CONTRAST SENSITIVITY

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THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Contrast sensitivity as a test of spatial function
- High spatial frequency limit to the CSF
- Comparison – Snellen acuity & spatial frequency
- Improving image quality

CONTRAST SENSITIVITY AS A TEST OF SPATIAL VISION

The testing of spatial vision makes up a large part of an optometrist's work, because we are very concerned with how well the patient sees images. This is important in itself, but also because sub-normal spatial vision may indicate an uncorrected refractive error or an ocular disease.

Snellen acuity is one way to test spatial vision, but a more complete description of spatial vision is the contrast sensitivity function (Figure 15-1). Also see and understand Schwartz, 2004 Fig. 7-11. It plots the limits of spatial vision; that is, the border between seeing and non-seeing. To test contrast sensitivity, we present a stimulus and vary two basic parameters:

- Stimulus size (spatial frequency)
- Stimulus contrast

In clinical contrast sensitivity tests, grating orientation is usually kept constant, to simplify the testing procedure.

To better understand contrast sensitivity (and visual acuity), consider what happens when you hold one of the variables, either size (spatial frequency) or contrast constant and vary the other. For example, how does the visibility of a target change if you keep its contrast constant, but vary its size? By making a target, such as a letter, smaller, it becomes harder to see, until it exceeds the visual acuity limit. When you decrease target size, you increase the spatial frequencies contained in the target, so this parameter change is indicated by moving from left to right on the CSF plot.

CONTRAST SENSITIVITY AS A TEST OF SPATIAL VISION (CONT.)

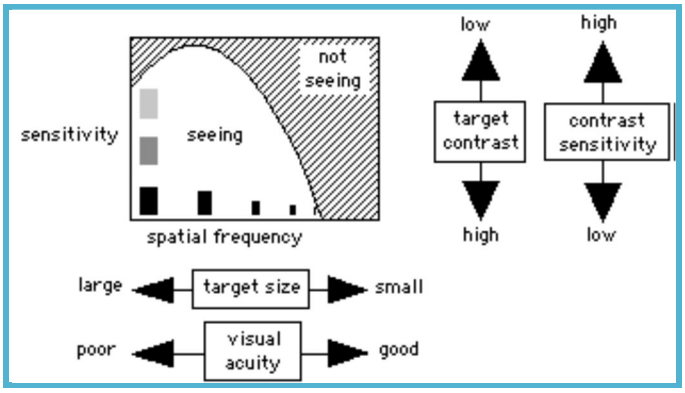

Figure 15-1: *CSF variables*

Or, we may keep target size constant, but decrease contrast until the target can no longer be seen. This parameter change may be indicated by a change in the vertical direction on the CSF plot.

In either approach (constant-contrast/change-size or constant-size/change-contrast), the endpoint of the test is when the person cannot see the target. We are therefore attempting to locate a point on the CSF curve that separates seeing and non-seeing. Note that Snellen visual acuity measures only one point on the CSF.

Q. Which point?

A. _____

To get a complete picture of a person's CSF, we should plot many points along the curve, but this can be time consuming. Instead, it may be sufficient to measure just enough points to judge the overall shape of the CSF. Figure 15-2 shows the data form used to record a patient's CSF using the Vector-Vision contrast sensitivity system (http://www.vectorvision.com). It measures just four points, at spatial frequencies of 3, 6 12 and 18 cycles per degree, so the test is fast and easy to perform. Since the spatial frequency equivalent of 20/20 is 30 cycles per degree, you should notice that the Vector-Vision test, as with other commercial contrast sensitivity tests, does not test contrast sensitivity out to the cut-off frequency (Fig.15-3). Rather, testing is limited to the low and mid-frequency range.

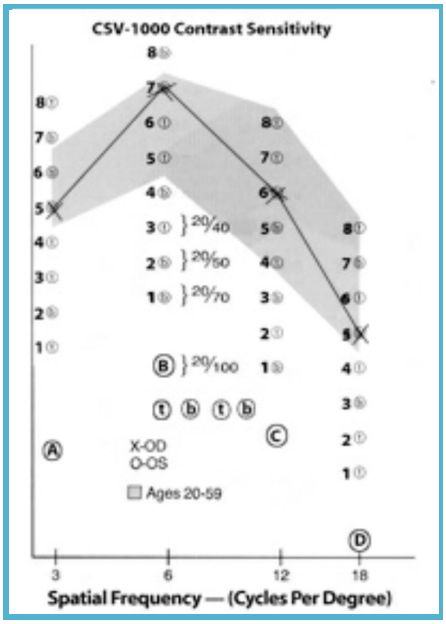

Figure 15-2: *Copy of the form provided by Vector-Vision, to record contrast sensitivity with their chart*

CONTRAST SENSITIVITY AS A TEST OF SPATIAL VISION (CONT.)

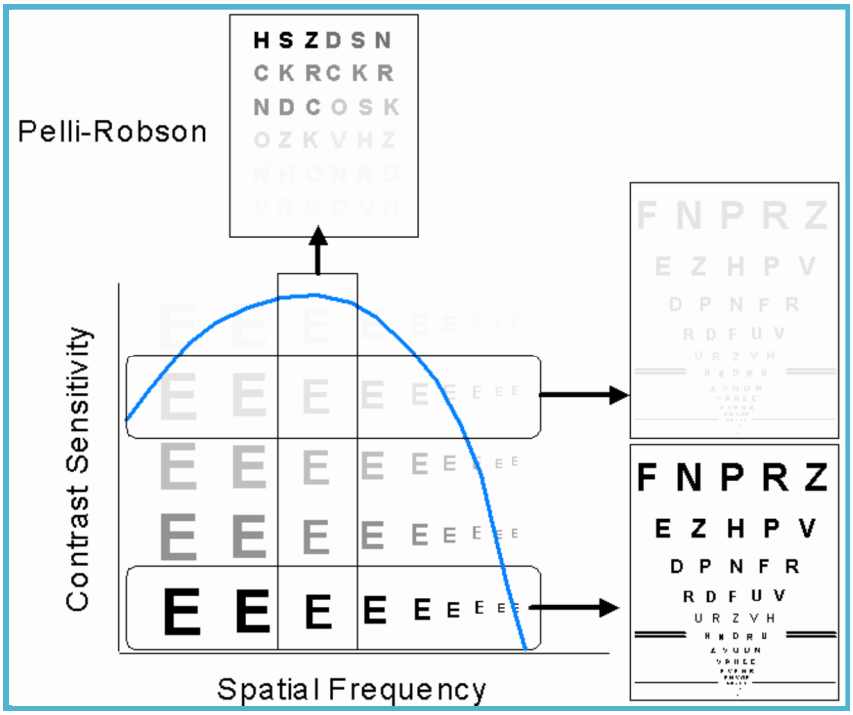

Figure 15-3: *Examples of vision charts that test either contrast sensitivity (top) or visual acuity (right; low contrast top, high contrast bottom). These are compared to the contrast sensitivity function. Copied from the British Society for Refractive Surgery web site*

HIGH SPATIAL FREQUENCY LIMIT TO THE CSF

The reduction in contrast sensitivity at high spatial frequencies is primarily due to the physical limitations of the eye's optics. That's why the shape of the human MTF and CSF are very similar for the high spatial frequencies. *For large pupil sizes*, it is primarily **aberrations** that degrade image quality and reduce the MTF to zero. *For small pupil sizes*, aberrations become insignificant and **diffraction** becomes the limiting factor. This assumes that the eye is healthy and has good optics; that is, a well-focused system (no refractive error) and no scatter (no cataracts, or media opacities).

There will be an even greater reduction in both the MTF and CSF at the high spatial frequencies if defocus (spherical refractive error) is added to the system. Schwartz, 2004 Fig. 7-13 illustrates what happens to the CSF when a person has an uncorrected refractive error. The cut-off frequency will be shifted to a lower spatial frequency. This means the person requires a larger size letter to read the acuity chart.

What if you had perfect optics? What would then limit the highest spatial frequency that a person could see? It would then be limited by the spacing of the photoreceptors. This is illustrated in Figure 15-4, below, and Schwartz 2004 Fig. 7-12.

The smallest grating that can be resolved is found when the width of a dark bar or light bar (half cycle) is equal to the diameter of one cone photoreceptor. Keep in mind that we are considering foveal vision, in which each cone is connected to one ganglion cell, and spatial summation areas are equal to one cone diameter.

HIGH SPATIAL FREQUENCY LIMIT TO THE CSF (CONT.)

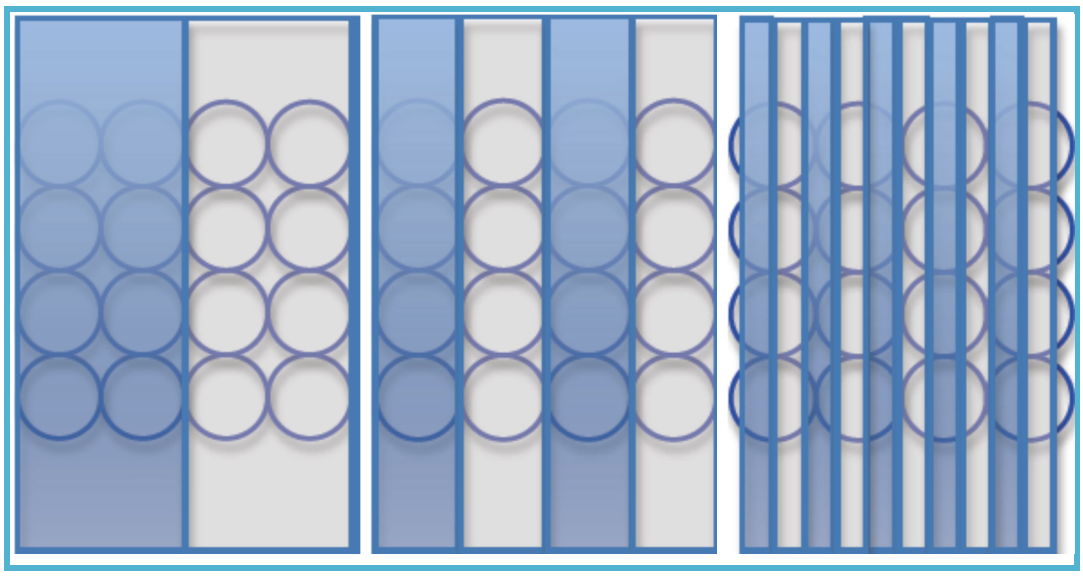

Figure 15-4: *Broad stripes (left) cover multiple photoreceptors and are easily resolved.If a stripe width equals one photoreceptor diameter (middle), the grating is still resolvable. If the stripes are narrower than a single photoreceptor (right), the array can no longer resolve the stripes.*

For higher spatial frequencies than this (finer gratings), both white and dark bars may fall on one photoreceptor, and it will not be able to resolve them as two. Therefore, the smallest resolvable grating is one in which one complete cycle is equal to the width of two photoreceptors. In other words, *it takes a minimum of two photoreceptors to correctly resolve a grating pattern.*

This is stated in the **Nyquist theorem**, which, in effect states (in the case of vision), that the highest spatial frequency that the foveal cones can correctly resolve is the frequency whose half-cycle width is equal to the width of one cone.

Based on the Nyquist theorem and the dimension of the foveal cones, we can compute the theoretical limit to spatial resolution, which is set by the diameter of a foveal cone:

- Foveal cones are about 2 µm in diameter
- One cycle requires two cones, so the width of one cycle is 2 x 2 µm = 4 µm
- One degree on the fovea is about 300 µm wide
- How many cycles (each 4 µm wide) will fit into one degree (300 µm wide)? 300/4 = 75

$$\frac{300\ \mu\text{m/degree}}{4\ \mu\text{m/cycle}} = 75\ \text{cycles/degree}$$

- This is the **Nyquist frequency**, or the cut-off frequency determined by the geometry of the cone array. In other words, this is the highest spatial frequency that a normal human eye could resolve if it had perfect optics
- To convert spatial frequency to the Snellen equivalent, divide 600 by 75 (See note below.). The equivalent of 75 c/d is 20/8 (6/2.4). Therefore, if you had perfect optics, the foveal cone array would limit visual acuity to about 20/8 (6/2.4)

COMPARISON – SNELLEN ACUITY & SPATIAL FREQUENCY

When comparing the fundamental frequency in a Snellen letter or square wave grating with the corresponding sine wave grating, you can convert the Snellen fraction to the equivalent spatial frequency (for the fundamental frequency) in cycles per degree (Fig.15-5) by using the simple conversion factor of 600 shown in the equations below:

$$\text{cpd} = \frac{600}{\text{Snellen denominator}}$$

$$\text{Snellen denominator} = \frac{600}{\text{cpd}}$$

Figure 15-5: *Considered as a visual stimulus, there are obvious similarities between a Snellen E (left) and a square-wave grating (middle), and between a square-wave and sine-wave grating (right)*

IMPROVING IMAGE QUALITY

The contrast sensitivity function provides a complete way to describe the quality of a person's spatial vision—that is, how well he/she sees images. If we improve a person's vision, we will see an improvement in his/her contrast sensitivity function. Two CSF curves are shown in Figure 15-6. The solid curve is higher and extends farther to the right. It describes an eye with better vision than the lower curve.

- A CSF farther to the right indicates better visual acuity—the person can see a smaller object
- A higher CSF mean better contrast sensitivity—the person can see an object with lower contrast

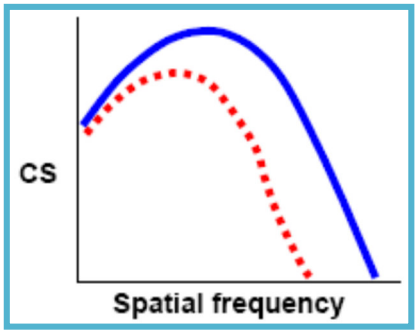

Figure 15-6: *The upper curve indicates a better CSF*

The most common way we improve the spatial vision of our patients is by correcting refractive errors. This expands the CSF by moving the curve farther to the right and increases its height.

In low vision, a person may have reduced visual acuity due to macular disease. In this case, the problem is not a refractive error; the retina limits the best visual acuity this person can achieve. We can help these patients with optical magnifiers. In terms of the CSF, what does a magnifier do? It increases the size of the retinal image, which is equivalent to reducing its spatial frequencies. This is illustrated in Figure 15-7 by Arrow A, which starts from a point outside the CSF (invisible), and moves to the left, to a point inside the CSF (visible).

IMPROVING IMAGE QUALITY (CONT.)

Another way to improve visibility of objects is to increase contrast. Arrow B in Figure 15-7 illustrates this. An invisible object with low contrast (above the CSF) becomes visible when its contrast is increased to the point that it falls within the CSF. Optometrists use this technique to improve visibility of corneal abrasions by adding fluorescein to the tears. In white light, a clear abrasion has such low contrast against the transparent cornea that it is invisible. With fluorescein, however, the abrasion glows in high contrast to its background (Fig.15-8). Fluorescein angiography is used to improve visibility of subtle retinal lesions, such as neovascularization, by enhancing contrast. An example is shown in Figure 15-9.

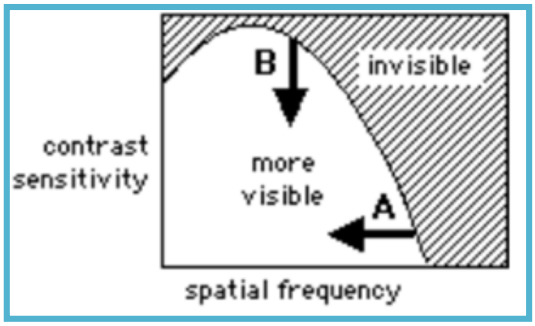

Figure 15-7: *Two ways to improve visibility*

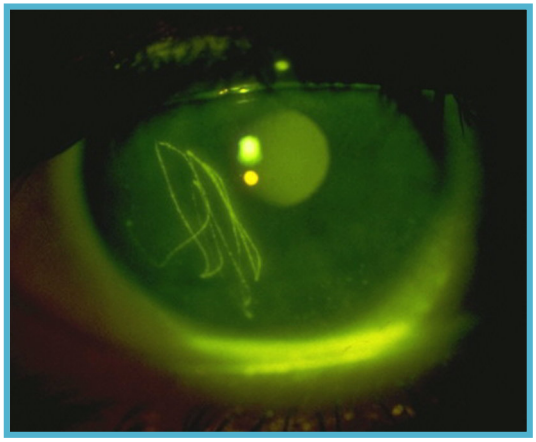

Figure 15-8: *Corneal abrasion with fluorescein. (Copied with permission of Dr. Ralph Latimer)*

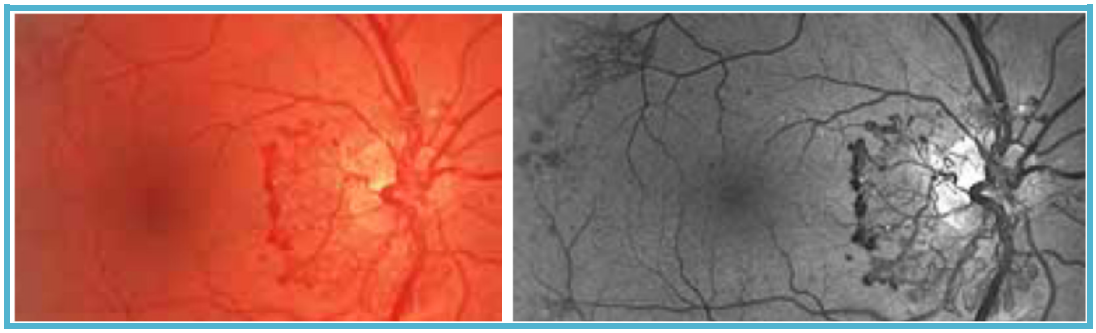

Figure 15-9: *Two images of the same diabetic retina, without and with fluorescein angiography. The retinal vasculature, including the neovacularization, is more visible due to higher contrast*

IMPROVING IMAGE QUALITY (CONT.)

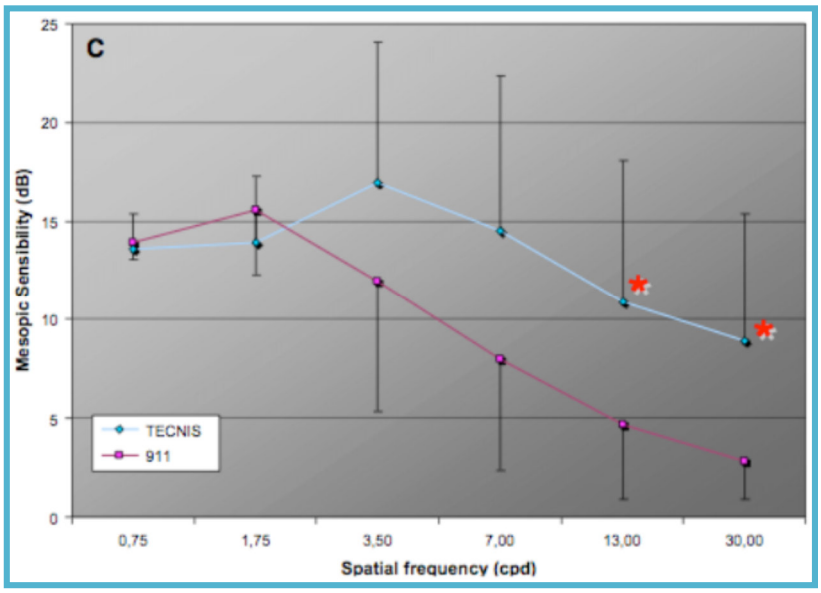

Figure 15-10: *Example of a contrast senstivity function*

The February 2007 issue of the Journal of Cataract and Refractive Surgery (JCRS): *Quality of vision after cataract surgery after Technis 9000 implantation* compares the mean visual performance of two IOLs in mesopic conditions (Fig 15-10). Tested on 40 eyes in each group 6 months post-op. The mean postoperative best-corrected visual acuity (logMAR) was 0.03±0.05 (mean±SD) in the Tecnis group and 0.01±0.05 in the CeeOn Edge 911 group (P = 0.41). They also evaluated optical performance and found a mean Z_4^0 = 0.01±0.06 µm for the Tecnis IOL and Z_4^0 = 0.16±0.12 µm for a 5.0-mm pupil.

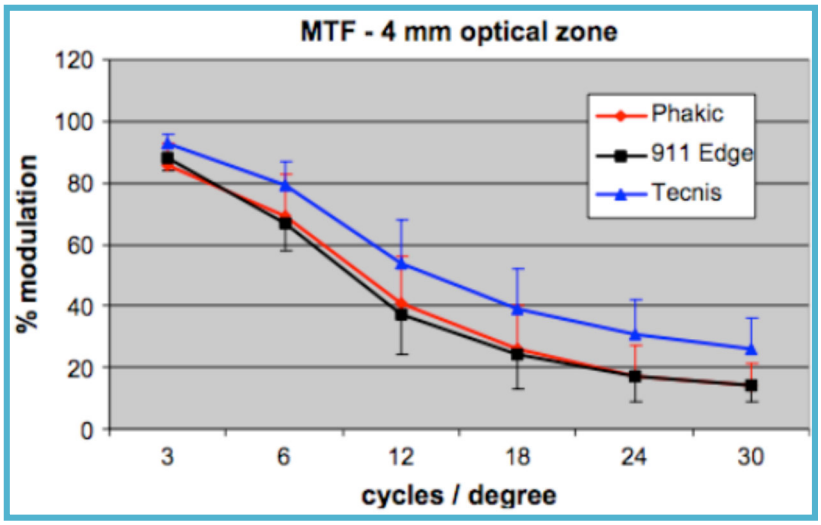

Figure 15.11: *Example of an MTF*

From the same issue of JCRS - Belluci et al. Spherical aberration and coma with an aspherical and a spherical intraocular lens in normal age-matched eyes. - Journal of Cataract and Refractive Surgery. 2007 33 2:203-209 - the mean aberration values for 30 eyes in three groups was studied and compared to the MTFs for three IOLs (see Fig 15-11).

SELECTED READING/REFERENCES

- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004