LECTURE 4

SENSORY ASPECTS OF VISION

We have already discussed retinal structure and organization, as well as the photochemical and electrophysiological basis for vision.

At the beginning of the course, we reviewed some definitions, which would aid our understanding about light as a quantity, and its measurement (as well as measurement of its perception).

Actually, we did jump the gun a bit because we should have discussed the sensory aspects of vision before entering the complexities of photochemical and electrophysiological aspects.

As we already know by now, the process by which light falls on the retina, and visual impulses are then sent to the brain, is a process of almost unimaginable complexity. The study of sensory aspects of vision is therefore an attempt to separate this complex monstrosity into a number of easy to understand categories:

- Light Sense
- Color Sense
- Form Sense

Light Sense

The simplest way to study light sense is to measure the ***absolute threshold*** of light.

We can do this by placing the subject in a completely dark room, and then on a dark background in front of the subject, we introduce a very faint spot of light. We keep increasing the intensity of that spot of light until the subject first notices its presence. The point at which the subject first identifies this spot of light is his threshold.

Very early experiments found that if the threshold of a subject is measured as soon as he enters from a well-lit environment into a completely dark one, his threshold would be very high (initially) and then fall gradually until it reaches a stable figure that is about 1/10,000 of its initial value.

The reason for this decrease in threshold (i.e. increase in the subject's sensitivity to light) is a phenomenon referred to as ***Dark Adaptation***. During dark adaptation, the subject's visual system is switching from one mechanism of vision ***(Cone/Photopic vision)*** to another ***(Rod/Scotopic Vision)***. The second mechanism is not fully switched on until after about 45 minutes. Therefore the period of Dark adaptation is a transition stage.

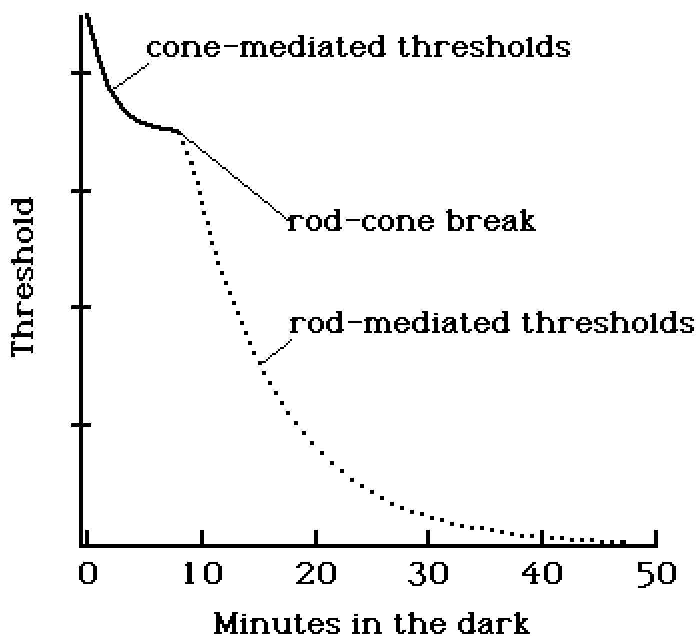


Figure 4.1 Schematic of Dark Adaptation Curve showing Rod-Cone Break

This double mechanism mediation of vision (at different levels of illumination) is described by the duplicity theory of vision. At levels of illumination below 0.01 mL (milliLux), vision is scotopic, and above that level, vision is photopic. However the transition is gradual and therefore there is a range of illumination (***mesopic*** range) where rods and cones function simultaneously to mediate the visual process.

Duplicity Theory

Under the duplicity theory of vision, it is important to note some of the differences between rod/scotopic vision, and cone/photopic vision.

Firstly, when looking at objects during the daytime (cone vision), we have to look at the objects directly to be able to see them clearly. Whereas at night (or when looking at an object of very dim illumination, such as a faint star), we have to look away from the object (so that its image falls peripherally on the retina), for it to be seen clearly.

Next, we notice that during the day, colors are very vivid and we can tell a dark green car from a navy one. At night though, it becomes difficult. Under mesopic levels of illumination such as driving at night with streetlights on, we can discriminate colors (although much less than in complete daylight). But under strictly scotopic conditions, vision becomes ***Achromatic*** so that we cannot distinguish colors (only lightness and darkness).

Finally, visual acuity is highest in the daytime and lowest under strictly scotopic conditions. This is because fine-detail vision (such as visual acuity) is mediated **only** by cones, and these are not active under scotopic conditions because they are not sensitive enough. However, under scotopic conditions, we are much more sensitive to moving or flashing objects.

The Differential Threshold or L.B.I.

We discussed earlier about the study of light sense by measuring the threshold to white light (at a particular level of adaptation).

Now, that sort of measurement has one drawback. For us to get a relatively consistent value for threshold, we must perform that test under dark-adapted scotopic conditions.

Suppose we wanted to measure a similar threshold but at brighter viewing conditions, we could do so by first getting a spot of light (of any brightness). Then we could introduce another spot of light (so that we would see both spots simultaneously), and vary the intensity of the second spot until the observer first notices a difference in brightness between the two spots.

The minimum change required for detection of a difference in brightness between two spots is called the ***Liminal Brightness Increment (L.B.I.) or Differential Threshold***. The advantage of the LBI is that it can be measured at any intensity of light.

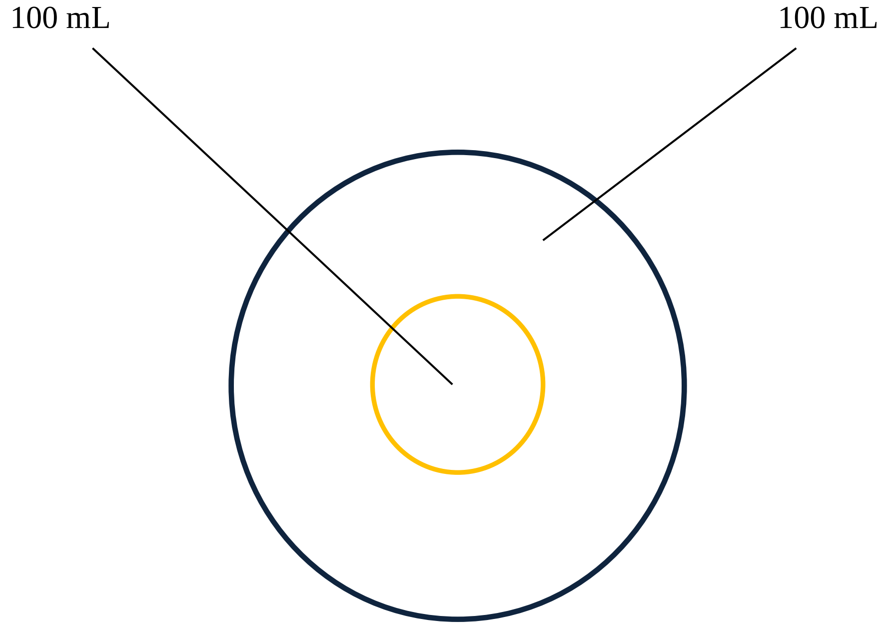


Figure 4.2 Liminal Brightness Increment Illustration

Weber-Fechner Law

The application of Weber's law of sensation (read up) to the eye, resulted in the Weber-Fechner law.

Basically, this law asserts that LBI/Intensity ($\Delta I/I$) is constant. So that if the intensity of light is 100 mL and the ΔI is about 2 mL, then if the intensity of light changes to 1000 mL, the ΔI should be about 20 mL.

However this law only holds in the illumination range between 0.1 and 1000 mL.

$\Delta I/I$ is referred to as the Fechner fraction and it has been determined that a high illumination levels (between 0.1 and 1000 mL) it is between 0.02 and 0.03. At lower levels of illumination though, this fraction increases such that by 0.0001 mL, it is 0.5. This means that at 0.0001 mL, two patches of light would have to have a 50% difference in luminance for this difference to be detectible.

Color Sense

Under normal photopic viewing conditions, the sensation of 'white' light is caused by the combined sensation of the following colors (hues or wavelengths) of light.

- Red 630 – 780 nm
- Orange 590 – 630 nm
- Yellow 560 – 590 nm
- Green 490 – 560 nm
- Blue 450 – 490 nm
- Indigo ------------
- Violet 380 – 450 nm

Indigo covers a very narrow range in the transition zone between blue and violet.

Above 780 nm, we have infrared light, which is not within the visible spectrum
Below 380 nm, we have ultraviolet light.

Note that even though IR and UV rays cannot be seen by the eye, the eye is still very sensitive to these wavelengths.

Hue

This has been defined as the (color) sensation corresponding to a single wavelength. Hue is the entity (wavelength essentially), which determines a particular color of light (i.e. red or blue, green or yellow).

Much like the Intensity Discrimination Curve, a Hue Discrimination Curve can be plot. This is done by presenting two patches of light of equal luminance but of differing wavelengths. The smallest detectable change is the threshold for that particular wavelength range.

Hue discrimination is not constant over any particular range of wavelengths. It is best at 500 nm in the Blue-Green region, and at 600 nm in the Yellow-Orange region.

Saturation

Light that appears red, for example, is not made up entirely of the ‘red’ wavelengths. Instead the light is made up of many wavelengths with a predominance of the red wavelengths. This red light is therefore said to be **Impure**.

When the ‘impurity’ of a color of light (red for example) is accounted for entirely by mixing the relevant wavelength (red in this case) with white light, we talk of ***Saturation***. The more saturated a color is then, the less light is mixed with that color, and therefore, the darker the color appears.

Variation of Hue with Intensity

Hue is not totally independent of saturation. If we had a yellow hue for example, and we continuously reduced its saturation, we would reach a point where the yellow changes to green.

In the same way, hue is not totally independent of luminosity. Thus, as the intensity of any colored light increases, its subjective hue makes a characteristic shift, and all hues if they are bright enough, eventually look yellowish white. This shift is described as the ***Bezold-Brücke*** phenomenon.

Also, as the luminous intensity of any particular hue decreases, we get to a state where all hues all look alike and vision becomes achromatic. This has to do with the ***Purkinje Shift*** phenomenon associated with dark adaptation.

Color Mixtures

Let us assume that we have any two hues (colors) in the visible spectrum. If we mixed those hues, the resultant color will be matched by a hue midway between the original hues. Of course, the resultant hue will also depend on the luminosity of the original colors, and the proportion in which those colors were mixed (e.g 50:50 or 60:40).

Remember the arrangement of hues in the visible spectrum (ROYGBIV). Now, if the two colors that were mixed in the example above were next to each other (like red and orange, or green and blue), and both colors were mixed in a 50:50 (or 60:40, or another ratio) mixture, we would be able to match the single resultant color formed by this mixture by adjusting the wavelength of light. In the case of a mixture of green and blue, the resultant color would be matched by adjusting the wavelength of light to somewhere between that for green and that for blue.

Now, as the two colors that are mixed get further apart from each other (for example red and green are further apart than red and orange), then the resultant color will be found to be more and more desaturated (i.e. the resultant color would be lighter), so that if we wanted to match that color just by altering the wavelength of light (to a wavelength somewhere in-between those of the original two hues), it would be impossible. First we would have to get the appropriate hue by wavelength adjustment. Next we would have to desaturate that hue by adding white light to it. Then we would be able to match this spectral hue with the result of our color mixture.

Now, as the colors get further and further apart, a point is reached where the result of the mixture of both colors (hues) is white. Any two hues, which when combined, give white light, are called ***Complementary Hues***.

In general, it can be stated that any color sensation with average intensities can be matched by a combination of not more than three spectral wavelengths (the spectral wavelengths are ROYGBIV).

The Chromaticity Chart

Any spectral hue can be matched by mixing a combination of the ***primary hues*** of Red + Green + Blue. Sometimes, a color can be matched by mixing only two of these hues.

The chromaticity chart is a means of graphically representing the composition of any hue in terms of the primary spectral colors.

Form Sense

Our ability to appreciate the form or structure of objects in the visual field is critically dependent on our being able to discriminate the different intensities and spatial locations of those objects.

For any one object, we determine its shape by analyzing and summating multiple stimuli of various intensities on various parts of the surface of the object.

Resolving Power of the Eye and Visual Acuity

When we speak of the resolving power of the eye, we refer to the smallest separation between any two objects in space, which the eye can discern. Any separation between these two objects smaller than this, the eye sees both objects as one.

The ability to see the space between the two objects above is dependent of the angle that this space subtends at the nodal point of the eye. This angle is usually expressed in minutes of arc and it is referred to as the ***minimum angle of resolution (MAR)***. For the space between two objects to be visible, the MAR of that space must be at least 1 minute of arc (1^1).

When the MAR is expressed in minutes of arc, 1/MAR = Visual Acuity. Under optimal conditions, MAR of the order of 30 seconds of arc may be measured. This corresponds to a V.A. of 1/0.5 = 2 (equivalent to 6/3 or 20/10).

Visual Acuity

Extrapolating MAR to V.A. measurement, each letter of the Snellen chart subtends an angle of 5^1 at the stipulated distance (for example, the 12 meter letters subtend 5^1 at 12 meters. So, if those are the smallest letter the patient can see from the standard test distance of 6 meters, the V.A. of that patient is 6/12 or 0.5).

Note that while each whole letter subtends 5^1 at the stipulated distance, the separations between the different parts of the letter subtend 1^1 at that same distance, and this is what is important. Because if those spaces (separations) cannot be resolved, the letters appear as black dots.

Finally it is pertinent to note that V.A. is determined by the following factors:

- Test target illumination
- The state of adaptation of the eye (which is only partly dependent on ambient illumination).
- Pupil size

INDUCTION

Whenever an area of retinal receptors are stimulated (for example by a spot of light), there are two direct consequences:

- Retinal receptors in other areas are affected (even though they are not directly stimulated (***Spatial Induction***).

- Retinal receptors in the directly stimulated area are affected for a considerable length of time (even after the stimulus has ceased) so that if a second stimulus is applied immediately (or almost immediately) after the first one ceases, the response to this stimulus changes. So that, this 'new' response to the second stimulus, is different from the response that the receptors in that area would have given to the stimulus had the first stimulus not been applied. This phenomenon is ***Temporal Induction***.

Note The continued stimulation of retinal elements after the stimulus has ceased leads to a continued subjective perception of the object (even though it is not there). This post-stimulus sensations are referred to as **After-Images**.

Spatial Induction

Spatial induction is also referred to as simultaneous contrast and it is important for the detection of the edges of an object. Edge detection is a critical initial component of visual perception, depth perception, and motion perception.

Temporal Induction

Imagine we have two sources of light (A and B). A is brighter than B.

Now we look directly at B, and B appears reasonably bright.

Let's say we take a short break of 2 minutes, and after that we look directly at A continuously for 1 minute. If we then switch our focus back to B, we will find that B now appears less bright than it did before.

This apparent reduction in the brightness of B is referred to by some as ***Light Adaptation***. It is responsible for preventing the confusion that would otherwise result from two images presented successively to the eyes.

The decrease in the absolute threshold of the eye with increase in dark adaptation is a form of temporal induction.

Temporal reduction is also referred to as ***Successive Contrast***.

LECTURE 5

CONCEPT OF THRESHOLD

Frequency-of-seeing curve

In the fully dark-adapted state, the minimum stimulus necessary to evoke the sensation of light is the absolute threshold.

Remember that we mentioned earlier that the minimum amount of light to evoke the sensation of light (at a particular state of adaptation) is the absolute threshold for that state. Now, add to that definition the fact that when the eye is ***totally*** dark-adapted, we cannot get a lower state of adaptation.

Therefore, the absolute threshold measured under full dark-adaptation the maximum (actually minimum) absolute threshold for that eye.

However we must note at this juncture that even this ‘maximum’ absolute threshold is not a constant quantity, but varies from moment to moment. Therefore is the test object was a patch of light, we would have to present it many times at any one luminous intensity, to determine a frequency of seeing curve.

We would therefore have to present a patch of light of 5mL intensity for example, 6 times. We would do the same for patches of light of say, 7mL, 10mL, 20mL, 30mL etc. Then we would set an arbitrary frequency of 50% for example. So that, when each stimulus is presented, we determine how many times that stimulus evokes a sensation of light out of 6 times. Tell the subject, if you notice light, say yes. Present the test patch at different locations and record the correct ‘yes’ responses out of 6. This value e.g 3/6, 2/6, 4/6, etc. is the ***frequency-of-seeing*** for that particular light intensity.

A typical frequency-of-seeing curve is depicted in figure 5.1.

Minimum retinal illumination

This absolute threshold may be recorded in a number of ways according to the manner of presentation of the stimulus. For example, did we present the test patch for a relatively long period e.g. 1 second? Or did we present the stimulus in short flashes?

The pupil size must be measured (since it determines the quantity of light falling on the retina), and the threshold is then expressed in trolands.

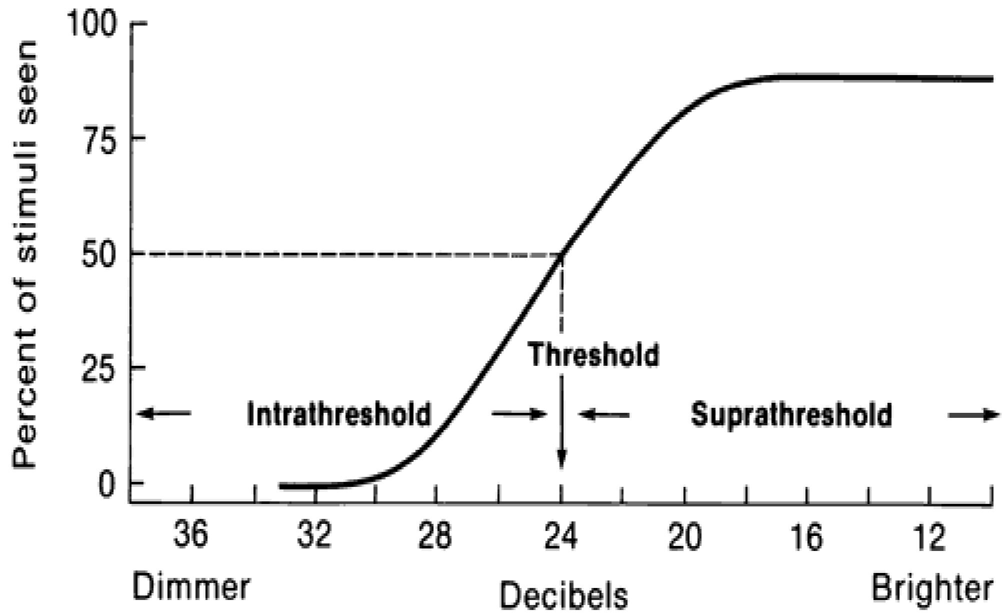


Figure 5.1 Frequency-of-seeing Curve

Minimum Flux Energy

If an effectively point source of light is used, the image is concentrated on to a point on the retina so that the concept of retinal illumination loses its value. Instead, we then define the threshold as the minimum flux of light energy necessary for vision. This flux is measured in quanta per second and a value of 90 – 144 quanta per second has been reported.

Minimum Amount of Energy

Finally, if a very brief flash of light is used as stimulus (less than 0.1 second) then threshold may be expressed as the total number of quanta that must enter the eye to produce a sensation of vision.

Minimum Amount of Energy is the measure of threshold that is most important, because it allows us to calculate just how many quanta of light a single receptor must absorb to be excited (i.e. minimum threshold).

Minimum Stimulus

In 1942 Hecht, Shlaer and Pirenne determined the minimum stimulus (for threshold vision) by presenting short flashes of light and determining the frequency-of-seeing curves at 60% frequency.

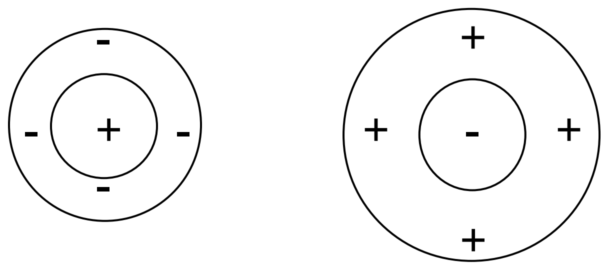
They estimated the amount of energy falling on the cornea to be between 54 and 128 quanta. Allowing for absorption by the ocular media, the useful energy (that reaching the retina) was 5 – 14 quanta.

The bottom line is that it requires at least 11 rods to be simultaneously stimulated for the light impulse to generate an action potential that would eventually result in the transmission of visual impulses to the brain.

Spatial Summation

We have defined the minimum stimulus intensity in three different ways. But, to appreciate the differences in these definitions, we need to understand the concepts of spatial and temporal summation.

Ganglion Cell Receptive Fields



On-centre (X+) ganglion cell **Off-centre (X-) ganglion cell**

- Each retinal ganglion cell will only respond to a stimulus if it falls within a circular group of rods and cones known as the ***receptive field*** of the ganglion.
- Looking at the receptive field schematics above, ganglion cells will display varying responses to light sources depending on whether these light spots fall within the center circle or the peripheral circle.
- The maximum response in either type of receptive field will occur if a spot of light completely fills but is limited only to the inner circle.
- If a spot of light falls inside the inner circle but does not fill it, the ganglion cells in that receptive field will respond to that light, though not maximally.
- If we have a light spot that completely fills the inner circle, and also fills part of the outer circle, we get a ***laterally inhibited*** response. A laterally inhibited response is a below maximum response as a result of the spot of light stimulating oppositely charged areas (+ and -).
- A large spot of light, which completely fills the larger circle, will elicit the minimum response from that particular receptive field.
- As a result of the phenomenon of receptive fields, it becomes clear that ganglion cells are more sensitive to contrast than to luminance. In other words, we are more

dependent on the difference between the brightness of an object and the brightness of its background (than the brightness of the object alone) to determine how bright or dark the object is.

- Two white objects with the same luminosity will appear to have different brightness values if they are placed against different backgrounds (one light and one dark). This phenomenon is referred to as ***Simultaneous Contrast*** (i.e. the dependence of the brightness of one region on the brightness of adjacent or surrounding regions).

- There are different sizes of receptive fields. Smaller receptive fields are associated with high-definition foveal vision, and larger receptive fields are associated with peripheral rod vision.

Having extensively discussed receptive fields, it becomes clear that for two spots of light falling within the central area of a receptive field, the larger spot will cause a greater excitation of that receptive field.

Ricco's Law ***Intensity X Area = Constant***

Therefore, for a particular stimulus source, the smaller an area it registers on the receptive field, the higher the intensity.

It's sort of the same principle as Pressure = Force/area.

Ricco's law holds only within certain aerial limits on the retina. In the parafoveal region, it holds in a 30 minute of arc region (with an eccentricity from the fovea of 4^0). At an eccentricity of 35^0, it holds over a much wider area. This fact is obviously related to the fact that the rod receptive fields are much larger than those of the cones.
Now, Ricco's law will apply as long as the stimulus does not exceed the total area governed by the law. In such a situation, we say that the summation is total.

A stimulus that falls on the parafoveal region (and covers an area larger than 30 minutes of arc), will not be summated according to Ricco's law. So that, in this case, we say the summation is ***partial*** and the stimulus intensity will have to increase to have the same effect as if it fell within the specified area.

After Ricco's law fails, ***Piper's*** law takes over and holds for an area of about 24^0.

Piper's law $\sqrt{\text{Area}} \times \text{Intensity} = \text{Constant}$

Temporal Summation

Here a stimulus presented in a series of flashes, has the same effect as one presented steadily for a longer time period. So that we can say that the longer duration stimulus is a summated version of the stimulus presented in flashes.

This total temporal summation only holds over a certain period (up to 0.1second) and is governed by the ***Bunsen-Roscoe law***.

Bunsen-Roscoe law = Intensity X time (exposure period) = Constant.

Beyond this 0.1 seconds, the temporal summation is no longer total, but partial.

LECTURE 6

FLICKER

Critical Fusion Frequency

The sensation of ‘flicker’ is invoked when intermittent light stimuli are presented to the eye. As the frequency of presentation increases, a point called the ***critical fusion frequency*** is reached at which the sensation of flicker disappears and is replaced by a sensation of continuous stimulation.

The study of flicker has proved a valuable method to approach the fundamental problems of visual phenomena.

The Talbot-Plateau law

This states that, as long as the critical fusion frequency has been reached, the intensity of illumination at a given surface is an average of the maximum and minimum flicker intensities.

This law reveals some rather interesting – if a bit contradictory – aspects of human vision.

First of all, going by the principle of after-effects, if we have two stimuli – one presented right after the other – the more intense the first stimulus, the longer its after-effects will persist on the retina. Now, so long as the second stimulus is presented during the after-effect period of the first, then, there should be a summation of the first and second stimuli (resulting in a greater brightness sensation – if both stimuli are light flashes). This should then mean, that the higher the stimulus intensity (luminance) of the flicker source, the lower the critical fusion frequency. However, the Talbot-Plateau law states just the opposite of that.

The Granit-Harper law

This states simply that the fusion frequency is directly proportional to the area of the flicker source. So that if we have two flicker sources of the same intensity but one had stimulated a 10 mm^2 retinal area, and the other, a 0.001 mm^2 area, the fusion frequency for the 10 mm^2 stimulus would be much higher than that for the 0.001 mm^2 stimulus.

It is however risky to draw simplistic conclusions from this law because, we must remember that the size of the stimulus determines not only the number of retinal

receptors stimulated, but also the relative involvement of cones and rods in the flicker process.

Brücke-Effect

This was discovered in 1864. Basically, the subjective brightness of a given patch of light is higher when the patch is presented as a flickering source than when it is presented as a continuous source. The best effect was obtained at a flicker rate of 10 cycles/sec.

This effect occurs when the brighter phase of the flicker lasts for a period one-third of that of the darker phase.

Effect of luminance on fusion frequency

The higher the luminous intensity of a flickering light source, the higher the critical frequency necessary to attain fusion.

When critical fusion frequency is plot against the logarithm of retinal illumination in trolands, we see that with foveal fixation, that the relationship is linear over a wide range (between 0.5 and 10,000 trolands).

The Ferry-Porter law

This states that the critical fusion frequency is proportional to the logarithm of the luminance of the flickering patch.

At very high luminances, the critical fusion frequency is maximum between 50 and 60 cycles/second. At very low luminances (within the scotopic range) the fusion frequency is very low (about 5 cycles/second).

If we plot a graph of the log of fusion frequency against the log of retinal luminance, as we move from the fovea to the periphery, we would reach a point where there is a well-defined transition (change) in the graph. This change (break) indicates a clear dichotomy of two separate mechanisms mediating flicker (the cone mechanism, and the rod mechanism). Interestingly enough, this change does not occur if the flicker source has a wavelength of up to 670 μm, since at this wavelength, only cones are stimulated.

So it then becomes clear that the rods are much less sensitive in mediating temporal resolution than cones, but they are not completely insensitive to temporal phenomena.