TEMPORAL SUMMATION, STILES-CRAWFORD EFFECT

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THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Ricco's law
- Temporal summation and Bloch's law
- Stiles-Crawford effect
- Summary of duplex retina

RICCO'S LAW

Ricco's law (spatial summation) states that within the critical diameter, the total number of quanta necessary for threshold detection remains constant. Quoting from Schwartz, p. 47:

Total spatial summation is represented mathematically by Ricco's law:

$$IA = K$$

Where,
I = stimulus intensity (quanta/area)
A = stimulus area
K = constant

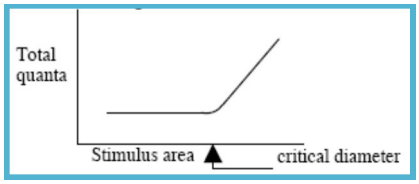

Figure 10-1: *Ricco's law*

Notice that, according to Ricco's law, the thing that remains constant is the product of I times A, not I. You can verify this by computing the units in the equation. The product of I (quanta/area) and A (area) is a value in quanta, since the area terms cancel. As stated in Ricco's law, within the critical diameter, the number of quanta needed to reach threshold remains constant.

$$\left(\frac{\text{quanta}}{\text{area}}\right)\left(\frac{\text{area}}{1}\right) = \text{quanta}$$

On the other hand, if you change the value for A (i.e., spot diameter), the value for I cannot be constant, but must be changed so that I times A remains constant. In order for I times A to remain constant, I and A must have a reciprocal relationship. The following table demonstrates this:

RICCO'S LAW (CONT.)

Table 10-1: *Relationship between I and A*

I (QUANTA/AREA)	AREA	K (CONSTANT)
10	1	10
5	2	10
2	5	10
1	10	10

Consider the following example test question:

Q. According to Ricco's law (spatial summation), as long as the spot is smaller than the critical diameter, the intensity (quanta/area) necessary for threshold detection

A. Will remain constant for all spot sizes.

B. Must increase with increasing spot size.

C. Must decrease with increasing spot size.

D. Is unrelated to spot size.

TEMPORAL SUMMATION AND BLOCH'S LAW

Just as the visual system sums the light it collects across an area, it also sums light collected over time. The time period over which light is summed is the **critical duration**. Summation over time is referred to as **temporal summation**.

The scotopic system has a relatively long critical duration of 100-200 msec; all the light collected within this time period is summed and treated as one light flash. If the total number of quanta exceeds the detection threshold, the light will be seen. No matter how many flashes are presented within the critical duration, they will all be seen as one. In order for two flashes to be temporally resolved as two, they must be separated in time by at least the critical duration. Schwartz Fig. 3-18 illustrates this.

The photopic system has a relatively short critical duration of 10-50 msec as illustrated in Schwartz Fig. 3-19. In order for the quanta from two flashes to sum, they must be presented in very rapid succession. This gives the photopic system high temporal resolution, but poorer sensitivity than the scotopic system.

The critical duration for temporal summation can vary with test conditions. The longer critical duration of the scotopic system allows it to collect photons over time, when few photons are available. The critical duration is not affected by wavelength.

The temporal equivalent of Ricco's law (spatial summation) is **Bloch's law for temporal summation**. It states that, within the critical duration, the total number of quanta needed to reach threshold remains the same for different flash durations. Beyond the critical duration, the light required for detection increases (Schwartz Fig. 3-20). This is expressed by the formula:

$$I(t) = K$$

Since 'I' is expressed in terms of quanta/time, the product of 'I' and 't 'is the total number of quanta required for detection. Bloch's law is also known as **time-intensity reciprocity**, since a decreasing intensity (I) is needed to detect the light as the duration (t) increases. Within the critical duration, intensity and duration are inversely proportional; that is, they have a reciprocal relationship.

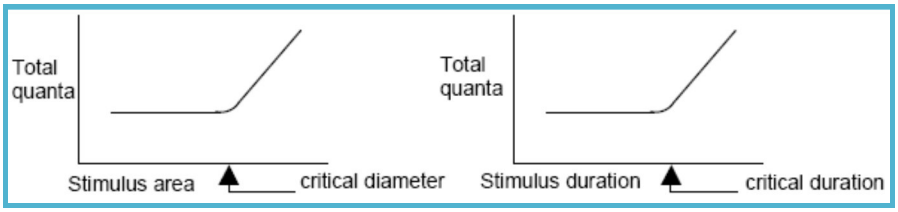

Figure 10-2: *Side-by-side comparison of spatial and temporal summation*

HYPOTHETICAL EXAMPLE OF BLOCH'S LAW

Bloch's law (temporal summation) holds within the critical duration. What happens beyond the critical duration? Then, Bloch's law no longer applies, and the number of quanta contained in the light must be increased, as illustrated by the ascending portion of the right curve in Fig. 10-2.

Figures 10-3 to10-7 demonstrates Bloch's law using hypothetical data from an experiment that measures the light detection threshold for various exposure times (durations).

Assume the critical duration is 4 msec and 20 quanta must be delivered within that time to be seen. In Figure 10-3, a light with duration of 1 msec, and intensity of 20 quanta/msec is presented. The total number of quanta delivered during that flash is 20 quanta/msec x 1 msec = 20 quanta. All 20 quanta fall within the critical duration, therefore the light will be seen.

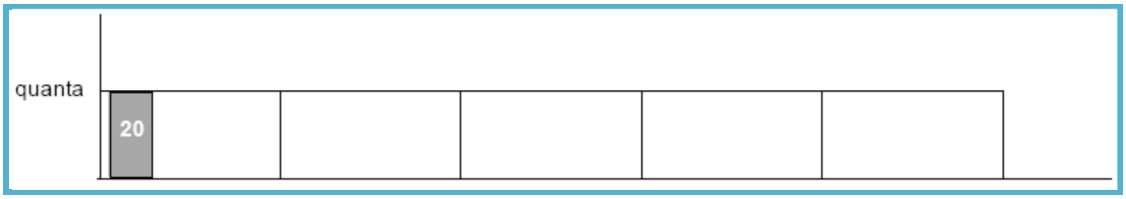

Figure 10-3: *A 1-msec flash with an intensity of 20 quanta/msec*

In Figure 10-4, a light with duration of 2 msec, and intensity of 10 quanta/msec is presented. The total number of quanta delivered during that flash is 10 quanta/msec x 2 msec = 20 quanta. All 20 quanta fall within the critical duration, therefore the light will still be seen.

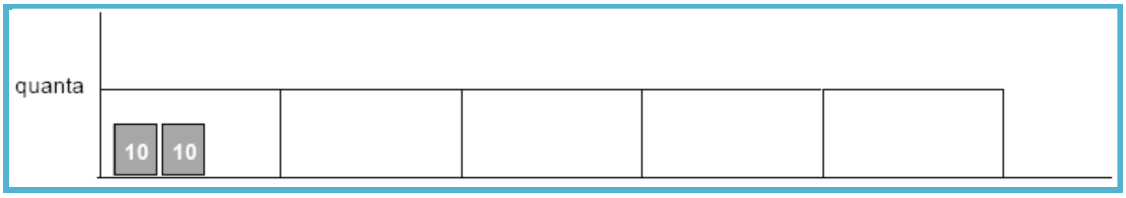

Figure 10-4: *A 2 msec flash with an intensity of 10 quanta/msec*

In Figure 10-5, a light with duration of 4 msec, and intensity of 5 quanta/msec is presented. The total number of quanta delivered during that flash is 5 quanta/msec x 4 msec = 20 quanta. All 20 quanta fall within the critical duration, therefore the light will still be seen.

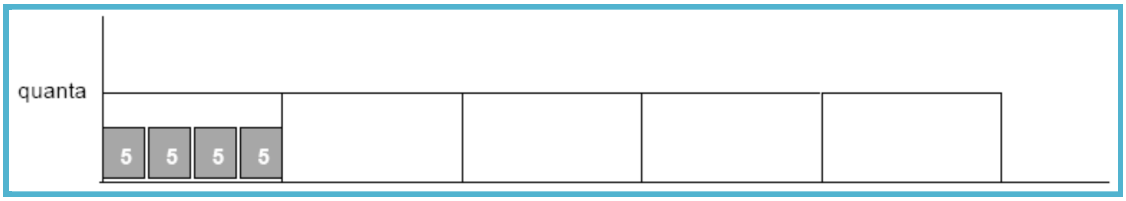

Figure 10-5: *A 4-msec flash with an intensity of 5 quanta/msec*

In Figure 10-6, a light with duration of 5 msec, and intensity of 4 quanta/msec is presented. The total number of quanta delivered during that flash is 4 quanta/msec x 5 msec = 20 quanta. Not all 20 quanta fall within the critical duration; only 16 do. This is not sufficient to meet threshold, so the light will not be seen. We will have to increase the intensity to 5 quanta/msec for detection. Now, if the 5-msec light has an intensity of 5 quanta/msec the total quanta will be equal to 5 quanta/msec x 5 msec = 25 quanta. Of these, 20 fall within the critical duration, and the light will be seen.

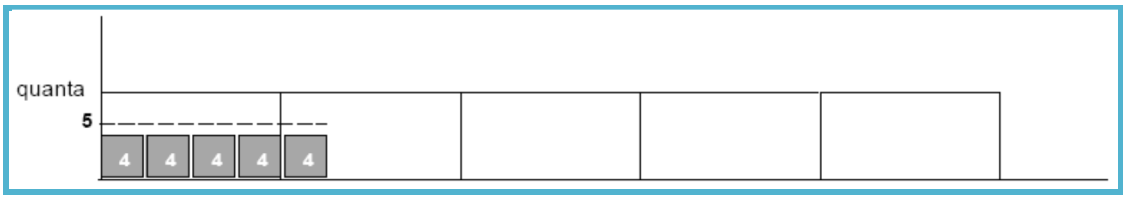

Figure 10-6: *A 5-msec flash with an intensity of 4 quanta/msec*

HYPOTHETICAL EXAMPLE OF BLOCH'S LAW (CONT.)

In Figure 10-7, the light has duration of 10 msec and an intensity of 4 quanta/msec. The total number of quanta delivered during the flash is 4 quanta/msec x 10 msec = 40 quanta. However, of these 40 quanta, only 16 fall within the critical duration, and this is insufficient for detection. We must increase the intensity to 5 quanta/msec. Then, the total quanta delivered will be equal to 5 quanta/msec x 10 sec = 50 quanta.

Figure 10-7: *A 10-msec flash with an intensity of 4 quanta/msec*

The results of this hypothetical experiment are recorded in Table 10.2 below and plotted in Figure 10.8.

Table 10-2: *Total quanta needed for detection for various durations.*

	INTENSITY (QUANTA/MSEC)	DURATION (MSEC)	TOTAL QUANTA
FIGURE 10-3	20	1	20
FIGURE 10-4	10	2	20
FIGURE 10-5	5	4	20
FIGURE 10-6	5	5	25

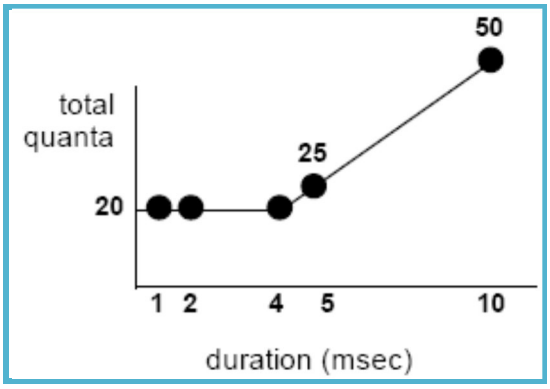

Figure 10-8: *Table 10-2 data plotted*

STILES-CRAWFORD EFFECT

Narrow pencils of light that enter the peripheral parts of the pupil, after refraction, strike the retina at increasingly oblique angles compared to axial pencils, which strike the retina more perpendicular to its surface. Because cones behave like **wave-guides**, and funnel light from their inner segments through to the outer segments, they capture photons most effectively when the incident beam strikes directly along its axis. This is illustrated in Schwartz Fig. 3-21.

Beams that enter the cone at a larger angle from parallel to the cone are less effective at stimulating cones. Because of this, light that enters the periphery of the pupil appears dimmer than light entering axially. This is known as the Stiles-Crawford effect of the first kind, or just the **Stiles-Crawford effect (SCE)**. The Stiles-Crawford effect of the second kind relates to color vision.

STILES-CRAWFORD EFFECT (CONT.)

Quoting from an article in the Journal of the Optical Society of America by He, Marcos and Burns (October 1999 issue, p. 2363-2369)

> *The apparent brightness of a light changes as its entry point is moved from one location to another within the pupil of the human eye. This change in the relative luminous efficiency as a function of pupil location is called the Stiles-Crawford effect of the first kind (SCE-I). The change in entry-pupil position for the incident light is associated with a change in the angle of the light at the retina, and thus the luminosity change with pupil-entry position is a measure of the angular sensitivity of the cone photoreceptors. The peak location of the luminous efficiency function is interpreted as the location in the pupil toward which the cone photoreceptors are oriented. The luminous efficiency function is typically modeled as a Gaussian distribution (or, equivalently, log sensitivity is represented by a parabolic change with pupil location); that is,*

$$S_{pupil} = S_0 \times 10^{-\rho\{(x-x_0)^2+(y-y_0)^2\}}$$

Where, S_0 is the sensitivity at the location in the pupil with maximal luminous efficiency (located at position x_0 , y_0), x and y are the test positions within the pupil, and rho (in inverse millimeters squared) represents a space constant (the larger the rho, the higher the directionality).

Considering only a two dimensional cross-section of the pupil, two examples of the SCE are plotted in Figure 10.9, below. The narrower curve (greater directionality) shows the SCE measured objectively (ρ = 0.1), and the upper curve shows the results of psychophysical measurements (ρ = 0.06).

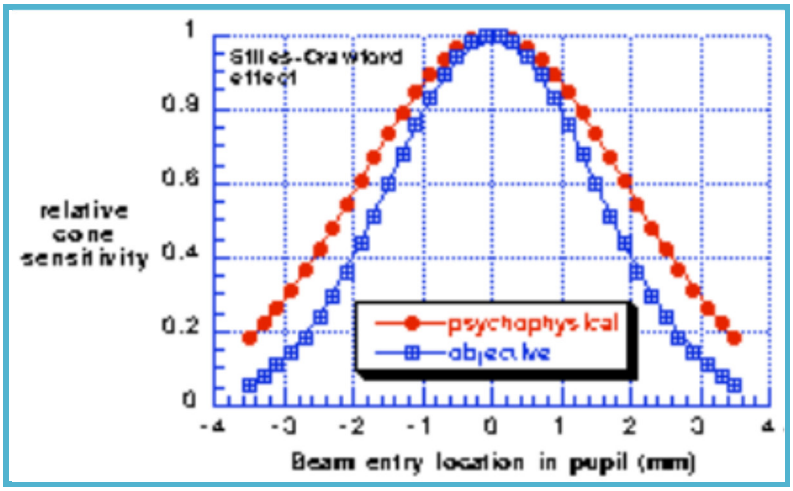

Figure 10-9: *Horizontal cross section of the SCE with rho values of 0.06 (upper, red curve) and 0.1 (lower, blue curve).*

CLINICAL IMPORTANCE OF THE STILES-CRAWFORD EFFECT

Susana Marcos, a scientist working at the Instituto de Optica 'Daza de Valdéz' (CSIC) in Madrid, Spain, suggested that measurement of the Stiles-Crawford effect might allow early detection of diseases of the photoreceptors: "Since normal photoreceptor directionality requires a normal cone morphology and relation to extracellular space, photoreceptor directionality has been of clinical interest."

(Marcos S, Burns SA. Cones spacing and waveguide properties from cone directionality measurements. J Opt Soc Am A16, 995-1004 (1999).)

There are other important clinical applications of the SCE. In refractive surgery, patients may experience poorer vision with large pupils because of large optical aberrations in the peripheral cornea. Patients with smaller pupils will probably have better vision following refractive surgery than those with large pupils. The SCE helps mitigate the adverse effects of peripheral aberrations since it reduces the light intensity of rays entering the peripheral pupil; rays entering the aberrated peripheral optics are therefore dimmer and will be less annoying. It is almost as if the pupil was covered with **apodizing neutral density filter** (Figure 10-10). The SCE can therefore reduce the **effective pupil size** to be smaller than the actual physical pupil size. Research by Salmon and West gives examples of the difference between actual and effective pupil sizes.

STILES-CRAWFORD EFFECT (CONT.)

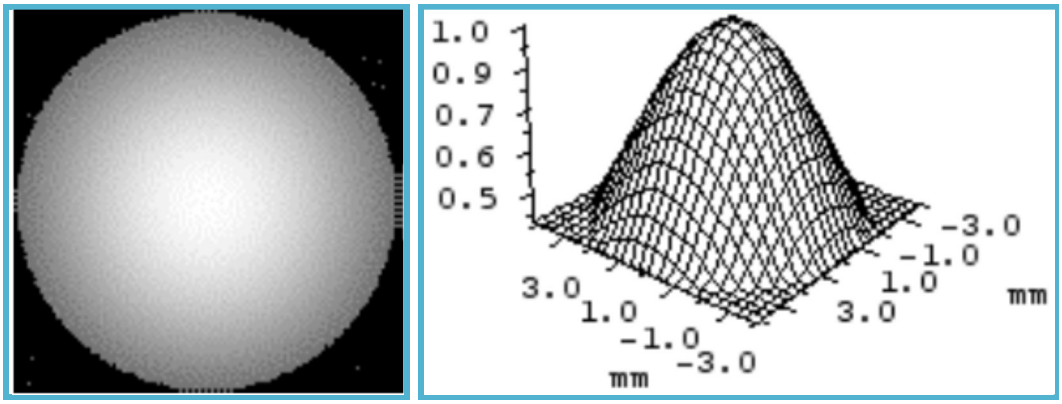

Figure 10-10: *The SCE is sometimes described as an apodization of the pupil, shown here by the grayscale plot (left) or the surface plot (right)*

Another benefit of the SCE is that it helps to reduce the effect of intraocular scattered light on the retinal image. Light scattered within the eye strikes the cones at an oblique angle, but because of the SCE, this light won't interfere as much with the light that forms the retinal image. Without the SCE, scattered light would "wash out" the image, reduce image contrast and degrade vision.

Cones are normally pointed toward the pupil center to maximize photon capture. If for some reason the pupil is decentered, the cones will gradually shift their orientations to point toward the new pupil center. Experiments have shown that if the pupil center is temporarily displaced, the cones will shift, and if the centrally located pupil is restored, the cones will re-orient themselves to the original positions (Schwartz Fig. 3-22). This shows that cones can move and orient themselves for maximum effectiveness.

There is no SCE for rods because rods inner segments do not act as waveguides, and as a result, rods do not receive any aberration-reducing benefit from the SCE. This, however, is not a problem since scotopic vision is incapable of good visual acuity anyway, due to the larger spatial summation zones. If, for example, aberrations blur the retinal image to the equivalent of 20/40, the affect of the aberrations will not be noticed since the scotopic system is only capable of 20/200.

In the case of scotopic vision, it is beneficial that the rods do NOT have a SCE. They accept light from a wider angle and therefore can collect more photons than cones. They, in effect, take full advantage of the full pupil diameter. The result is better sensitivity under reduced illumination.

Sample test questions on the SCE from the Optometry Examination Review book, by Casser et al, 1986 (Old review book):

#418 Which of the following contributors to 'stray light' within a young eye has the least effect on vision because of the Stiles-Crawford effect?

A. Scatter from the cornea

B. Scatter from the lens

C. **Reflections from within the retina**

D. Transmission through the iris

E. None of the above

#453 The visual effect of intraocular stray light that originates from light scattered by the neural retina may be reduced by

A. Maxwell's spot

B. **The Stiles-Crawford effect**

C. Birefringence of the fibers of Henle

D. The Troxler phenomenon

E. The Broca-Sulzer effect

SUMMARY OF DUPLEX RETINA

The duplex nature of our retina enables us to see over a very large range of illuminances, from the very low luminance on a dark night to that of a bright sunny day. Our eyes can adjust and see well over a 10 log unit difference in object luminance.

The scotopic system has been optimized to operate in low light conditions. It specializes in high sensitivity; that is, detection of objects in dim illumination, when photons are sparse. The following unique features of the scotopic system enhance sensitivity, but compromise visual resolution:

- Large spatial summation zones, which collect photons over a large area
- Long critical period for temporal summation, so it can collect photons over a long time period
- Absence of a SCE, so rods can collect photons over wide angle

The photopic system operates when light is abundant, so there is no need to “scrounge” for photons. It is designed to provide detailed information from the visual scene. Photopic vision provides us with excellent spatial resolution (visual acuity), high temporal resolution (motion perception) and color vision. The following features enhance resolution and detailed vision, but compromise sensitivity:

- Smaller spatial summation zones (in fovea, one cone per ganglion cell)
- Shorter critical period for temporal summation
- The cone wave-guide structure and motility give rise to the SCE, which reduces the influence of optical aberrations and scattered light (but also reduce photon capture)
- Three classes of photoreceptors, each of which has a different photopigment. This is the basis for color vision.

SELECTED READING/REFERENCES

- Casser Locke L, Chang FW, Gerstman DR and Pietsch PA. **Optometry Examination Review. Appleton & Lange**, 1986

- Marcos S, Burns SA. **Cones spacing and waveguide properties from cone directionality measurements**. J Opt Soc Am A16, 995-1004 (1999)

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