LIGHT ADAPTATION, WEBER'S LAW, SPATIAL SUMMATION

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THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Light adaptation
- Clinical application
- Spatial summation

LIGHT ADAPTATION

Just as your eyes adjust their sensitivity when going from light to dark, your eyes also have the capacity to adjust when moving from dark to light. This is called **light adaptation**. Light adaptation is studied by measuring the person's ability to detect a faint light against a uniform background (increment threshold) as you gradually increase the background luminance. This is illustrated in Schwartz, 2004 Fig. 3-15.

Schwartz Figure 3-15A shows the stimulus is a test light in the center of an annulus (ring) that serves as a background light. At first the subject adapts to a completely dark background (the annulus). The luminance of the center is then increased slightly above the background until he/she can just detect it. Next, the annulus luminance is increased. The subject adapts to the new background brightness and again determines the minimum luminance increment above the background that he/she can detect. The process continues with increasingly brighter background.

LIGHT ADAPTATION (CONT.)

Typical results of such an experiment are shown in Figure 9-1. Sections of the curve marked 1-4 show light adaptation for rods. After that the cones take over.

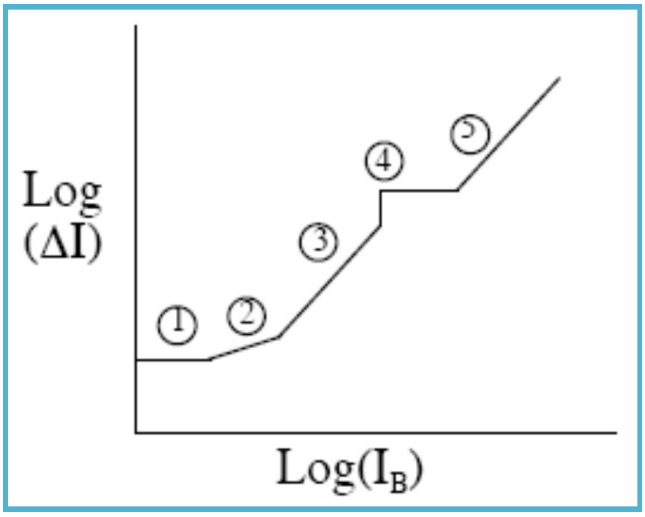

Figure 9-1: *Log of increment luminance (ΔI) plotted as a function of log background luminance (IB). Sections 3 and 5 have slopes equal to 1.0, which indicates that Weber's law holds over most of the scoptopic and photopic ranges, respectively. [Thanks to Andrew Carkeet, PhD (Singapore) for his suggestions on this figure. Compare this to Schwartz Fig. 3- 15]*

Note the following:

- **Section 1** - Very dark background, neural noise (or "dark light") determines the increment (ΔI) required for detection
- **Section 2** - Still very low background luminance; fluctuations in background (annulus) luminance largely determine the increment threshold. The DeVries-Rose law predicts that over this portion, the increment (ΔI) increases with the square root of background luminance (Ib)
- **Section 3** - Long section covering a 4-log unit range has a slope of about 1 (when plotted on log/log coordinates). This indicates that the increment (ΔI) increases as a constant proportion of the background because Weber's law applies. That is, over this range the increment threshold is a constant fraction of the background

The constant fraction is called **Weber's fraction or Weber's constant**, and we will be studying this in more detail later (Schwartz Ch. 11). Weber's fraction for rods is ~0.14. Therefore if the background luminance is 100, an increment of 14 above background is needed to detect the stimulus. If the luminance is 1000, the increment must be 140. This illustrates an important principle of visual perception. The eye is designed more to respond to relative differences in luminance (or ratios of light levels) rather than absolute levels of luminance. This is closely related to the concept of contrast, which we will also study in greater detail later.

It also means that sensitivity, in terms of the ability to detect an absolute increment, decreases with increasing illumination. This is necessary to allow the eye to operate over a wide range of illumination and is called **sensitivity regulation or gain control**.

- **Section 4** shows an infinite slope, and this indicates that the rods are saturated and at their limit. This actually occurs when only about ~10% of the rhodopsin is bleached
- **Section 5** shows the cone portion. It also shows a constant slope of 1.0 therefore, Weber's law holds for cones. Weber's fraction for cones is ~ 0.015. Cones therefore show a smaller relative reduction in sensitivity with increasing light than do the rods

LIGHT ADAPTATION (CONT.)

The most important point to observe in Figure 9-1 is that the slopes for Sections 3 (scotopic range) and 5 (photopic range) are equal to 1.0. On log-log axes, this occurs when the increment (ΔI) values are a constant fraction of the background (IB). This is consistent with Weber's law, which says that the increment threshold in a psychophysical task will be a fixed fraction (Weber's fraction) (Fig. 9-2) of the background.

The following table and figures show that, when Weber's law holds, and log increment threshold is plotted as a function of log background intensity, the slope is equal to 1.0.

Table 9-1: *Demonstration that when Weber's law holds, the slope of the log increment threshold, plotted as a function of the log of the background is equal to 1.0. This is true for any value for Weber's fraction.*

BACKGROUND	LOG BACKGROUND	INCREMENT (W = 0.14)	LOG INCREMENT	INCREMENT (W = 0.015)	LOG INCREMENT
0.1	−1.00	0.014	−1.85	0.0015	−2.82
1	0.00	0.14	−0.85	0.015	−1.82
10	1.00	1.4	0.15	0.15	−0.82
100	2.00	14	1.15	1.5	0.18
1000	3.00	140	2.15	15	1.18
10000	4.00	1400	3.15	150	2.18
100000	5.00	14000	4.15	1500	3.18

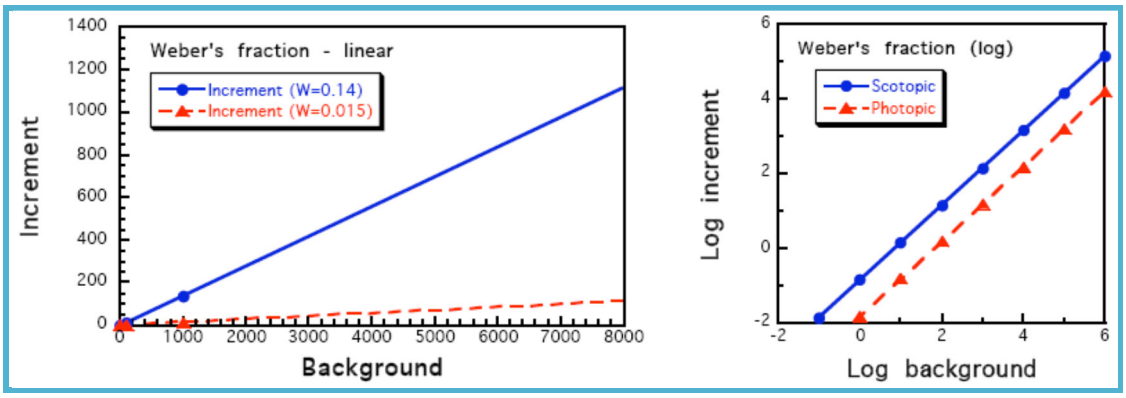

Figure 9-2: *When the relationship summarized by Weber's law is plotted on linear axes,the slope is equal to Weber's fraction. When plotted on log axes, the slope is equal to 1.0 for both lines*

CLINICAL APPLICATION

Weber's law has some important applications to clinical optometry:

LOOKING FOR CELLS IN THE ANTERIOR CHAMBER DURING A SLIT-LAMP EXAM

Injuries to the cornea or anterior segment often cause iritis, which releases scattered leucocytes into the anterior chamber. Doctors use this sign (cells in the anterior chamber), to diagnose and monitor iritis. For low grades of iritis, the cells are extremely difficult to see, especially for new clinicians. This is because the contrast of the tiny white cells against the dark background of the pupil is so low. You can increase contrast by increasing brightness of the slit-lamp. This increases the ΔI value, while the background (the black pupil) remains the same. If you increase ΔI to the point that it exceeds Weber's Fraction, the clinician will then be able to see the cells.

CLINICAL APPLICATION (CONT.)

VISUAL FIELDS TESTING

This was also an important consideration in the design of the Humphrey Visual Field Analyzer. Quoting from p. 21 and 22 of *Automated Static Perimetry*, by DR Anderson and VM Patella (2nd Ed., Mobsy, St. Louis, 1999):

> *The intensity of a perimeter's background illumination affects visual threshold. Most significantly, it determines the state of the light- versus dark-adapted retina. The visibility of a stimulus is not simply a matter of its luminous intensity; it also is affected by its contrast with the background illumination*.

The contrast of an object under view (a stimulus) with its background is in fact the governing factor for visibility under strongly photopic conditions. When threshold visibility strictly is a matter of contrast, the mathematical representation of threshold stimulus intensity is a constant if expressed as the contrast ratio (known as the Weber fraction) of the stimulus intensity to the background intensity (Weber's law).

There are theoretical advantages if perimetry is performed with a background sufficiently intense to have Weber's law operating. First, increasing or decreasing the pupil area has little effect on stimulus contrast because both background and stimulus are affected equally. Second, small changes in background intensity do not change the visibility of a stimulus if its intensity changes by an equal percentage. Goldmann took advantage of this principle to improve the reliability of his perimeter. It has only one light bulb, which supplies both the stimulus and the background lighting, and if the bulb varies in intensity (e.g., from variations in electric voltage), both the stimulus and the background intensities are affected equally - contrast, and thus stimulus visibility, stays more or less constant.

SPATIAL SUMMATION

In order to see under a broad range of light levels, we need the special features provided by both the scotopic and the photopic systems.

PHOTOPIC SYSTEM

- Operates when retinal illumination is high
- Light is abundant
- Designed to provide highly detailed vision; VA, contrast sensitivity, color vision etc.
- Compromises absolute sensitivity

SCOTOPIC SYSTEM

- Operates when retinal illumination is low
- Light is limited and photons are sparse
- Designed to provide maximum sensitivity: low detection thresholds
- Compromises quality of vision (poor VA [poor spatial resolution], no color perception, etc.)

Quoting from Schwartz, 2004 p. 44-45:

> *While visual resolution and contrast sensitivity are superior under photopic conditions, absolute sensitivity is greater under scotopic conditions. This trade-off between visual resolution and visual sensitivity is, to a large extent, due to the manner in which the rods and cones are connected to the post-receptoral elements of the retina. Rods are connected in such a manner as to sum up information over space and time. This produces great sensitivity, but poor resolution. Cones, on the other hand, manifest connections that maximize visual resolution at the expense of sensitivity*.

Schwartz Fig. 3-16 (top) illustrates the flow of information from a large array of rods that collect light over a large area and funnel their data into one ganglion cell. To interpret this figure, recall from the study by Hecht et al. that a minimum of 10 photons must be absorbed by a group of rods in close proximity in order to detect the light. Two relatively widely separated lights shine on a patch of retina containing many rods, all of which are connected to one ganglion cell. Since these rods all send information to the same ganglion cell, the effect of light stimulation of these rods is summed or pooled together and treated as one signal and one spot of light. In this case, the signal for 10

photon absorptions is combined. Note that the ganglion cell can only signal the presence of one light, even though two spots of light (5 photons each) are shining on this zone of the retina.

Schwartz Fig. 3-16 (bottom) shows the corresponding organization for cones. Fewer cones are connected to a single ganglion cell. They each cover a smaller area of the retina. Let's assume that the same stimulus as before (two faint spots, but more closely spaced) illuminates the retina. Assume that the threshold for detection of a light received by one ganglion cell is 10 photons worth of signal from the photoreceptors. We see that in this example, each group of cones pooling into each ganglion cell receives only 5 quanta of input from its respective set of cones. This is sub-threshold and no light will be seen. If, however, we double the brightness so that there are 10 photons in each spot, this will be sufficient to stimulate each ganglion cell. Since two separate ganglion cells are stimulated, the two lights will be resolved as two.

In the scotopic system, ganglion cells receive input from a large number of rods (300+). In effect, it integrates (adds up) all the input it receives within this area. This is known as spatial summation—the input collected across an area is summed and treated as one signal.

The benefit of spatial summation is that it allows us to see under very low light conditions. On the other hand, large spatial summation results in poor spatial resolution, that is, poor visual acuity. Scotopic visual acuity is only about 20/200 at best. Patients with cone dystrophies may have acuities of these levels.

Fewer cones are connected to a single ganglion cell; therefore cone spatial summation areas are smaller than those of the rods. The sizes of the spatial summation areas vary in different parts of the retina and they are smallest at the fovea where each cone photoreceptor has its own ganglion cell. This allows us to have very good visual acuity (i.e., 20/15 or better) in the fovea, but poor sensitivity for detecting dim lights. In general, diseases that affect the peripheral retina first, such as glaucoma, preserve visual acuity.

RICCO'S LAW

When you are trying to determine the minimum number of quanta that the eye can see, as Hecht et al did, how will target size affect the results? This depends on how big the spatial summation area is. In Hecht's case, he found that, as long as the light all fell within a 10-arc-minute diameter area, the total number of quanta needed to reach threshold was constant.

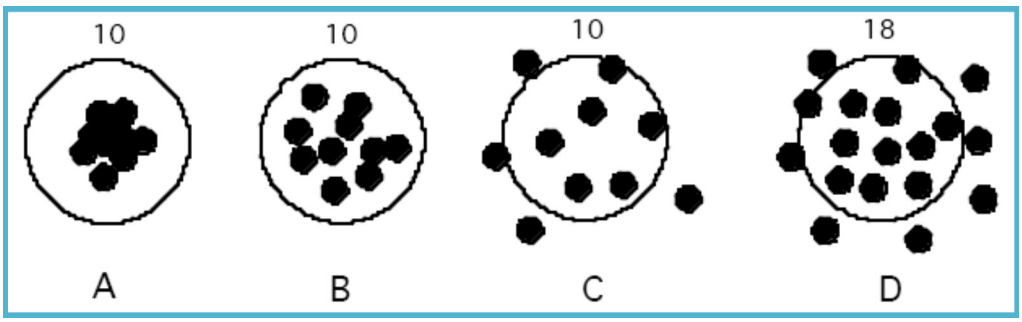

Figure 9-3: *Various distributions of ten photons across a spatial summation field on the retina.*

Figure 9-3 shows the spot pattern for lights of various sizes shining on one summation area. Each dot represents a photon. In A, the spot size is small and all photons fall within the summation area. In B, the spot is larger, but still smaller than the summation zone, so all photon are collected, and their signal is sent to one ganglion cell. In C, the spot diameter exceeds the summation zone and some photons fall outside the summation area. The summation zone therefore will collect fewer than 10 photons and a sub-threshold signal will be sent to the ganglion cell. The light will not be seen; that is, the now larger light is no longer sufficiently intense for the person to detect. In D, the spot size is the same as in C, but the photon density is higher, and a threshold number of photons now fall within the summation area.

If a total of ten quantal absorptions within the summation area are needed for detection, it doesn't matter how large the light is, as long as all the photons fall within the summation zone. If the light is larger than the summation zone, some of the photon will fall outside the summation area and the actual number of quantal absorptions within the zone will be less than ten. A larger light must contain more photons to ensure that at least ten will fall inside the summation zone.

Figure 9-4 illustrates **Ricco's law** based on the principle illustrated in Figure 9-3. Ricco's law is also described by the mathematical equation (I*A = K) that states that, within a **critical diameter**, the product of image area and light intensity (quanta/area) is constant. In other words, for any size area that is smaller than the critical diameter, the total number of quanta (I*A) needed to detect the light is constant. If the illuminated area exceeds the critical diameter, more quanta will be needed as indicated by the ascending portion of the curve in Figure 9-4.

SPATIAL SUMMATION (CONT.)

I*A = K

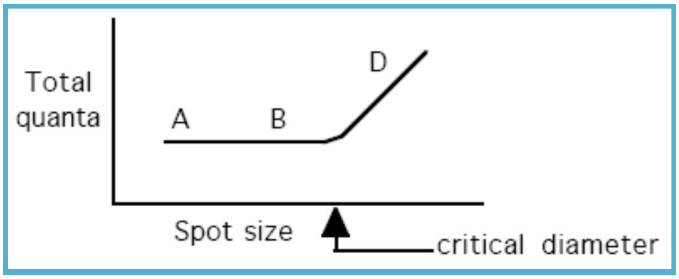

Figure 9-4: *Ricco's law*

Table 9-2: *Summary of the trade-off between sensitivity and visual acuity for the photopic and scotopic systems.*

SYSTEM	SUMMATION AREAS	SENSITIVITY	SPATIAL RESOLUTION
Scotopic	large (up to 300+ rods)	excellent	poor (20/200)
Photopic	small (fovea: 1 cone)	poor	excellent (20/15)

SELECTED READING/REFERENCES

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