychophysical Methods

As discussed, there are psychophysically "correct" methods for obtaining CSFs. Two major factors act to undermine the use of these methods in clinical settings: the fact that patients are not trained, highly motivated psychophysical observers, and lack of time.

Patients as Psychophysical Observers

Two-alternative, forced-choice (2AFC) methods guard against blind guessing and, to some extent, against the unwillingness of observers to report the presence of near-threshold stimuli. These concerns remain important in a clinical setting. Patients may have very different motivations from those of a volunteer observer in a laboratory. They may wish to prove the existence of a problem, or its absence. They may be relatively uncooperative. Forced-choice methods can help to overcome these impediments to accurate measurement. The central elements of any such method should be a true forced choice. For example, is the stimulus in location 1 or 2? Is the grating tilted left or right or is it vertical? (Note: A three-alternative, forced-choice method as is used in many clinical contrast sensitivity devices is a perfectly valid method with properties only slightly different from those of the 2AFC.) Just as important, the patient should be "forced" (or cajoled or whatever) into making a response. If all tests are administered with consistent, firm instructions to make one of the designated choices, the effects of the patients' response criteria and biases will be reduced.

Clinical Shortcuts

The 2AFC staircase method outlined earlier in this chapter is reasonably efficient by laboratory standards but may still take too long for routine clinical use. Several shortcuts are possible based on the demands of the particular clinical situation and on some simplifying assumptions. The existence of six to eight spatial frequency channels suggests that no more than six to eight spatial frequencies need be chosen to obtain an estimate of the overall shape of the CSF. Great savings may be obtained with the further assumption that the CSF is roughly parabolic. If that is so, as a quadratic function the CSF could be completely specified by two free parameters. In practice, these numbers could be an acuity measure and a single contrast sensitivity measure designed to give the height of the peak of the CSF. Pelli, Legge, and Rubin[56] have proposed such a test and have presented data showing that abnormal CSFs can be treated as if they are normal CSFs (see Fig. 2.11) that are shifted either to the left (reduced acuity) or down (reduced sensitivity), or both. The two numbers required for their method can be obtained with two letter charts: one a version of a Snellen chart and the other a chart with letters of fixed, large size but decreasing contrast.[57] This method, appealing as it is, relies on the assumption that notches and other departures from the parabolic shape of the CSF are either nonexistent or at least of no clinical significance. As indicated previously, this assumption is controversial.

Without a strong assumption about the shape of the CSF, it is necessary to measure more than two points. However, particularly in screening tests where the clinical task is to simply distinguish between normal and abnormal findings, a high level of precision is not needed. Substantial savings in time may be effected by reducing the theoretical accuracy of the estimate of a point on the psychometric function that underlies threshold measures. An example is the Vistech contrast sensitivity (VCTS) wall chart that has been incorporated into a number of testing devices. In this test, patients do what amounts to a one-reversal staircase. For each of five spatial frequencies the patient is asked to identify the orientations of a succession of grating patches of decreasing contrast. There are three possible orientations, so this is a three-alternative, forced-choice situation (always assuming that the patient is required to respond, an assumption at variance with the test's published instructions). The estimate of threshold is taken as the contrast step higher than the first incorrect response. (This can also be considered a one-trial version of a "descending method of limits.")

Obviously, observer errors and guessing can adversely affect this measure.[57] However, with fairly widely spaced contrast steps, the chance of error is reduced, and tests of this sort do appear to provide a rapid estimate of the CSF that is comparable to the estimates obtained with other methods.[58] This type of test would be expected to identify individuals with abnormal CSFs and could give a reasonable estimate of the magnitude of the departure from normal. However, for more fine-grained use of CSF testing (e.g., detailed longitudinal testing of the CSF), it seems likely that more precise and thus more laborious methods will be needed.

A Note About Glare Testing

In a book entitled *Glare and Contrast Sensitivity for Clinicians*, a chapter on the basics of contrast sensitivity testing needs to say something about glare testing, if only that the two topics are logically separable. Glare testing refers to the measurement of visual function in the presence of a glare source. One could measure the CSF in the presence of a glare source. In fact, this is probably an excellent idea in early cataract (e.g., Rubin*). However, one could also measure acuity or color vision or motion detection or any other visual function in presence of the same glare source. From the point of view of contrast sensitivity testing, the glare source acts to degrade the stimulus by reducing the contrast of the stimulus image on the retina. The reduction will be a function of the position and intensity of the source and the light-scattering properties of the visual optics (see Chap. 4). If the glare reduces the retinal contrast below the detection threshold, the grating will not be seen, regardless of its physical contrast. This could be considered as a version of a masking paradigm (see previous discussion). Because of the possibility that light scatter of the glare source may have different effects at different frequencies, glare testing with the contrast sensitivity as the underlying measure is no doubt a good idea. Nevertheless, glare testing does not require a CSF, nor does measurement of the CSF require a glare source.

General Conclusions

Contrast sensitivity testing provides more information about spatial vision than do simple acuity measures. It tests optical and neural properties of the visual system that acuity measures cannot test. Accurate assessment of the CSF can be fairly time consuming but is possible within a clinical setting. Moreover, radically shortened methods can provide useful information. Firm criteria for basing treatment options on specific CSF test results await further research. It is clear, however, that CSF testing can document and quantify visual loss that other visual tests cannot measure.

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