

## II   ◇◇◇   THE EXPERIMENT OF HECHT, SCHLAER, AND PIRENNE

IN 1942, Hecht, Schlaer, and Pirenne reported an experiment of extraordinary significance.<sup>1</sup> They presented flashes of light to normal human subjects, and determined the lowest possible intensity of that light that the subjects could see. The results were extremely surprising, and led immediately to many strong conclusions about the structure of the visual system and the nature of perceptual processes.

Their experiment is also very useful in a different way. The considerations that Hecht *et al.* had to entertain in order to design and perform the experiment form a useful outline of a large part of our knowledge of perceptual phenomena and of their underlying physiological pro-

<sup>1</sup>The articles and books referred to in the text are listed in the bibliography at the end of the book.

cesses. These considerations, and the results of the experiment, will be described briefly in this chapter and elaborated in succeeding chapters.

**THE GENERAL DESIGN OF THE** An apparatus was built that permitted the experimenters to present a subject with flashes of light at a particular location in his visual field.

**EXPERIMENT** The intensity, color, size, and duration of these flashes could be controlled very accurately. The location, color, size, and duration were then set at particular values (chosen by the criteria to be discussed below), and a series of flashes was presented at varying intensities.<sup>2</sup>

Each time a flash was given, the subject said whether or not he saw it, and the intensity at which he said he saw the flash on 60% of the trials was defined as the threshold intensity.

The immediate goal of the experiment was to find the lowest possible intensity that permitted the subject to see the flashes, and it was already well known that the color of the light, its location on the eye, its timing, and its size all influenced this threshold level. It was also known that the state of the subject's eye critically affected his threshold. Therefore, Hecht *et al.* chose the values for each of these aspects of the experiment that yielded the lowest possible threshold.

**THE STATE OF THE SUBJECT—DARK ADAPTATION** It was already well known, at the time that Hecht *et al.* performed their experiment, that a subject is more sensitive to dim flashes of light if he has been in the dark for a period of time than if he has just come in out of the light. It is a common experience to be almost blind when first entering a movie theater, but to be able to see quite a lot after 5 or 10 minutes. This phenomenon is dark adaptation.

<sup>2</sup>The names and classes of photometric units (units describing amounts of light) have grown over the years into an unbelievably confusing jumble. There are few among even the most scholarly who can tell you how many nits (sic) there are in an apostilb, or even whether or not there are any. (There are either  $1/\pi$  or  $1.018/\pi$ , depending upon whether in the book I am referring to, cd stands for candle or candela; or maybe there are  $1.10/\pi$  if the apostilbs are in German [Hefner] units.) Worse yet, a few words that have useful and unambiguous meanings to the typical speaker of English have been assigned specific definitions, so that it is now improper to use those terms to refer to what they used to refer to. The difficulties involved in correctly using photometric units are further compounded in a book of this kind because the meanings of most units depend upon certain optical and perceptual concepts and facts with which the reader is not yet acquainted.

The term "intensity" is improperly used throughout this book. Technically, it applies only to point sources of light; it is not proper, for example, to say anything about the intensity of light falling on a surface, or the intensity of the stimulus (unless it happens to be a point source). Nevertheless, it is probably better, pedagogically, to use the word "intensity" improperly. When used in this book, it means just what you think it means.

The curve in Fig. 2.1 is the result of a study of this phenomenon. The subject was first exposed to a bright light for a few minutes, then the light was extinguished, and his sensitivity to brief flashes of light was measured, under conditions similar to Hecht's experiment, as a function of time after the offset of the bright light. Notice that his sensitivity increases rapidly at first, and then more slowly for 30 or 40 min. Dark adaptation is virtually complete after about 40 min in the dark. Because of this, Hecht *et al.* dark-adapted their subjects for at least 40 min before they began to take their data.

At the time that Hecht *et al.* performed their experiment, some of the physiological properties of the visual system related to dark adaptation were understood. In order for a subject to see that a lighted test spot is in fact lighted, some of the light from the spot must interact with some part of his system. In almost all light-sensing elements, whether they are in a human eye, a photographic film, or a satellite tracker, this interaction is the absorption of light by some of the molecules of material in the sensor. The molecules that absorb light in the receptors of the eye are called visual pigment molecules. When any one of these molecules absorbs light, it changes its state, and, if enough molecules change their state, these changes are signaled to the rest of the subject's system, and he says he sees the light. After a visual pigment molecule has been in this new state for a very short time, it is almost incapable of absorbing more light. Therefore, if a subject were shown a flash

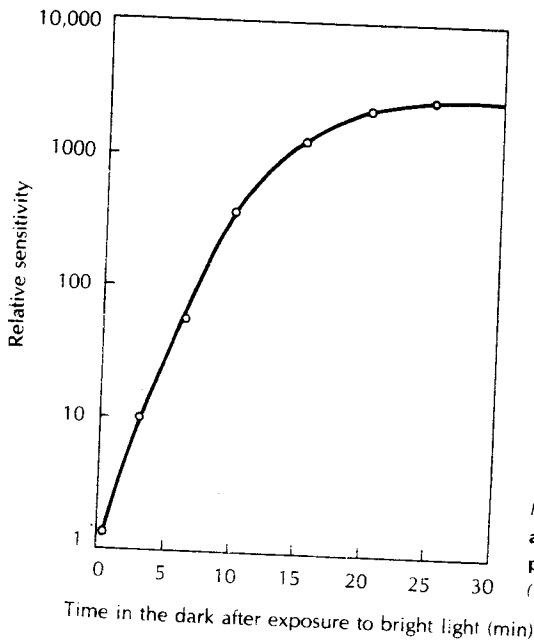


Fig. 2.1 Change in human visual sensitivity as a function of time in the dark after exposure to a bright light. [After Kohlrausch (1931), curve for green light.]

of light so intense that it changed the state of virtually all of his visual pigment molecules, he would subsequently be very insensitive to a second flash (since his eyes would contain very few molecules capable of absorbing the light from the new flash).

However, if a molecule has absorbed some light and is in its insensitive state, it will have a tendency to regenerate to its original, sensitive, state if it is in the presence of the various other chemicals in the eye. For the kind of visual pigment relevant here, the strength of this tendency is such that any single molecule in the insensitive state will have a 50% probability of regenerating in a period of about 5 min. The regeneration of each molecule is independent of the states of the other molecules. Thus, if all the molecules were in the insensitive state at the beginning of a period in the dark, about half of them would be regenerated after 5 min in the dark, 75% after 10 min (that is 50% plus half of the remaining 50%), 87.5% after 15 min, etc. Obviously, as the number of molecules that are in the sensitive state increases, the subject's sensitivity, as it is shown in Fig. 2.1, will increase.

For a long time, this physiological property of the visual system was accepted (in a more formal and quantitative form) as a complete explanation of the perceptual phenomenon called dark adaptation. In fact, almost every textbook in psychology and in visual perception written before the 1960's (and too many written since then) offer this explanation. However, it is now firmly established that this explanation is inadequate as it is stated above. Several modifications of the theory, and some altogether different explanations of dark adaptation, have recently been proposed. These will be discussed and evaluated in Chapter V. At the time of this writing, however, there is no entirely satisfactory physiological explanation of dark adaptation.

#### **LOCATION OF THE TEST FLASH IN THE VISUAL FIELD**

Suppose that a subject is in a room that is entirely dark except for a single small point of light (say a flashlight bulb), and he closes one eye and fixates the light with the other eye. A top view of the subject's eye and the fixation point is shown in Fig. 2.2. Light from the fixation point radiates in all directions, and some of it enters his eye, where it is refracted by the surfaces and forms an image of the fixation point on the back of the eyeball. (These processes, and all the others discussed in this chapter, will be explained in more detail in the succeeding chapters.) In other words, there will be a small spot of light at a particular location on the back of the subject's eye. The location of that image is determined by the location of the fixation point and the shape of the eyeball. For the time being, it is sufficient to understand that a straight

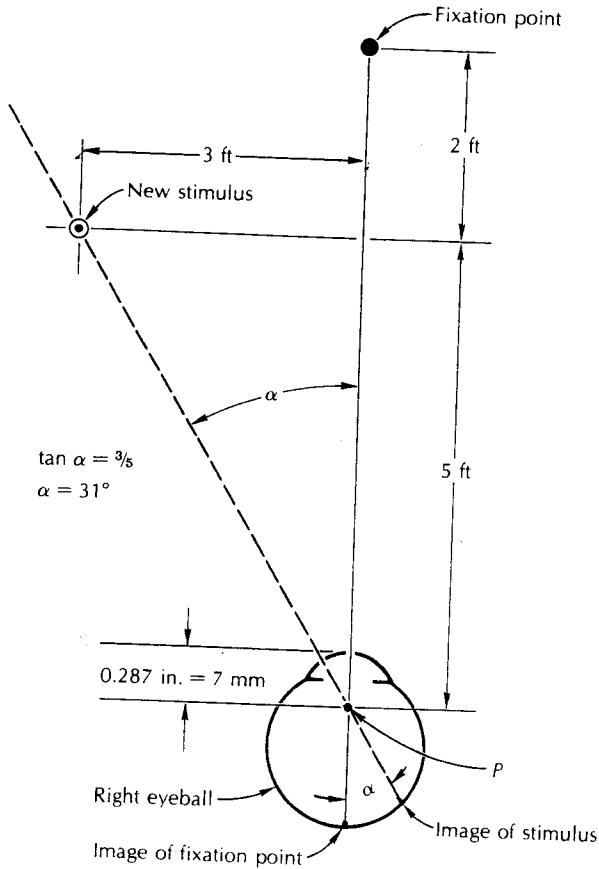


Fig. 2.2 Top view of the right eye of a subject looking at a fixation point. The new stimulus is presented at  $31^\circ$  of visual angle to the left of the fixation point.

line drawn from the fixation point through a particular point,  $P$ , within the eye, will intersect the back of the eye in the center of the image of the fixation point, as indicated in Fig. 2.2. Now suppose a second bright point is introduced into the room, as indicated by the point labeled "new stimulus" in Fig. 2.2, but the subject keeps looking at the original fixation point. Some of the light from the new stimulus will also enter his eye, and an image of the new stimulus will be formed as in Fig. 2.2, in a location determined by the line between the new stimulus and the point,  $P$ . (The location of  $P$  in the eye is determined by the structure of some of the parts of the eyeball, and therefore does not vary as the location of the stimulus is changed.)

Now it would be useful to develop a scale for defining the location of the new stimulus with respect to the fixation point. From Fig. 2.2, it is obvious that the position of the new stimulus could be completely defined with respect to the fixation point by stating that, "It is 3 ft to the left of the subject's line of sight at a distance from him such that a line

drawn through the new stimulus and perpendicular to the line of sight intersects the line of sight 5 ft from the subject.” However, that description contains more information than we really need, if we are interested in vision, rather than in the apparatus itself, for the following reason: So far as the subject is concerned, the new stimulus might be anywhere along the dashed line in Fig. 2.2. (Remember that only one eye is open in this example.) The only information he has about the apparatus is what is on the back of his eye, and if the new stimulus were moved to any new position along the dashed line, its location on the back of his eyeball would not change.<sup>3</sup> Therefore, there is no point in describing the location of the new stimulus as completely as it was described above. It is sufficient to locate the stimulus by locating the dashed line with respect to the fixation point, and this may be done simply by stating the size of the angle between the dashed line and the line of sight. This angle, called the visual angle, is the angle whose tangent is 3 ft/5 ft, that is,  $31^\circ$ . Note also, from Fig. 2.2, that the angle formed by the lines connecting the point *P* with the images of the fixation point and the new stimulus is this same visual angle.

Lining the back of the eyeball, where the images are formed, is a surface called the retina, which contains millions of very tiny cells, some of which are rod-shaped, and are called rods. The curve in Fig. 2.3

<sup>3</sup>It is true that, under most conditions, the sharpness of focus of the new stimulus might change as it is moved along the dashed line, but for the purposes of this discussion we are concerned only with the location of the center of the image. Focusing will be discussed later.

Fig. 2.3 Rod receptor cell density as a function of the horizontal location across the retina of the right eye. (The “blindspot,” a region where there are no visual receptors, will be discussed later.) [After Pirenne (1967), p. 32.]

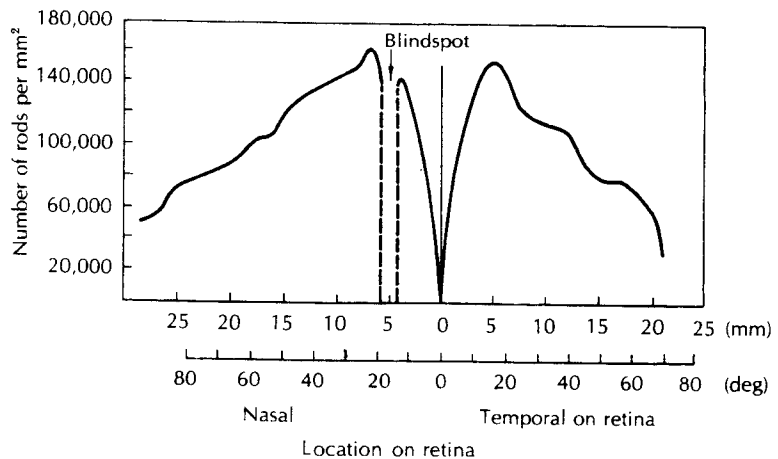
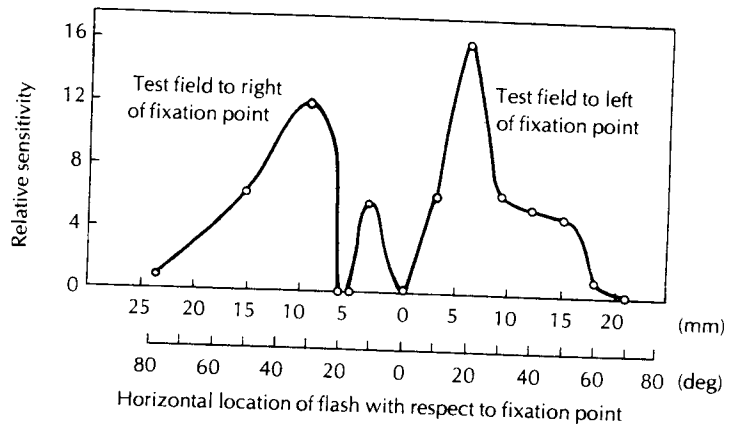


Fig. 2.4 Relative sensitivity of the right eye as a function of the angular position of the test flash with respect to the fixation point. [After Pirenne (1967), p. 46, for blue light.]



shows the distribution of these rods across the retina. The horizontal axis in this figure has two scales. One is simply the distance, in millimeters (mm), between an anatomically defined point in the retina called the fovea, and the region where the density of rods is measured. It is known, from data to be discussed later, that, when a subject is instructed to fixate a point, he moves his eyes until, in each eye, the image of the point falls on the fovea. Therefore, the millimeter scale in Fig. 2.3 corresponds simply to the other horizontal scale, visual angle, the fovea being located at zero angle with respect to the line of sight. (The distance from the point *P* to the retina, in Fig. 2.2, is approximately 17 mm. This is the factor required to convert millimeters on the retina into visual angles.)

The rods are the cells that respond to very dim light. Therefore, Hecht *et al.* reasoned that the light constituting their stimulus should fall  $20^\circ$  to the right of the subject's fovea (temporal retina for the right eye), where the rods are most tightly packed together. To accomplish this, they presented the subject with a dim point of light to look at, and their test stimulus was flashed  $20^\circ$  to the left of the fixation point.

There is a common experience that is closely related to the reasoning of Hecht, *et al.* If you look directly at an object, you can see its fine details much better than you can if you are not looking right at it. However, if the object is simply a very dim spot of light in an otherwise dark field, for example, a star, and if your eyes are dark-adapted, then you are more likely to see it if you look a little to the side than if you look directly at it. You can see a star "out of the corner of your eye" that might be too dim to be seen when you look directly at it. Hecht *et al.* assumed that this perceptual phenomenon was at least partly attributable to the increased rod density farther from the fovea, as plotted in Fig. 2.3, and thus chose to put their test stimulus  $20^\circ$  from the fovea.

The relationship between the sensitivity to dim light and the location of the stimulus on the retina has been studied more recently, and the results that are plotted in Fig. 2.4 generally verify the supposition that the sensitivity follows the rod density.

### SIZE OF THE TEST FLASH—SPATIAL SUMMATION

Next, Hecht *et al.* had to decide how large the flash should be. That is, over how large an area on the back of the subject's eye should the light be spread? There are perceptual data in the literature that provide an answer to this question, and these data are presented in Fig. 2.5. In this figure, the labeling of the axes requires some explanation.

The vertical axis is labeled "threshold (log mean relative number of quanta required for 60% seeing)." A beam of light may be described as a stream of packets of energy, each of which is called a quantum. Whenever light is absorbed by anything (e.g., the rods in the eye), the resulting events can be described as though the light consisted of these elementary packets, each packet being either wholly absorbed or not absorbed at all. (There is no such thing as the absorption of half a quantum.) Similar events occur when light is being generated. That is, a source of light emits a stream of quanta, and cannot emit half a quantum.

The intensity of a light is usually measured by causing the light to be absorbed by some detector. Therefore, the intensity may be measured in terms of the number of quanta per unit of time that are absorbed by the detector. The data in Fig. 2.5 are thresholds for short flashes of fixed duration. The total number of quanta in each flash is a measure of the flash intensity.

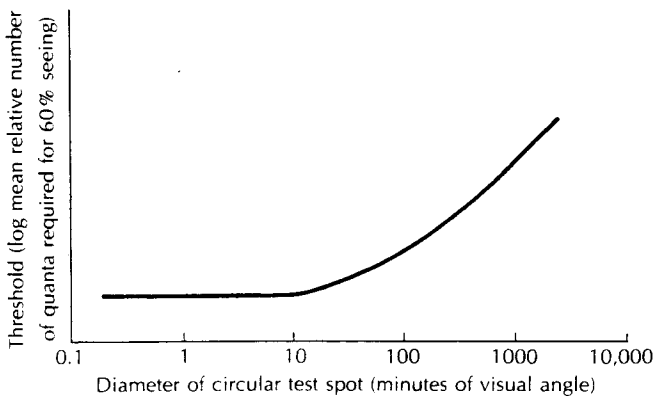


Fig. 2.5 Total light required for seeing a flash as a function of the size of the test spot. [After Barlow (1958), test flash duration 0.0085 sec, dark background.]



There are many ways by which the *threshold* for a flash of light may be measured. The method used for collecting the data in Fig. 2.5 (also used by Hecht *et al.*) involves, in essence, the following procedure: The subject is presented with a series of flashes of different intensities, that is, different numbers of quanta, and, after each flash, he signals whether or not he saw it. If there were some intensity above which flashes were always seen and below which they were never seen, that intensity would be called the threshold intensity. However, that is not the case. At very low intensities, the flashes are almost never seen, and at very high intensities they are almost always seen, but between those levels, there is a range of intensities for which the likelihood of seeing the flash gradually and smoothly changes from low to high.

The result of a typical set of measurements is shown in Fig. 2.6. There is no "threshold" in the common sense meaning of that term; thus, the intensity that will be called the threshold must be chosen arbitrarily. In the experiment represented in Fig. 2.5 and in the Hecht *et al.* experiment, the threshold intensity was defined as that intensity at which the subject reported that he saw the flash 60% of the times that it was delivered at that intensity; this threshold is indicated on Fig. 2.6. Thus, the vertical axis in Fig. 2.5 indicates the threshold, measured by the number of quanta required in a short flash in order that the subject see the flash 60% of the time, for each area represented along the horizontal axis.

Note that the threshold and sensitivity are inversely related. That is, a high threshold means low sensitivity (many quanta are required for seeing), and vice versa. Thus the vertical axes in Figs. 2.4 and 2.5 are inverted with respect to each other.

The horizontal axis on Fig. 2.5 is the area of the (disk-shaped) test flash, in units of visual angle. [One degree equals 60 minutes (60') of arc.] (See Appendix I for a table of the sizes of common objects in units of visual angle.)

The curve in this plot indicates that, so long as the test spot diameter

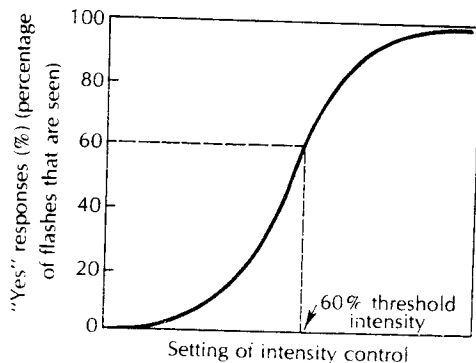


Fig. 2.6 Typical result of a set of measurements to determine the threshold intensity of a flash. The percentage of flashes that are seen increases gradually as the intensity is increased. The threshold intensity must be arbitrarily chosen.

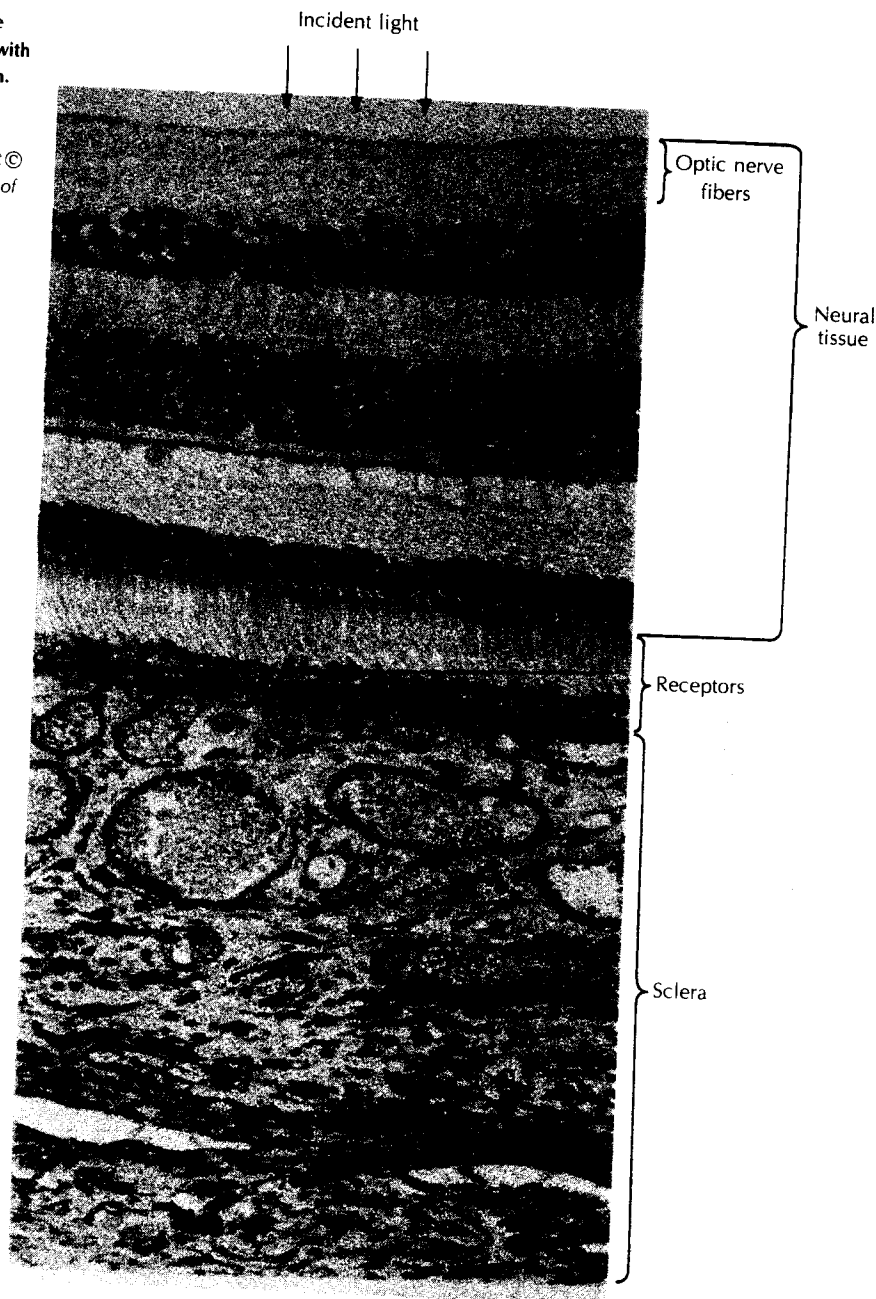
is smaller than about 10 minutes ( $10'$ ) of arc (the size of a thumb tack about 10 ft away), the threshold is the same. In other words, if the subject could just see a flash containing 1000 quanta spread over a disk  $10'$  in diameter, he would also just see a flash containing 1000 quanta spread over a disk only  $1'$  in diameter. The intensity per unit area at threshold would thus be greater for smaller test spots, but the total number of quanta is constant. For test spots larger than  $10'$  in diameter, the curve slopes upward—as the area increases, the threshold number of quanta also increases.

Hecht *et al.* might therefore have chosen any test spot diameter equal to or smaller than about  $10'$  in order to achieve the lowest possible threshold. They chose a diameter of  $10'$  probably because it is difficult to build an apparatus that can present smaller spots. (For example, pieces of dust in the apparatus are more likely to impair the viewing of a small spot than of a larger spot.)

The data in Figs. 2.4 and 2.5 are called psychophysical data, because they show the relationship between some physical characteristic of the stimulus and the corresponding psychological, or perceptual, events.

The physiological properties of the visual system that underlie the psychophysical data in Fig. 2.5 are not easy to present in simple graphical form. They will be discussed briefly here, and examined more thoroughly in Chapter VI. Figure 2.7 is a photomicrograph of a cross section through the back of the human eye. Light entering the eye passes through some neural tissue and part of the light is absorbed by the visual pigment in the receptors, where it is converted into neural signals. Those signals undergo a series of transformations as they travel (upward in the figure) toward the optic nerve. Physiological and anatomical studies have shown that each of the optic nerve fibers leading from this part of the eye ( $20^\circ$  from the fovea) is connected, through intervening neurons, with a large number of rods; the signals from all or most of the rods in a given area feed to the same optic nerve fiber, where their effects are summated. At least 300 rods are connected to each optic nerve fiber in this region of the human retina. Figure 2.8 shows a schematic view of the rods and their neural connections. Each large circle represents one of the “summation” areas. Now suppose that the subject is presented with two flashes of light, each delivering ten quanta to one summation area, but in one flash, the quanta are spread out over a larger area than in the other. The absorptions of quanta are represented by solidly colored receptors for the small flash and by shaded receptors for the larger one. The effects on the optic nerve fiber will be exactly the same for these two flashes, since the optic nerve fiber “sees” the sum of the signals from all the rods

Fig. 2.7 Cross section through the back of the human retina, stained with haematoxylin and eosin. Magnification approximately  $\times 150$ . [From Polyak (1957) Copyright © 1957 by the University of Chicago Press]



within the summation area, that is, ten signals. This process is called *spatial summation*.

So long as most of the quanta in a flash are absorbed by rods all within one summation area, the size of the flash does not matter. This consideration leads to the expectation that the curve in Fig. 2.5 will be

horizontal for small areas. That is, the threshold number of quanta should be the same for all areas equal to or smaller than one summation area.

It is very difficult to obtain and interpret physiological information about the human retina, and as a consequence, there are no good quantitative physiological or anatomical estimates of the sizes of the summation areas in the human retina. However, the data in Fig. 2.5 suggest that the areas in this region of the dark-adapted eye are at least 10' in diameter.<sup>4</sup> Although quantitative data are absent, physiological

<sup>4</sup>The actual size of the summation area cannot be deduced from the data in Fig. 2.5 unless the extent of the overlapping of summation areas is known. (It is not known.) (See problem 2.3 at the end of this chapter.)

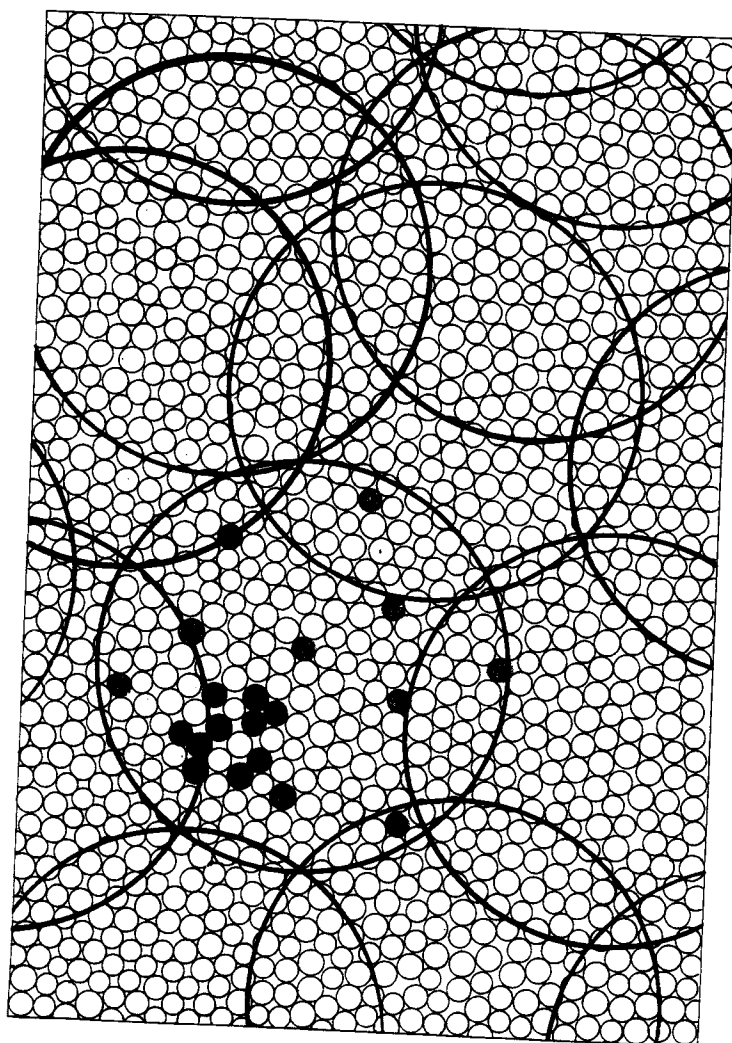


Fig. 2.8 Semischematic representation of the summation areas of the dark-adapted human retina, 20° from the fixation area (the fovea). Each small circle represents the end view of a rod, and each large circle represents the area over which the excitations in all the rods it contains summate. The summation areas overlap, but the actual extent of overlapping in the eye is not known.

and anatomical evidence does indicate that many rods converge on each optic nerve fiber, and this seems to explain, qualitatively, the fact that the curve in Fig. 2.5 is horizontal for some distance.

**DURATION OF  
THE TEST FLASH—  
TEMPORAL  
SUMMATION**

The psychophysical data in Fig. 2.9 were collected by dark-adapting the subject for 40 min and then presenting him with flashes of a test spot 2' in diameter and 15° to the side of the fixation point. The duration of the flashes was the independent variable. This curve looks strikingly similar to the curve in Fig. 2.5, in which the test spot area was the independent variable. So long as the flash is shorter than about 0.1 sec [100 milliseconds (msec)], its duration has no effect on the threshold, no matter how short it is (even a millionth of a second). When the duration is longer than about 100 milliseconds (msec), more light is required for a threshold flash. Knowing this relation, Hecht *et al.* could have chosen any test flash duration shorter than 100 msec, and they arbitrarily chose a duration of 1 msec.

The physiological correlates of the data in Fig. 2.9 are very poorly understood, and research is actively being carried out on this problem. However, it is appropriate here to point out the relationship between these data and those in Fig. 2.5. *Spatial* summation may be said to occur over areas smaller than 10' in diameter (20° away from the fovea), in that the effects of quanta absorbed anywhere within such an area are added together by the visual system. Put another way, the spatial distribution of the quanta has no effect on the threshold so long as the distribution extends over less than about 10'. From Fig. 2.9, it

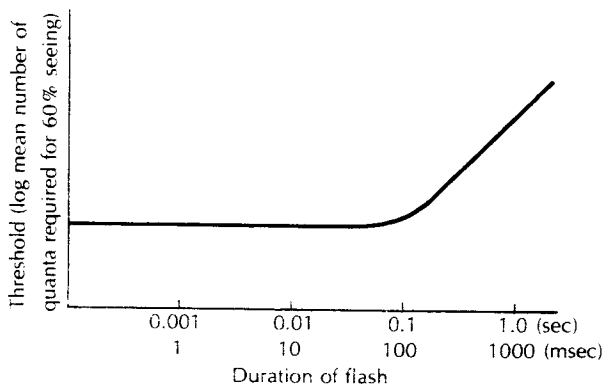


Fig. 2.9 Total light required for seeing a flash as a function of the duration of the flash. [From Graham and Margaria (1935), 2' curve.]

can be seen that the temporal distribution of quanta has no effect on the threshold, so long as it extends over less than about 100 msec. All the quanta can be delivered in 1 microsecond ( $\mu\text{sec}$ ) or they can be spread out evenly over 100,000 microseconds ( $\mu\text{sec}$ ) and they still produce the same effect on the visual system. Although it is not shown explicitly in this figure, it is also true that the same effect will result if half of the quanta are delivered in a 1- $\mu\text{sec}$  flash and the other half in another 1- $\mu\text{sec}$  flash 100,000  $\mu\text{sec}$  later. This means that the effect of each single absorption of a quantum must somehow last for at least 100 msec, so that it can add to the effects of any other quanta that are absorbed within 100 msec. This process is called *temporal summation*.

**COLOR OF THE TEST FLASH – THE SPECTRAL SENSITIVITY CURVE** Hecht *et al.* now had to select a color for the test spot. It is often convenient to consider a beam of light as consisting of a stream of quanta – individual packets of energy. Light was described that way earlier in this book. On the other hand, if light is passed through a very small hole in an opaque surface, it spreads out widely on the other side of the hole and this and many other optical phenomena can be most easily explained by saying that the beam of light, or the quanta in the beam, have wave properties. That is, a beam of light behaves, in some ways, like the waves on the surface of a pool of water. Quantitative measures of this aspect of the behavior of light may be interpreted by ascribing particular wavelengths to the quanta in a light beam.

When a beam of light from the sun or from an ordinary light bulb is passed through a slit and a prism, and allowed to fall on a screen, a spectrum of colors can be seen on the screen (provided that the light is intense enough and the observer has normal color vision), as diagrammed in Fig. 2.10. Now suppose that the screen has a narrow slit opening in it, and any light that passes through the slit falls on a device that measures the wavelength, as in Fig. 2.10. As the slit is moved along the spectrum, the measured wavelengths will be as plotted in the figure. Several conclusions can be drawn from this demonstration. First, light from the bulb contains quanta of many wavelengths (and since the light looks white if the prism is not in the path, this mixture of wavelengths looks white). Second, the prism interacts differentially with the quanta of different wavelengths, bending the paths of the quanta of shorter wavelength more strongly. Third, since repetitions of this demonstration give the same results,

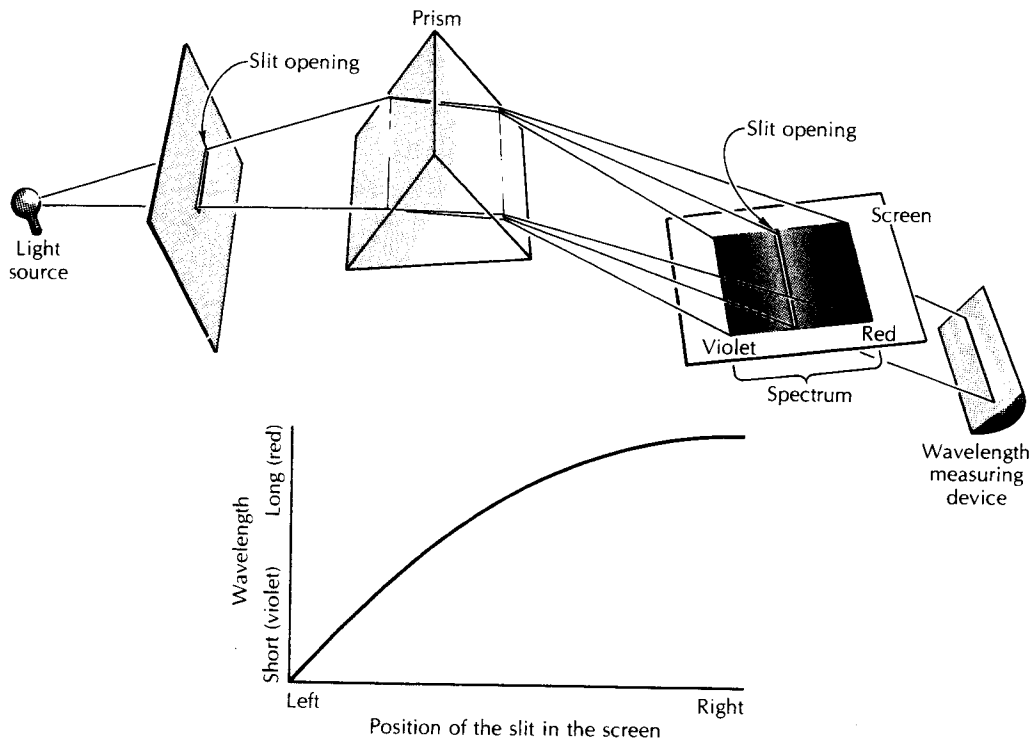


Fig. 2.10 A means of separating and spreading out the wavelengths of light emitted from a light bulb.

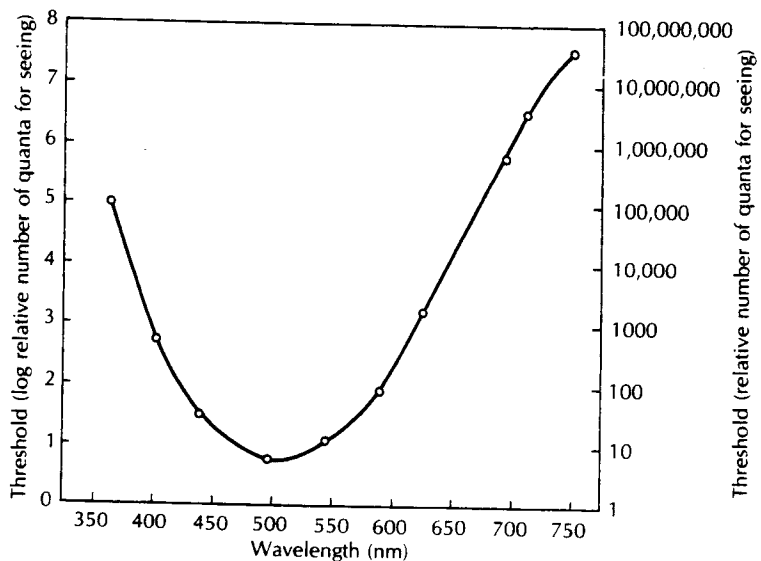
there is a fixed relationship between the wavelength of the light and the color that the observer reports (again, provided that the light is intense enough and the observer has normal color vision). Fourth, this device can be used to obtain light of any desired wavelength in the visible spectrum.

Now let us perform a psychophysical experiment in which flashes of light of different wavelengths are presented to a completely dark-adapted subject (for example, by putting his eye where the wavelength measuring device used to be), and his threshold for seeing the flash is measured at each wavelength. The results of such an experiment are shown in Fig. 2.11. (The subject was completely dark-adapted, the flash was presented peripheral to the fixation point, the test spot was small, and the flash was short.) The plot, called a spectral sensitivity curve, indicates that when the light is chosen from the middle of the spectrum, relatively fewer quanta are required for him to see it than if it is chosen from either end of the spectrum,

and he is maximally sensitive to quanta of about 510 nanometers wavelength. [One nanometer (abbreviated nm), or millimicron, is  $10^{-9}$  meters.] Therefore, Hecht *et al.* used test flashes whose wavelength was 510 nanometers (nm).

(You may wonder why Hecht *et al.* bothered to perform their experiment if the data in Fig. 2.11 were already available. There are several reasons that they went ahead. First, many of the earlier experiments were not sufficiently precise for the exact determination they wished to make. Second, none of the previous experiments optimized all of the experimental conditions. Third, all of the graphs presented thus far, have, on their vertical axes, *relative* number of quanta, or some similar relative measure. The determination of the *absolute* number of quanta at threshold is very much more difficult than a determination of the relative numbers under different conditions, and none of the previous experiments had been designed or performed with provision for such precise absolute measurement.)

Fig. 2.11 Relative number of quanta required to see a short flash to the dark-adapted retina, peripheral to the fixation point, as a function of the wavelength of the quanta. The unit of length applied to wavelengths of light is the nanometer. One nanometer is  $1/1,000,000,000$  m (i.e.,  $10^{-9}$  m). The threshold may be expressed either in relative terms, as on the right, or as logarithms of relative units, as on the left. Note that the logarithmic units are merely the exponents of ten. That is, the numbers on the left are simply the numbers of zeros contained in the corresponding numbers on the right. The curve is called the *spectral sensitivity curve of the rods*. [From Wald (1945), rod curve, corrected from energy to quantal units.]





The title of this section is "The color of the test flash— . . .," but the discussion has centered around the choice of a *wavelength* for the flash. The word *color* was used because it is a familiar one, but it is not a good one in this context. The word *color* refers to a perceptual phenomenon that is closely associated with the physical property of light called wavelength; in general, particular wavelengths give rise to the experiences of (or if you prefer, reports of) particular colors. However, this relationship does not always obtain, and under the particular conditions of the Hecht experiment, it does not hold at all. As a consequence of some of the properties of the eye, to be discussed in detail in later chapters, a dark-adapted observer looking at very dim lights will see no colors at all over most of the spectrum of wavelengths. He will describe all of the stimuli (except those at the very long-wavelength end of the spectrum) as colorless or grey. Light of the wavelength that Hecht *et al.* used in their test flash looks bluish-green when it is intense, but under their conditions, the subject saw only colorless flashes.

The spectral sensitivity curve in Fig. 2.11 has nothing whatever to do with color vision. It does show that the sensitivity of the dark-adapted subject varies with the wavelength of the test light, but the data are determined only by whether or not the subject saw the flash. He is never even asked whether he saw any color in the test flashes.

The lack of color at low illuminations is easy to observe. On a moonlit night, the flowers in a garden can be easily seen, but they are colorless. The physical properties of the flowers have hardly changed, but the intensity of light is too low to bring into operation the color-sensing apparatus in our visual systems.

The physiological correlates of the dark-adapted spectral sensitivity curve are quite well understood. If the subject sees the light in the test flash, then one or more of the quanta must have been absorbed by the visual pigment in his rods. The structure of each pigment molecule is such that, as a quantum passes through it, the quantum has a certain probability of being caught by the molecule. This probability can be imagined as depending upon the fit between the sites on the molecule and the wavelength or energy of the quanta. All of the visual pigment molecules in human rods have the same structure, and that structure fits or resonates best with quanta whose wavelength is about 510 nm. Quanta at 510 nm are most likely to be captured by the pigment, and quanta of other wavelengths are less likely to be captured. If each quantum in a flash is more likely to be captured, fewer quanta must be put into the eye in order that any particular number are captured. Therefore, if it is assumed that a certain number of quanta must be cap-

tured by the visual system in order for the subject to see the flash, then the visual threshold would be expected to be lowest at 510 nm.

**THE EXPERIMENT ITSELF** The subject was dark adapted, one eye was covered, and he was carefully positioned in the apparatus where he looked at a very dim red fixation point with his uncovered eye. The fixation point was just bright enough to see, but not bright enough to interfere with his seeing the test spot when it was flashed  $20^\circ$  away. When the subject was ready, he pressed a key that opened a shutter, delivering a flash having the properties described in the preceding sections. He then signaled whether or not he had seen the flash. This procedure was repeated over and over for many different test-flash intensities. Several subjects were run in this way.

The results for one subject are shown in Fig. 2.12. The other subjects' results were similar. The horizontal scale in this figure is in arbitrary intensity units. The scale on the device that controlled the test-flash intensity was arbitrarily labeled, say on a scale from 0 to 100. On this scale, a setting of 5 will yield an intensity that will be reported as seen 60% of the time. In order to determine how many quanta are contained in this threshold test flash, the intensity control knob might be set at 5, the shutter fired, and the number of quanta arriving at the eye measured with some quantum counting device.

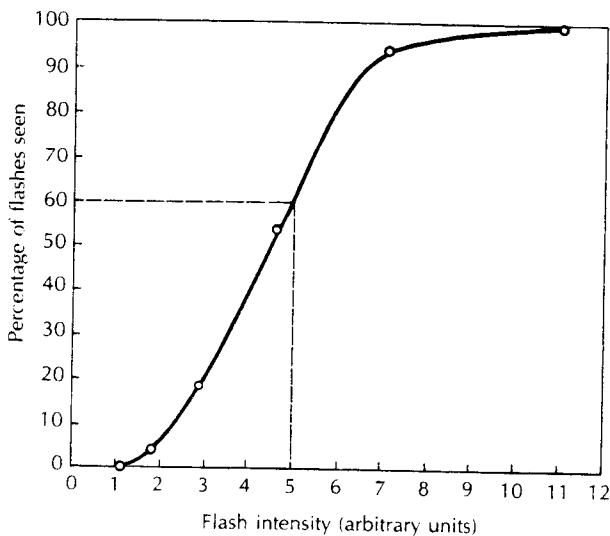


Fig. 2.12 "Frequency of seeing" curve. The data from one subject in the Hecht et al. experiment. [From Hecht et al. (1942), subject S.S.]

If Hecht *et al.* had tried to follow that procedure, (and they may have), they would have found that the number of quanta was so small that it simply could not be measured with the devices that were available to them. In other words, the eye is considerably more sensitive than any physical device that existed at the time. The way in which Hecht *et al.* solved this problem and arrived at a correct intensity calibration will be explained in the next chapter, where those aspects of the physics of light that are important in visual perception will be discussed. From their intensity calibrations, they determined that the flash contained an average of about 90 quanta when the intensity knob was set at 5, that is, at the 60% threshold level.

### THE INTERPRETATION OF RESULTS

Hecht *et al.* determined that the monocular human visual system, under optimal conditions, can detect a flash 60% of the time when it contains about 90 quanta. Thus the eye is remarkably sensitive compared with most physical light-detecting devices. However, that finding is probably the least interesting and least important of their conclusions.

Under their conditions, it is the rods themselves that are the primary receivers of light. That is, any light lost before it gets to the rods cannot affect the subject; he cannot assimilate any visual information about the light if it is not absorbed by the visual pigment in his rods. Therefore, Hecht *et al.* went on to estimate the actual number of quanta absorbed by the visual pigment in the rods during a threshold test flash.

Consider a group of quanta heading for the eye. About 3% of them will be reflected from the front surface of the eye, the cornea. (In the Hecht *et al.* experiment, the light was focused in such a way that none of it struck the subject's iris.) About half of the remaining quanta are absorbed by pigment in the media that fill the eyeball itself. Thus, about 48% of the quanta incident on the eye actually arrive in the region of the rods.

If the back of the human eye 20° from the fovea is examined under a microscope, it will be evident that the rods, seen end on, are spaced approximately as shown in Fig. 2.13. Because of this spacing, some of the quanta that get to the rod surface fall between rods and are lost to the visual system. Even if a quantum does finally enter a rod, it is not necessarily absorbed by a visual pigment molecule. The percentage of incident quanta absorbed depends upon the fit between the quanta and the pigment molecules, and also upon the density of pigment in the rods. From independent observations, Hecht *et al.* estimated that at

a wavelength of 510 nm, no more than 20% of the quanta incident on the retina are actually absorbed by the visual pigment in the rods.

Taking all these losses into account, it may be concluded that a subject will report seeing a flash, under optimal conditions, when only about nine or ten quanta are absorbed by the visual pigment. That is an extraordinarily small amount of energy. A typical lighted flashlight bulb radiates about  $2 \times 10^{15}$  quanta every millisecond (two million million million million).

Hecht *et al.* were able to carry their conclusions even further. In the average threshold flash about ten quanta are absorbed, but they are spread out over an area of the retina 10' in diameter, (about the size of the retinal patch in Fig. 2.13). They estimated that such an area contains about 500 rods. If ten quanta are distributed randomly over an area containing 500 rods, the chances that two quanta will be absorbed by the same rod are very small. Therefore, they concluded that a visual effect will be produced if about ten rods, all within an area 10' in diameter, each absorb a single quantum during the 1-msec flash. This means that a single quantum must be sufficient to activate a rod, and that the effects of the activation of about ten rods all near each other are somehow added up by the visual system.

Since the time that Hecht *et al.* performed their experiment, some of their estimates of the parameters have been superseded (e.g., it is now estimated that the area stimulated contains only about 350 rods), but none of the new estimates are sufficiently different to require a substantial alteration in their conclusions. Other workers have made similar measurements in somewhat different ways, and some have concluded that the total number of quanta absorbed by visual pigment at threshold is only two, rather than ten (Bouman, 1955). However, the

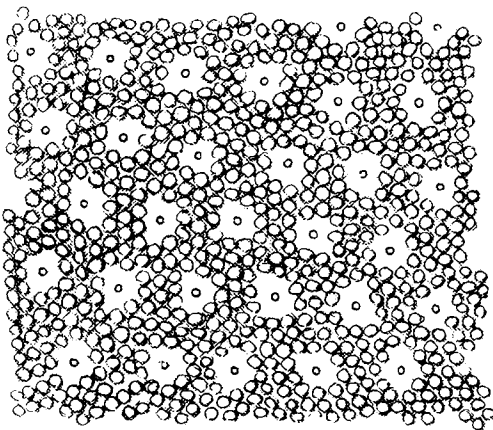


Fig. 2.13 Spacing of the rods, seen end on, results in the loss of about half of the incident quanta. The small circles in this drawing are receptors of a different kind (cones), which are evidently inoperative at threshold intensities in the dark-adapted eye.

[From Schultz (1866), *periphery*.]

90  
1200  
1500

principal finding of Hecht *et al.*, that a single quantum is sufficient to activate a rod, is firmly established.

Hecht *et al.* drew still another conclusion of fundamental importance from their study. Why is it true that, as the intensity of the flash is increased, the proportion of "yes" responses increases *gradually*? Why does it not simply jump from zero, when the apparatus is set to deliver fewer than ten quanta, to 100% when more than ten quanta are absorbed? Put another way, why is it that, with the apparatus set to give a constant intensity, say at the threshold level, the subject sometimes sees the flash and sometimes does not? It is easy to "explain" this observation by simply saying that the subject is human, after all, and is thus variable. Hecht *et al.* demonstrated that, in fact, a large part of the variability is a consequence of the physics of the light itself, and that when this source of variation is taken into account, the subject's judgments are remarkably consistent. This conclusion requires considerable explanation, and is of such fundamental significance to the understanding of visual perception that it will be covered at length in Chapter IV.

- PROBLEMS** 2.1 (a) What is the visual angle subtended by a bull's-eye 1 in. in diameter, 50 yd away?

Answer:

1'56".

- (b) What are the visual angles subtended by the side of a barn ( $40 \times 100$  ft) 50 ft away?

- 2.2 (a) What is the visual angle subtended by an image on the retina that is 1 mm long?

- (b) How big (in millimeters) is the retinal image of the bull's-eye in problem 2.1a?

Answer:

0.009 mm.

- 2.3 (a) What is the diameter of the area of total spatial summation, given that the curve in Fig. 2.5 begins to go up at 10' and that the summation areas overlap to such an extent that each point on the retina is part of two different summation areas, on the average? (If you wish to simplify this problem conceptually, assume that the summation areas are all square.)

- (b) What is the diameter if, on the average, each point is part of three different areas?

- 2.4 From the data in Fig. 2.11, calculate and plot the relative probability of absorption of a quantum by the visual pigment versus wavelength.