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Temporal Resolution

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The eye can function over a large range of luminance levels; it must also be able to handle the different rates of change in luminance. Our eyes are constantly sampling information of images projected onto the retina in a periodic manner. Information is then integrated so objects around us appear to be stable or move smoothly. Because there is a finite amount of time required to collect and process information, there are limitations to the responsiveness of our visual system to rates of change. When intermittent stimuli are presented to the eye, they are perceived as separate if the rate at which they are presented is below a certain value. If the rate of presentation of the intermittent stimuli is slow, it appears to stay on but with changes in intensity, producing the sensation called flicker. Above a certain critical rate, the flicker ceases. This point is called the critical flicker frequency and is influenced by a number of factors. The first factor to be considered is the temporal summation property of the visual system.

Temporal Summation

Temporal Resolution and Temporal Summation

In the spatial domain, detection of two lights in space requires the appropriate detector array (Fig. 1). For us to discriminate the two lines, a response given by detector array C to F is required. All of these detector arrays provide a Yes-No-Yes response and thus allow the discrimination of the two lines.

In the temporal domain, the same principle applies, except now the stimulus is separated in time (Fig. 2). The separation between the two lines is in the temporal domain (two flashes are delivered) after a time interval t. The detector array now has different temporal integration times. For example, detector A integrates over time = t, whereas detector array B has an integration time of time = $0.5t$, array C, time = $0.33t$, and so on. Because of the shorter integration time for detector array C and beyond, such an array will be able to discriminate the two flashes that are separated by an interval of t.

To detect a flash of light one after the other, an appropriate integration time is required (Fig. 3). The period of integration is up to 0.1 seconds or 100 ms (for rods) and 10 to 15 ms for cones. The advantage of long integration time is that under limited light level conditions, a threshold will be reached, whereas when light levels are not limiting (cone or photopic vision), a short integration time is preferable to improve temporal resolution.

Temporal integration time is related to temporal summation. Temporal summation refers to the eye's ability to sum the effects of individual quanta of light over time. However, temporal summation only occurs within a

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certain period of time, called the critical duration or critical period. According to Bloch's law of vision, within this critical duration, the threshold is reached when the total luminous energy is reached. Bloch's law of temporal summation is analogous to Ricco's law of spatial summation. Bloch's law states that total luminous energy is a constant value (k), thus threshold is reached when the product of luminance (L) and stimulus duration (t) equals this constant. In other words, when luminance is halved, a doubling in stimulus duration is required to reach threshold. When luminance is doubled, the threshold can be reached in half the duration. Bloch's law is expressed as:

$$L \cdot t^{n} = k$$

where L is the luminance of the stimulus, t is the duration of the stimulus, k is a constant value, and n describes whether temporal summation is complete ($n = 1$) or partial ($0 < n < 1$). No temporal summation occurs when $n = 0$ (Fig. 4).

Critical duration is shorter for stimulus of high luminance as threshold is reached faster and slower for stimulus of low luminance as a longer period of time is required to sum the quanta to reach threshold. Temporal summation ceases beyond the temporal integration time. Above this value, threshold is dependent only on luminance rather than the product of luminance and duration.

Temporal summation is also affected by other test variables, such as background luminance and the size of the stimulus. Critical duration is longer for brighter background and smaller test stimuli. When temporal summation data areplotted as log$L$ t *versus* log$t$ rather than log$L$ *versus* log$t$ (as in Fig. 4), the slope of zero identifies Bloch's law (Fig. 5).

The above plots show that temporal summation is longer for low light levels, indicating the larger temporal summation characteristics for scotopic vision. As light intensity is increased, e.g., 25,000 trolands, the critical duration is of the order of 20–30 msec. The interrelationship between temporal integration and spatial summation is shown on the right panel, where Bloch's law is measured for different sizes of test stimuli. Decreasing test size results in increased temporal summation, and hence poorer temporal discrimination. We will investigate this phenomenon further when we review flicker discrimination for different sized stimuli in the next section.

Broca-Sulzer Effect

In addition to basic discrimination characteristics of temporal resolution, there are several interesting perceptual phenomena. One of these phenomena is the Broca-Sulzer effect, which describes the apparent transient increase in brightness of a flash of short duration. Subjective flash brightness occurs with flash durations of 50 to 100 milliseconds. This phenomenon is associated with temporal summation and explains the leveling off of brightness to a plateau. When the light is turned on, time is required for temporal summation to reach threshold for light of low luminance. Light of high luminance reaches this threshold very quickly. As flash duration increases, brightness levels off to a plateau as temporal summation begins to breakdown, according to Bloch's law, after the critical duration. The apparent transient peak in brightness is probably attributable to an underlying neural mechanism (Fig. 6).

Critical Flicker Frequency

Critical flicker frequency (CFF) is the transition point of an intermittent light source where the flickering light ceases and appears as a continuous light. There are a multitude of factors that determine our perception of flicker that includes the intensity and size of the test stimulus.

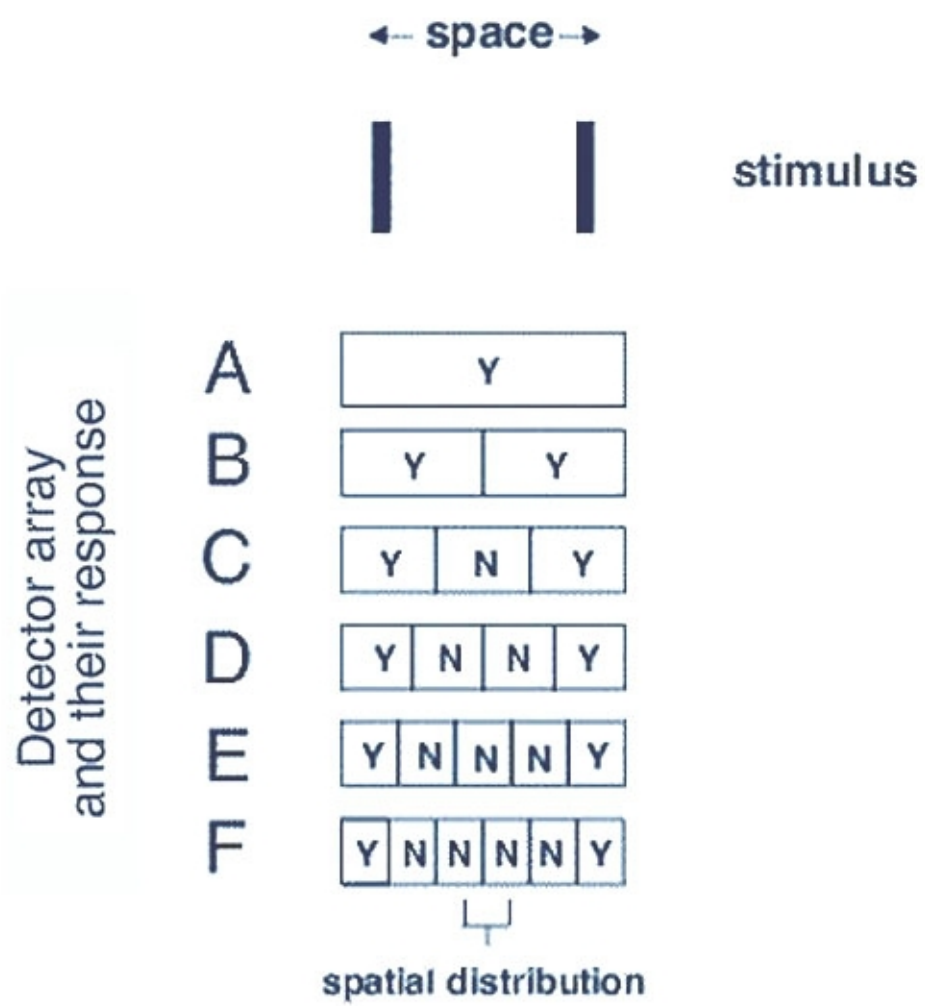

Figure 1. Detector array C and beyond allows the detection of the two lines.

Factors Affecting CFF

The **Ferry-Porter law** states that CFF is proportional to the logarithm of the luminance of flickering stimulus (L). It can be expressed as:

$$CFF = a \log L + b$$

where a and b are constants. With foveal observation, this relationship holds over a wide range (0.5 to 10,000 trolands) (Fig. 7). The above equation implies that when CFF is plotted as a function of log$L$, a straight line will identify the region where the Ferry-Porter law holds. As the intensity of the test stimulus is increased, our perception of flicker also increases. From a practical point of view, if a stimulus is flickering, such as computer monitor, decreasing the intensity level will eliminate the flicker.

Spectral Composition

Under photopic levels, lights of different wavelengths, when adjusted to match them for brightness, conforms to the Ferry-Porter law and follows the logarithmic function as brightness increases. However, under scotopic levels (rods functioning), the wavelengths fan out (Fig. 8). This is attributable to the different spectral sensitivities of the scotopic system to the photopic system. If plotted as scotopic photons, the bottom part of the

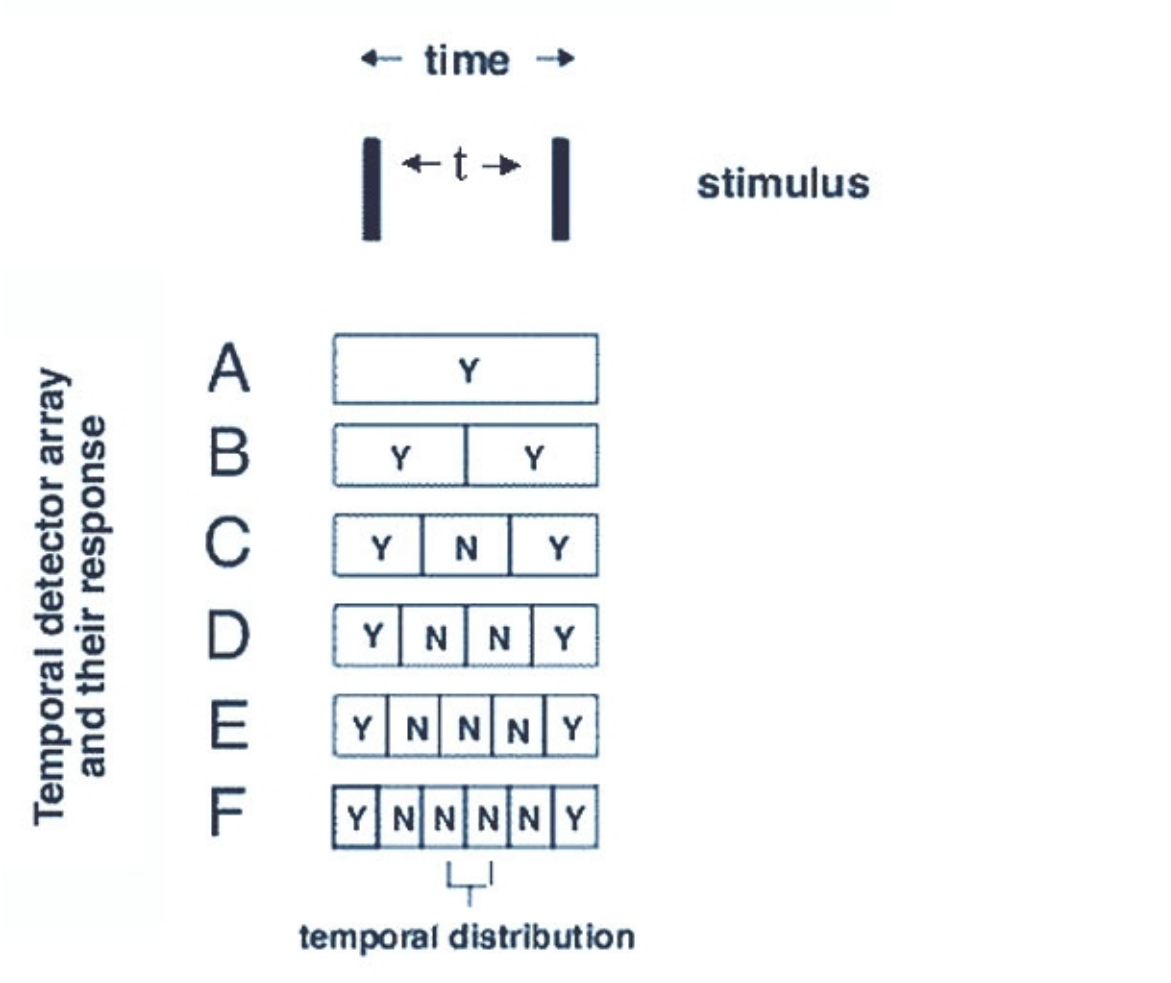

Figure 2. Speed of integration allows the detection of intermittent stimuli. Detector arrangement C and beyond allows discrimination of the stimuli over time.

curve would collapse into one and appear like the 19° curve in Fig. 10. Note that the temporal resolution to short wavelength test stimuli is different. However, in general terms, the plot below is correct, although the units chosen for the scotopic component (lower branches) give the misconception that temporal resolution is different for the rod system.

An important aspect of cone vision is that when the short-wavelength pathway is isolated (1), the temporal resolution is lower, close to 10–15 Hz, rather than the closer to 60 Hz for the longer wavelength pathways. This general phenomenon is characteristic of the short-wavelength pathway that is known to have larger spatial summation approximately 15' at about one degree eccentricity (the location of high S-cone density), whereas the longer wavelength pathways have a spatial summation of 4' (2). In the temporal domain, at high light levels, the S-cone pathways has a temporal summation time of approximately 100 ms, whereas the longer-wavelength cone pathway has a temporal integration of approximately 50 msec (3).

Retinal Position

Because the CFF is different for rod and cones, the CFF for the test field will depend on the proportion of rods and cones being stimulated. Because the proportion of rod and cones changes with eccentricity, a foveal test stimulus will follow the Ferry-Porter law and show no kink (one branch only) in the curve because only cones are present at the fovea. An extrafoveal test stimulus will show a kink (two branches) in the CFF function because the rods determine the CFF at low retinal illuminances and the cones determining CFF at higher retinal

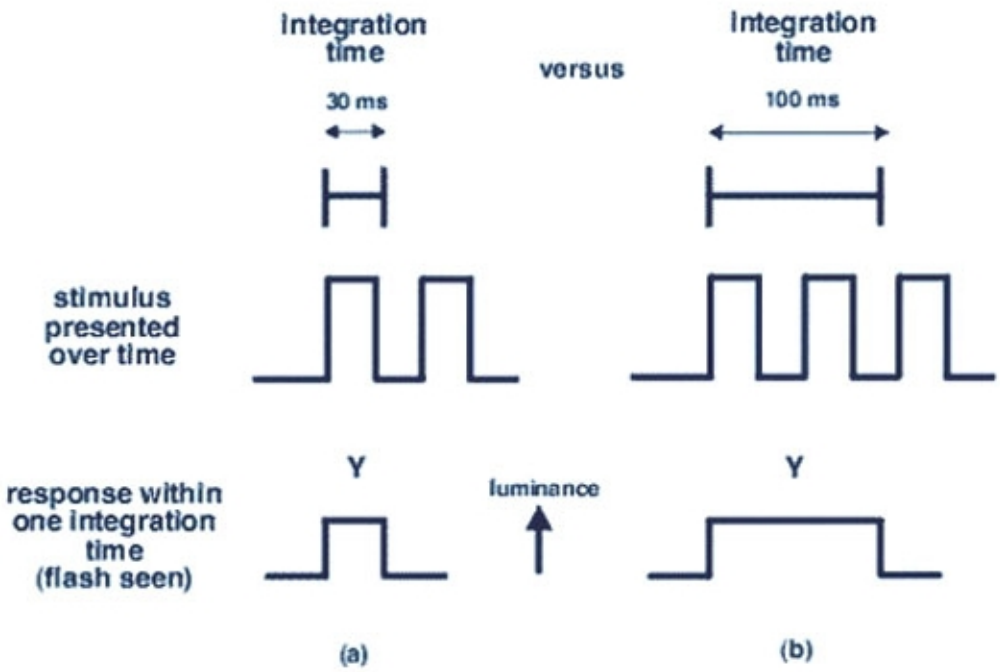

Figure 3. Flashes of light are presented to the eye. (a) With a short integration time, the flashes are detected. (b) No flashes are perceived (that is, the stimulus appeared as one bright flash) with a long integration time.

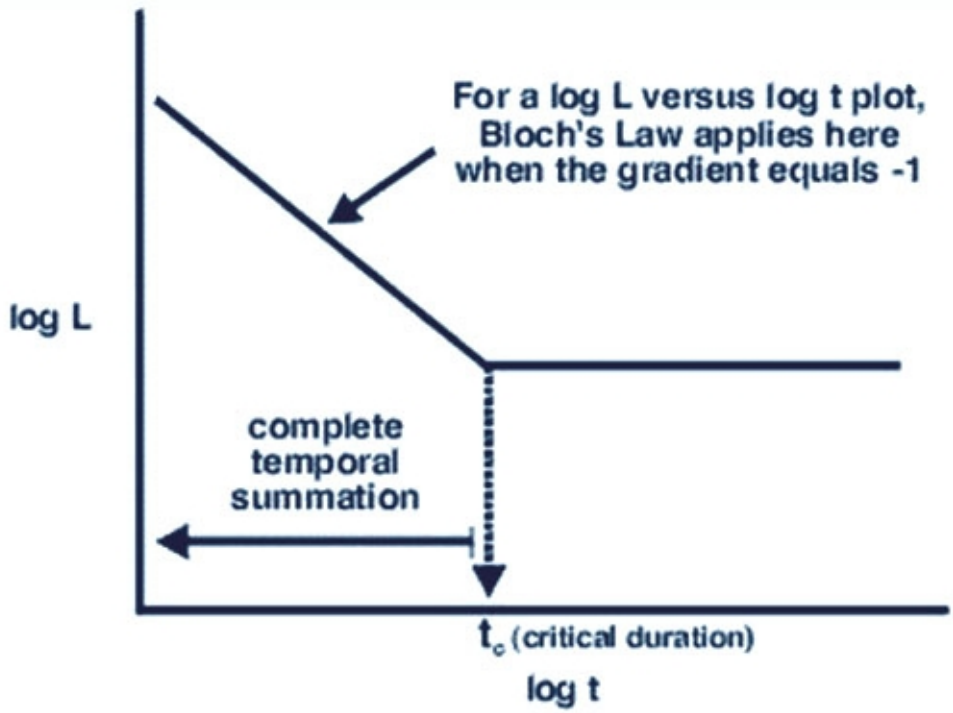

Figure 4. Temporal summation data plotted as log*L* *versus* log*t*, showing where Bloch's law applies.

illuminance. Note that the Ferry-Porter law applies over a decreasing range as the eccentricity increases, and that temporal resolution is poorer for eccentric locations (Fig. 9).

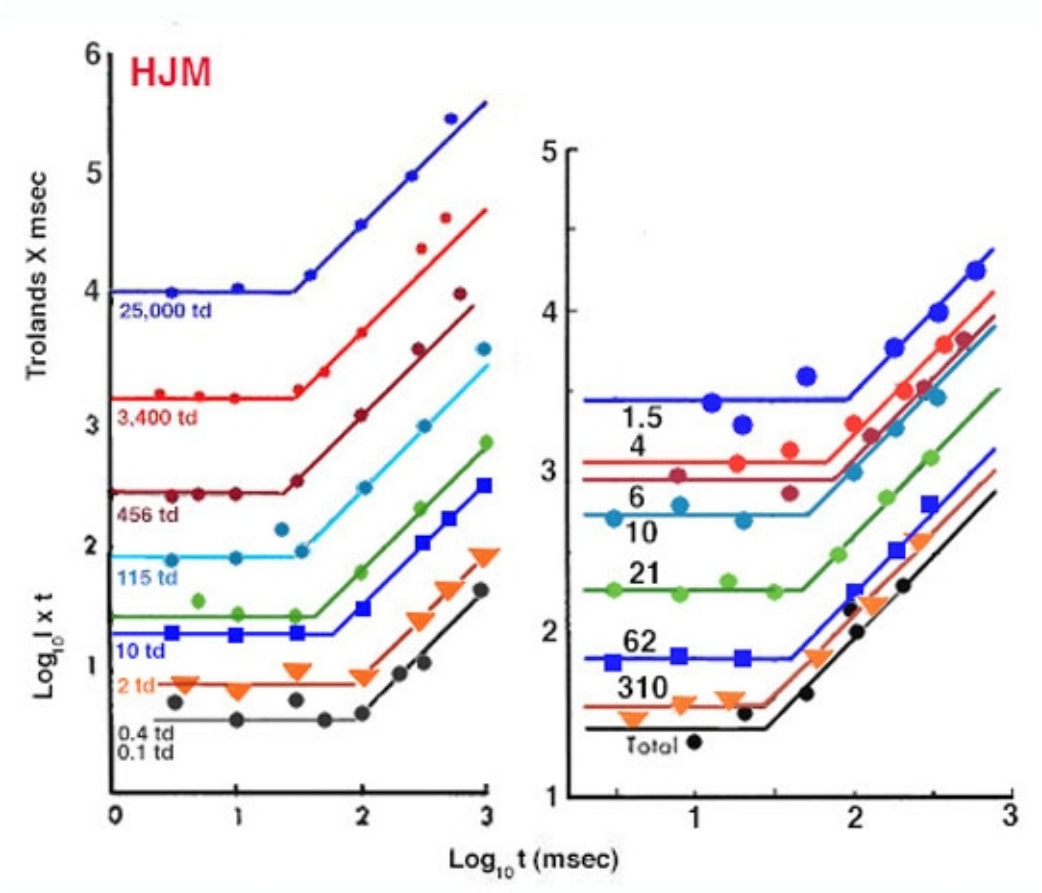

Figure 5. Luminance-duration *versus* time curves. Bloch's law holds when the gradient of the line is zero. Integration time (critical duration) can be determined from above. Beyond critical duration, Bloch's law breaks down (when the gradient is greater than zero). (a) 1° foveal test spot on different backgrounds. (b) Foveal test spots of different diameter (in minutes of arc) and for whole-eye stimulation (total). Kahneman and Norman's data from Hart (8).

The Ferry-Porter law has been further examined for a single cone type, using conditions that eliminate detection of the flickering stimulus by rods. Under these conditions, the law has been found to hold, despite changes in stimulus size or modulation amplitude (4). However, the slope of the Ferry-Porter law changes with eccentricity, becoming steeper with eccentrically presented targets. This latter finding is consistent with previous work, suggesting that there is an increase in the speed of photopic retinal responses in the periphery, once stimuli have been appropriately scaled (5). This increase in speed has been hypothesized to relate to the change in cone photoreceptor outer-segment length that occurs in the periphery (5). Such scaling has not been performed to the classic data sets presented here.

Size of Test Field

Because of the different populations of rods and cones in the retina and different spatial summation properties, CFF will be dependent on the area of the retina being stimulated. Instead of varying retinal eccentricity as above, the size of the centrally fixated test field is varied (Fig. 10). As the test field increases, two branches begin to appear. The lower branch represents rod function. The maximum CFF, and hence maximum temporal resolution, is achieved by large test targets that have the shortest integration time noted earlier.

The **Talbot-Plateau law** describes the brightness of an intermittent light source that has a frequency above the CFF. This law states that above CFF, subjectively fused intermittent light and objectively steady light (of equal color and brightness) will have exactly the same luminance. In another words, brightness sensation from the

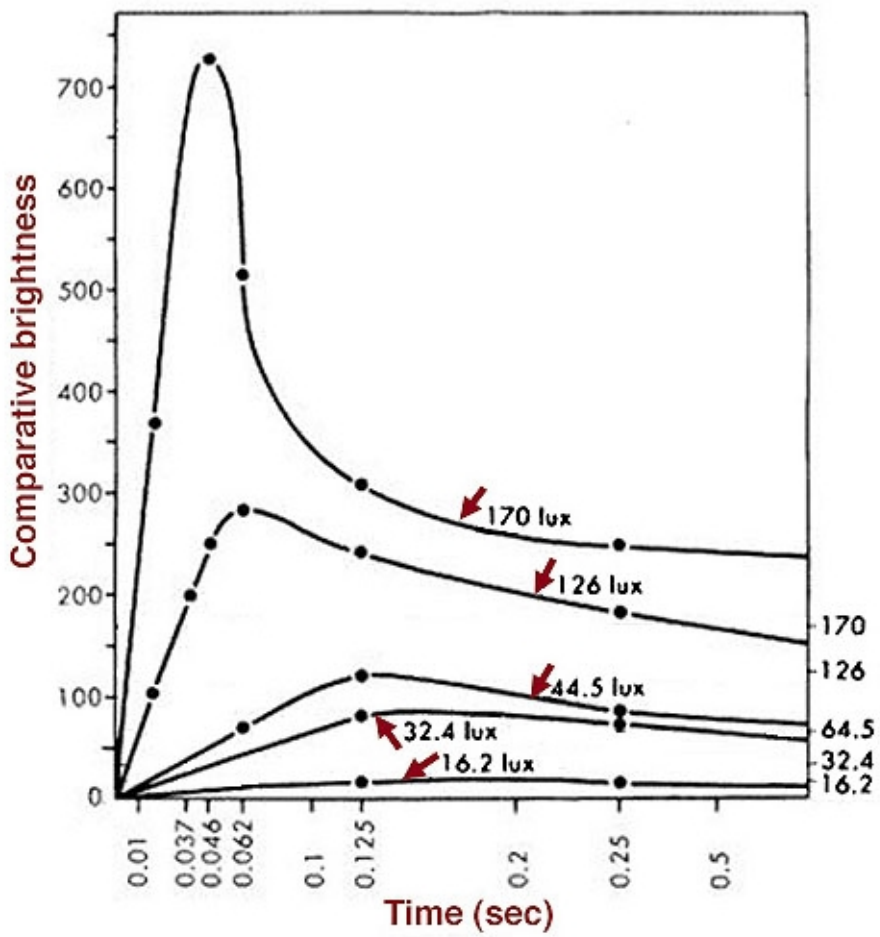

Figure 6. Apparent brightness of flashes with various luminances, as a function of flash duration. Broca and Sulzer data from Hart (8).

intermittent light source is the same as if the light perceived during the various periods of stimulation had been uniformly distributed over the whole time. The Talbot-Plateau law applies only above the CFF.

The **Brücke-Bartley** (brightness enhancement) effect is a phenomenon related to the Broca-Sulzer effect. When the frequency is gradually lowered below the CFF, the effective brightness of the test field begins to rise. Not only does the brightness reach a value equal to that of the uninterrupted light, but the brightness even transcends it, reaching a maximum when the flash rate is about 8 to 10 Hz.

Temporal Contrast Sensitivity

In the spatial domain, spatial vision can be characterized by the contrast sensitivity function (CSF). To thoroughly investigate the visual system to flicker, a Temporal Contrast Sensitivity Function (TSF), or a de Lange function, can be plotted (6). A TSF is a plot of how flicker varies with contrast and *vice versa*. Above the curve represents no flicker, whereas flicker can be detected below the curve (Fig. 11). The eye appears to be most sensitive to a frequency of 15 to 20 Hz at high luminances (photopic vision). At photopic light levels, less than 1% contrast is required to detect the stimulus, and the high temporal frequency cut off is close to 60 Hz. At low light levels, the maximum contrast is about 20% and the high temporal frequency cut off is approximately 15 Hz. To detect flicker of high frequencies, maximum contrast is required. Temporal resolution is not as efficient at low luminances (scotopic vision).

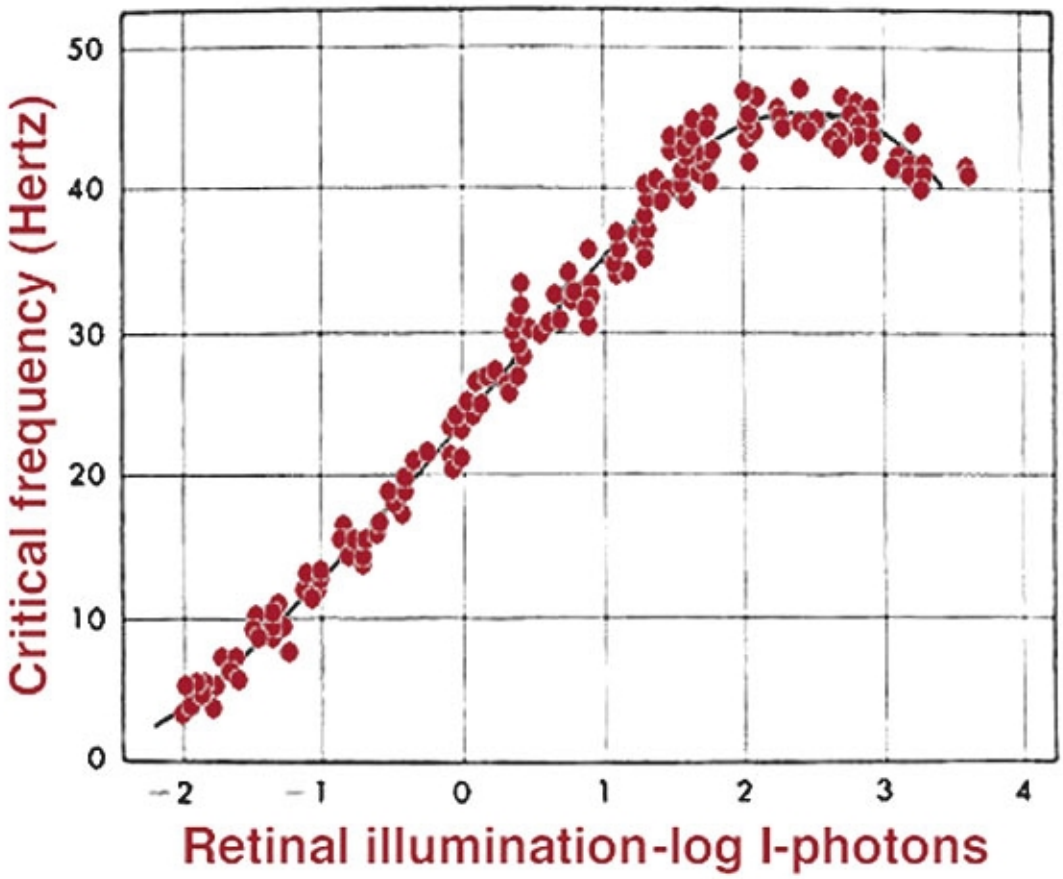

Figure 7. CFF at the fovea over a range of retinal illuminance (photon = troland) of the test field, showing conformity of the Ferry-Porter law over four logarithmic units. Hecht and Verrijp's data from Hart (8).

Different sensitivity profiles exist for the different components of the visual system (opponent *versus* non-opponent) to discriminate motion. For the luminance system, detection, identification, and direction discrimination provide equivalent thresholds. However, at all eccentricities tested, the chromatic system required approximately 0.3 log units higher contrast levels to signal direction of motion (Fig. 12) (7). Overall, these results imply that both luminance (non-opponent) and chromatic (opponent) visual channels are involved in motion discrimination.

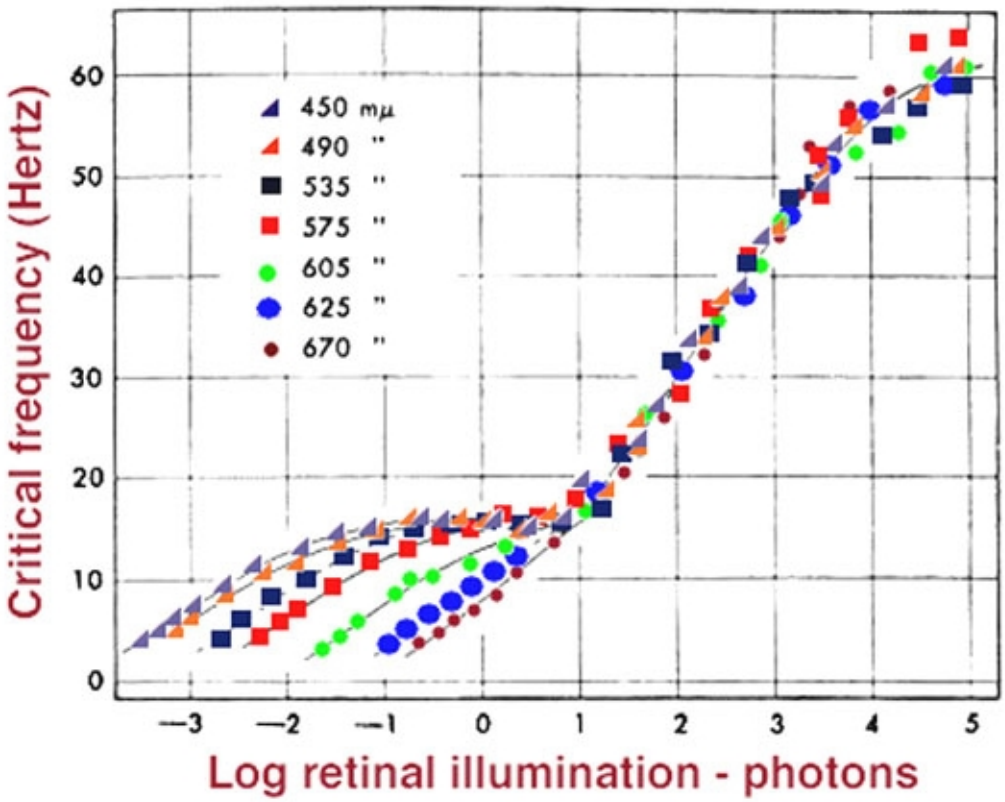

Figure 8. CFF of 19° test field over a range of retinal illuminance (photon = troland) for different monochromatic lights of different wavelengths. Hecht and Shlaer's data from Hart (8).

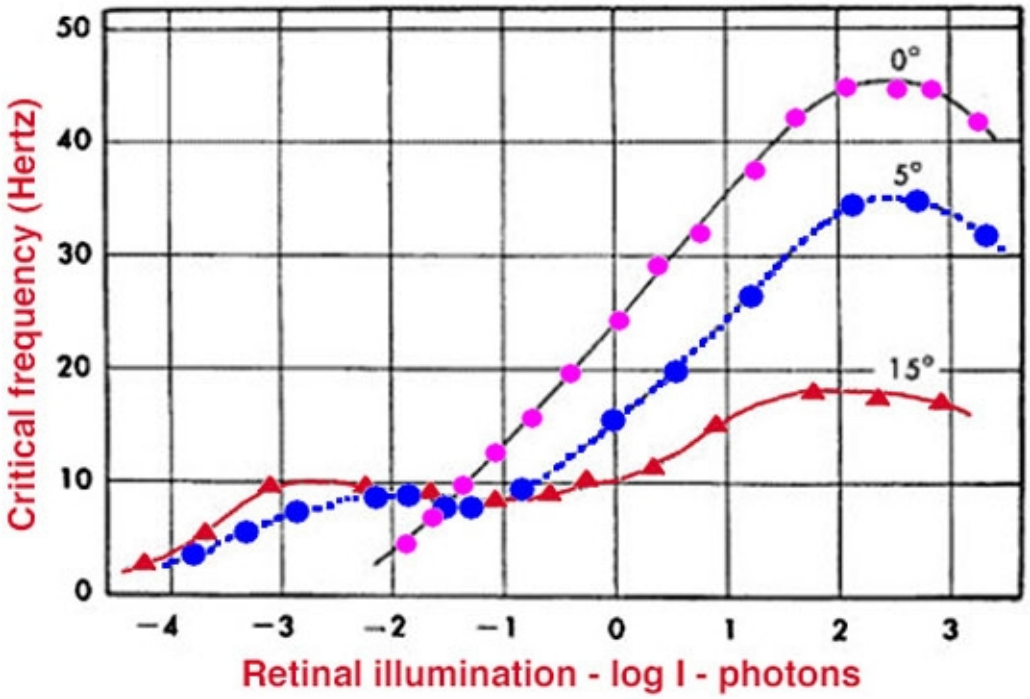

Figure 9. CFF of a 2° white test field over a range of retinal illuminances (photon = troland) measured at the fovea, 5° above the fovea, and 15° above the fovea. Hecht and Verrijp's data from Hart (8).

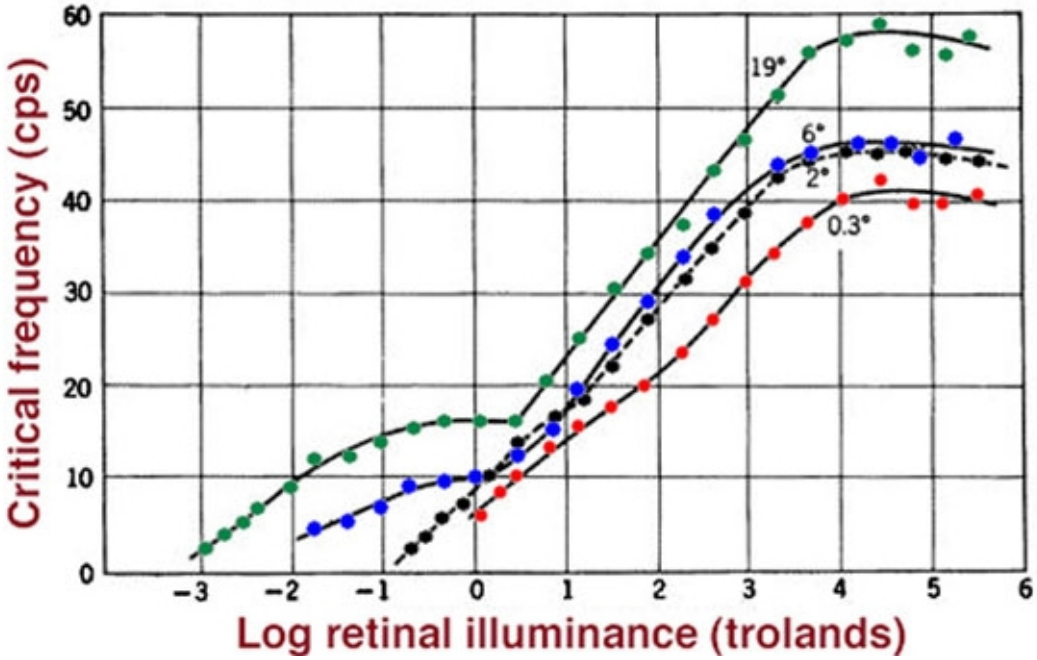

Figure 10. CFF over a range of retinal illuminance (photon = troland) for a centrally fixated test stimulus of different sizes. Hecht and Smith's data from Brown (9).

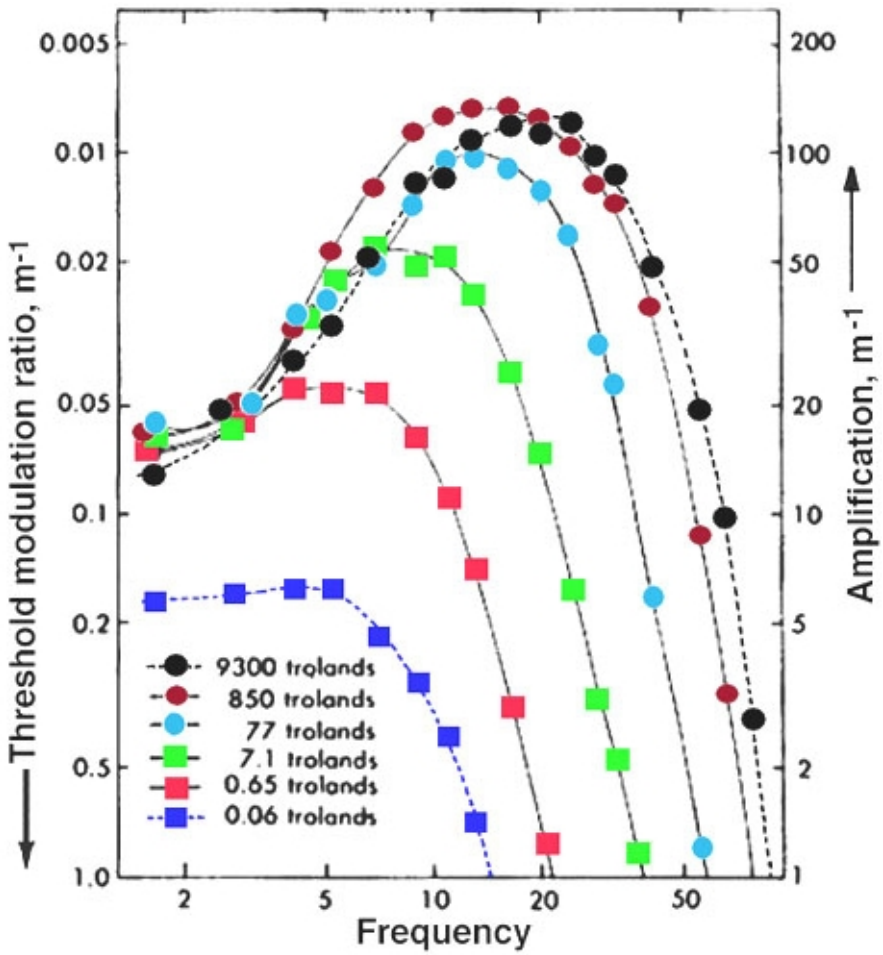

Figure 11. Temporal Contrast Sensitivity Function (TSF) for various adapting fields. Kelly's data from Hart (8).

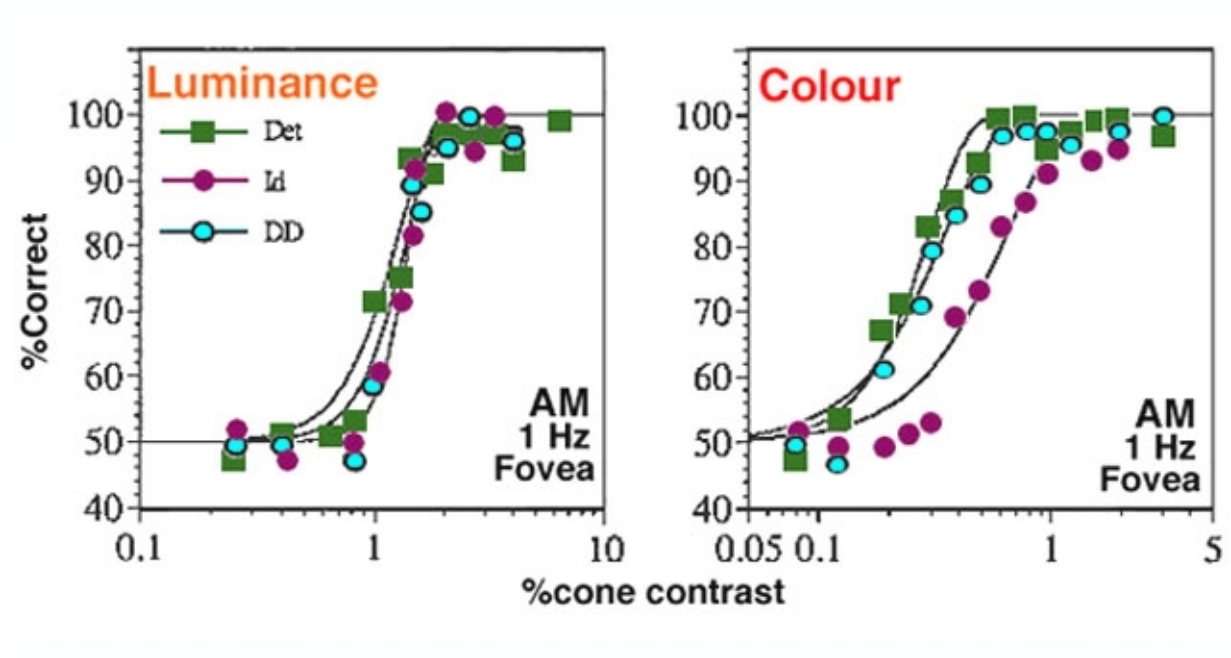

Figure 12. Psychometric functions for detection (squares), identification (filled circles), and direction discrimination (open circles) for 1 Hz stimulus that selected for the luminance channel (left panel) or chromatic channel (right panel). Data modified from Mehta et al. (7).

About the Authors

Michael Kalloniatis was born in Athens Greece in 1958. He received his optometry degree and Master's degree from the University of Melbourne. His PhD was awarded from the University of Houston, College of Optometry, for studies investigating colour vision processing in the monkey visual system. Post-doctoral training continued at the University of Texas in Houston with Dr Robert Marc. It was during this period that he developed a keen interest in retinal neurochemistry, but he also maintains an active research laboratory in visual psychophysics focussing on colour vision and visual adaptation. He was a faculty member of the Department of Optometry and Vision Sciences at the University of Melbourne until his recent move to New Zealand. Dr. Kalloniatis is now the

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Charles Luu was born in Can Tho, Vietnam in 1974. He was educated in Melbourne and received his optometry degree from the University of Melbourne in 1996 and proceeded to undertake a clinical residency within the Victorian College of Optometry. During this period, he completed post-graduate training and was awarded the post-graduate diploma in clinical optometry. His areas of expertise include low vision and contact lenses. During his tenure as a staff optometrist, he undertook teaching of optometry students as well as putting together the "Cyclopean Eye", in collaboration with Dr Michael Kalloniatis. The Cyclopean Eye is a Web based interactive unit used in undergraduate teaching of vision science to optometry students. He is currently in private optometric practice as well as a visiting clinician within the Department of Optometry and Vision Science, University of Melbourne.

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