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# OPTICAL GENERATION OF THE VISUAL STIMULUS

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## 5.1 GLOSSARY

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$A$	area
$D$	distance
$E_r$	illuminance at the retina (retinal illuminance)
$f$	focal length
$f_e$	focal length of the eye
$L_s$	intrinsic luminance of the source
td	troland (the unit of retinal illuminance)
$x$	position
$\Delta$	change in position
$\Phi$	flux (general)
$\Phi_p$	flux at the pupil
$\tau$	transmittance

We have also consistently used subscripted and/or subscripted versions of  $A$  and  $S$  for area,  $D$  for distance,  $f$  for focal lengths,  $x$  for positions, and  $\Delta$  for changes in position.

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## 5.2 INTRODUCTION

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This chapter presents basic techniques for generating, controlling, and calibrating the spatial and temporal pattern of light on the retina (the visual stimulus). It deals with the optics of stimulus generation and the control of light sources used in the vision laboratory. Generation of stimuli by computer video displays is covered in detail in Chap. 22. Units for measuring radiation are discussed in Chap. 34, “Radiometry and Photometry,” by Edward Zalewski and Chap. 37, “Radiometry and Photometry for Vision Optics,” by Yoshi Ohno in Vol. II.

### 5.3 THE SIZE OF THE VISUAL STIMULUS

The size of a visual stimulus can be specified either in terms of the angle which the stimulus subtends at the pupil, or in terms of the physical size of the image of the stimulus formed at the retina, for most purposes vision scientists specify stimuli in terms of the angular subtense at the pupil. If an object of size  $h$  is viewed at distance  $D$  then we express its angular extent as

$$\text{Degrees visual angle} = 2 \left( \tan^{-1} \left( \frac{h}{2D} \right) \right) \quad (1)$$

or, for angles less than about 10 deg

$$\text{Degrees visual angle} \cong \frac{360h}{2\pi D} = \frac{57.3h}{D} \quad (2)$$

In this chapter we specify stimuli in terms of the actual retinal area, as well as the angular extent. Angular extent has the advantage that it is independent of the eye, that is, it can be specified totally in terms of externally measurable parameters. However, an understanding of the physical dimensions of the retinal image is crucial for understanding the interrelation of eye size, focal length, and light intensity, all of which are part of the design of optical systems for vision research.

### 5.4 FREE OR NEWTONIAN VIEWING

There are two broad classes of optical systems that are used in vision research. Free viewing, or *newtonian* viewing, forms an image of a target on the retina with minimal accessory optics (Fig. 1a).

#### Retinal Illuminance

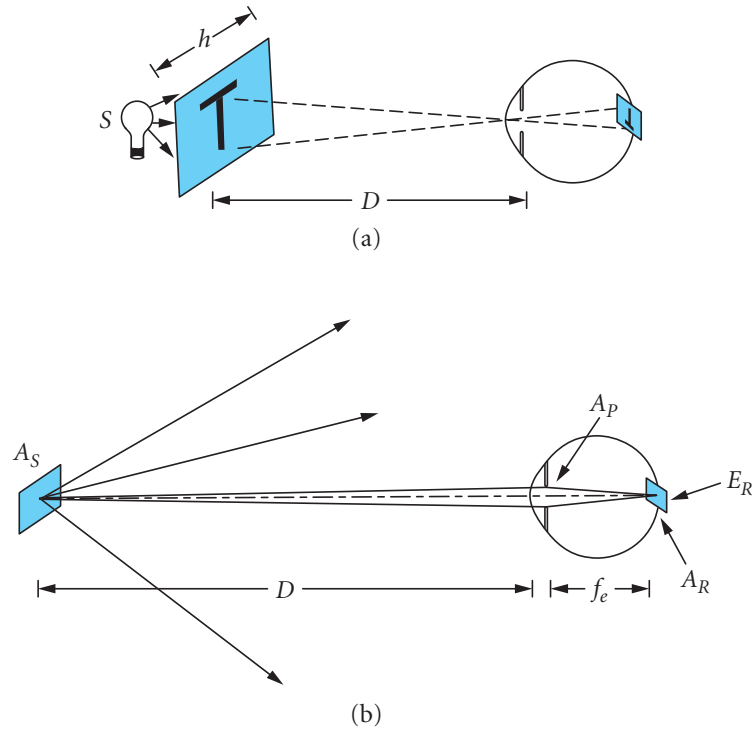
Photometric units incorporate the overall spectral sensitivity of the eye, but that is the only special property of this set of units. That is, there are no terms specific to color (for a discussion of colorimetry, see Chap. 10) and no allowances for the details of visual perception. The eye is treated as a linear detector which integrates across wavelengths. The retinal illuminance of an object in newtonian view is determined by the luminous intensity of the target and the size of the pupil of the eye. The luminous power at the pupil [dimensions are luminous power or energy per unit time, the SI units are lumens (lm)]

$$\Phi_p = L_s A_s \frac{A_p}{D^2} \quad (3)$$

where  $L_s$  is the luminance of the source [the SI units are lumens per meter squared per steradian ( $\text{lm}/\text{m}^2/\text{sr}$ ) or candelas per meter squared ( $\text{cd}/\text{m}^2$ )],  $A_s$  is the source area,  $A_p$  is the area of the pupil, and  $D$  is the distance from the pupil to the source [so  $(A_p/D^2)$  is the solid angle the pupil subtends].

The area of the image element on the retina is

$$A'_R = A_s m^2 = A_s \left( \frac{f_e}{D} \right)^2 \quad (4)$$



**FIGURE 1** (a) In free viewing or newtonian viewing the eye's optics are used to image a target onto the retina. (b) Computation of the retinal illuminance in free-viewing.  $A_s$  the area of the source,  $D$  the distance between the source and the eye,  $A_p$  the area of the pupil,  $f_e$  the optical focal length of the eye,  $A_R$  the area of the image of the source on the retina, and  $E_R$  the retinal illuminance.

where  $m$  is the magnification of the eye and  $f_e$  is the effective focal length of the eye (Fig. 1b). From this we compute the illuminance at the retina as

$$E_R = \frac{\Phi_p}{A_R'} = \frac{A_p L_s}{(f_e)^2} \quad (5)$$

(The SI units of illuminance are  $\text{lm}/\text{m}^2$ ). A typical value for  $f_e$  is 16.67 mm.<sup>1,2</sup> Note that the retinal illuminance does not depend on the distance. That is, the retinal illuminance when viewing an extended source such as a video screen is independent of the viewing distance and is dependent only on the size of the eye's pupil, the luminance of the source, and the focal length of the eye. In most cases, the focal length of the viewer's eye is not known, but it is possible to measure the size of the pupil. For this reason a standard unit for specifying retinal illuminance was developed, the *troland*.

**The Troland (td)** The troland is a unit of illuminance (luminous power per unit area). The troland quantifies the luminous power per unit area at the retina (the retinal illuminance). One troland was defined as the illuminance at the retina when the eye observes a surface with luminance = 1  $\text{cd}/\text{m}^2$  through a pupil having an area of 1  $\text{mm}^2$ . Using Eq. (5) and a standard  $f_e$  of 16.67 mm we find that the troland is defined by

$$1 \text{ td} = 0.0035 \text{ lumens}/\text{m}^2 \quad (6)$$

This definition ties the troland to the illuminance on the retina of a standard eye assuming no transmission loss in the ocular media at 555 nm. Thus, two observers with different-size eyes, different-size pupils, or different relative losses in the ocular media, viewing the same surface, will have different retinal illuminances. Wyszecki and Stiles<sup>2</sup> have recommended that the term *troland value* be used to distinguish the trolands computed for a standard eye from the actual retinal illuminance. General usage is that the retinal illuminance is determined simply by measuring the luminance of a surface in  $\text{cd}/\text{m}^2$  and multiplying this value by the area of the pupil in  $\text{mm}^2$ .

### Limitations of Free Viewing: An Example

There are two major limitations to newtonian view systems. The first is that the retinal illuminance is limited. For instance, a 60-W frosted incandescent bulb can produce a 120,000-td field, but to obtain a uniform 20 deg field it must be placed 17 inches from the observer's eye. This requires an accommodative effort that not all observers can make. A comparable illuminance at more realistic distances, or with variable focus, requires larger light sources or more elaborate optical systems. The second limitation of free viewing is that variations in pupil size are not readily controlled. This means that the experimenter cannot specify the retinal illuminance for different stimulus conditions or for different individuals. Maxwellian view optical systems solve these problems.

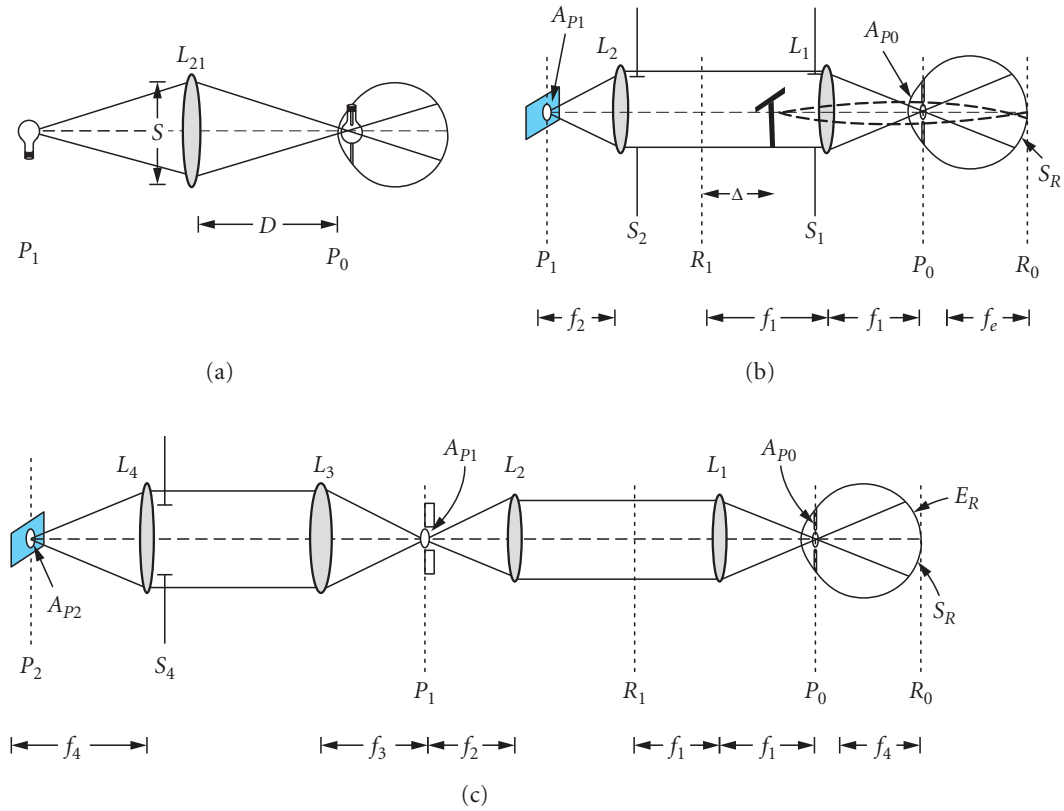
## 5.5 MAXWELLIAN VIEWING

Figure 2a shows a simple *Maxwellian* view system. The key factor that distinguishes the maxwellian view system is that the illumination source is made optically conjugate to the pupil of the eye. As a result, the target which forms the stimulus is not placed at the source, but rather at a separate plane optically conjugate to the retina. In the system of Fig. 2a the plane conjugate to the retina, where a target should be placed, lies at the focal point of lens  $L_2$ , between the source and the lens (see Chap. 6). Light from the source is diverging at this point, and slight changes in target position will cause changes in both the plane of focus and the magnification of the target. For this reason most real maxwellian view systems use multiple lenses. Figure 2b shows such a maxwellian view system where the single lens has been replaced by two lenses. The first lens collimates light from the source and the second forms an image of the source at the pupil. This places the retinal conjugate plane at the focal plane of  $L_1$ . We label the conjugate planes starting at the eye, so  $R_1$  is the first plane conjugate to the retina and  $P_1$  is the first plane conjugate to the pupil.

### Control of Focus and the Retinal Conjugate Plane

The focus of the maxwellian view system is controlled by varying the location of the target.<sup>3-5</sup> Moving the target away from  $R_1$  allows the experimenter either to adjust for ametropia or to require the observer to accommodate. To see this we compute where lens  $L_1$  (Fig. 2b) places the image of the target relative to the eye. If the target is at the focal point of  $L_1$ , the image is at infinity, which means there is a real image in focus at the retina for an emmetropic eye. If we move the target toward lens  $L_1$ , the lens of an emmetrope must shorten the focus to bring the image back into focus on the retina. We quantify this required change in focus as the change in the dioptric power of the eye (or the optical system if spectacle correction is used) where the dioptric power is simply the inverse of the focal length measured in meters. If the target is displaced by  $\Delta$  from the focal point of  $L_1$  then using the newtonian form of the lens formula ( $x'x = f^2$ ) we find that

$$\text{Change in dioptric power} = \frac{\Delta}{(f_1)^2} \quad (7)$$



**FIGURE 2** (a) In a minimal Maxwellian view system a lens  $L_{21}$  images a source in the plane of the eye's pupil. The lens is shown at a distance  $D$  from the eye equal to twice its focal length. The field stop ( $S$ ) in the aperture of  $L_{21}$ . (b) A Maxwellian view optical system with an accessible retinal conjugate plane ( $R_1$ ). Lens  $L_2$  collects light from the source and collimates it. Lens  $L_1$  images the source in the plane of the eye's pupil ( $P_0$ ). Pupil conjugate planes ( $P_i$ ) and retinal conjugate planes ( $R_i$ ) are labeled starting at the eye. For an emmetrope lens  $L_1$  images the retina ( $R_0$ ) at  $R_1$ . This is the plane where a visual target will appear in best focus for an emmetropic observer. Moving the target away from  $R_1$  a distance  $\Delta$  changes the plane of focus of the retinal image, requiring the emmetrope to accommodate. The maximum size of the retinal image ( $S_R$ ) is limited for this system to the aperture of lens  $L_2$  ( $S_2$ ). The pupil is imaged at position  $P_1$ , where the light source is placed. (c) Shows a more complex system where a second set of pupil conjugate and retinal conjugate planes have been added. An artificial pupil ( $A_{P1}$ ) is added at  $P_1$ . It is the image of this pupil at the source ( $A_{P2}$ ) that limits the retinal illuminance produced in this optical configuration. Other symbols as above.

If the target move toward the lens  $L_1$ , this compensating power must be positive (the focal length of the eye or eye plus spectacle shortens). If the target moves from  $f_1$  away from lens  $L_1$ , the required compensation is negative. If the eye accommodates to keep the target in focus on the retina, then the size of the retinal image is unchanged by the change in position.<sup>3,4</sup>

## Size

For this system the area of the illuminated retinal field is determined by the limiting aperture in a retinal conjugate plane between the light source and the retina (the field stop  $S_2$  in Fig. 2b) and is

$$S_R = \left( \frac{f_e}{f_1} \right)^2 S_2 \quad (8)$$

or for the schematic eye we use

$$S_R = \left( \frac{16.67}{f_1} \right)^2 S_2 \quad (9)$$

where  $f_e$  is the focal length of the eye (in mm) and  $f_1$  is the focal length of lens  $L_1$ . This formula is used to compute the physical size of an image on the retina. Note that the linear magnification is  $(f_e/f_1)$  and the areal magnification is  $(f_e/f_1)^2$ . The angular subtense of the field is the same as in Eq. (1), substituting the diameter of  $S_2$  for  $h$  and  $f_1$  for the distance  $D$ . Also note that the angular extent is independent of details of the optics of the eye. This convenience is the main reason that angular extent is the most widely used unit for specifying the stimulus in vision research.

## Retinal Illuminance

One of the *principal advantages* of a maxwellian view system is that it provides a large, uniformly bright field of view. This mode of illumination is called Kohler illumination in microscopy. The light available in a maxwellian view optical system is determined by two main factors, the luminance of the light source, and the effective pupillary aperture of the optical system being used. In Fig. 2b we see that lens  $L_2$  collects light from the source. The amount of light collected is the maximum amount of light that can be presented to the eye and is<sup>1,3</sup>

$$\Phi = A_{p1} L_s \frac{S_2}{(f_2)^2} \quad (10)$$

where  $A_{p1}$  is the area of source being considered (or, equivalently, a unit area of the source),  $L_s$  is the luminance of the source (in lm/m<sup>2</sup>/sr),  $S_2$  is the aperture of lens  $L_2$ , and  $f_2$  is the focal length of lens  $L_2$ . We have used the area of lens  $L_2$ , for this example, although in actual practice this area might be reduced by later field stops. This quantity will cancel out in the subsequent calculations. Finally, if all of the light collected by lens  $L_2$  is distributed across the retina, then the retinal illuminance is

$$E_R = \frac{\Phi}{S_R} = A_s L_s \left( \frac{f_1}{f_2 f_e} \right)^2 \quad (11)$$

where  $S_R$  is obtained from Eq. (8). Note that only the luminance of the source, the source area, and the focal lengths of the optical elements are important in setting the retinal illuminance. Using different diameters for lens  $L_2$  will change the amount of light collected and the size of the retinal area illuminated. Such a change will be reflected by changing the area parameter in both Eqs. (8) and (10), which cancel.

In Eq. (11) the area of the source image ( $A_{p1}$ ) at the pupil is

$$A_{p0} = A_{p1} \left( \frac{f_1}{f_2} \right)^2 \quad (12)$$

If the eye's pupil ( $A_{p0}$ ) is smaller than this source image then the eye's pupil is limiting and

$$E_R = \frac{A_{p0} L_s}{(f_e)^2} \quad (13)$$

Equation (13) for the maxwellian view system is identical to Eq. (5) which we obtained for the newtonian view system, but now the entire field is at the retinal luminance set by the source luminance. Thus, in maxwellian view a large, high retinal illuminance field can be readily obtained.

To control the size of the entry pupil rather than allowing it to fluctuate with the natural pupil, most maxwellian view systems use a pupillary stop. Figure 2c shows a system where a stop has been introduced at an intermediate pupil conjugate plane  $A_{p1}$ . This has the advantage of placing the pupillary stop of the system conjugate to the eye's pupil. The projection of  $A_{p1}$  at the source is  $A_{p2}$  and it is  $A_{p2}$  that limits the available luminous area of the source. Lenses  $L_3$  and  $L_4$  image the source onto the artificial pupil, and lenses  $L_1$  and  $L_2$  image the artificial pupil in the plane of the eye's pupil ( $A_{p0}$ ). The retinal illuminance of this more complex system can be computed as follows: the field stop over which light is collected by lens  $L_4$  is  $S_4$  and can be computed by projecting the retinal area illuminated ( $S_R$ ) back to lens  $L_4$ .

$$S_4 = S_R \left( \frac{f_1 f_3}{f_2 f_e} \right)^2 \quad (14)$$

$A_{p2}$  is the area of the source which passes through the artificial pupil:

$$A_{p2} = \left( \frac{f_4}{f_3} \right)^2 A_{p1} \quad (15)$$

Therefore the total amount of usable light collected is

$$\Phi = L_s A_{p2} \frac{S_4}{(f_4)^2} = S_R L_s A_{p1} \left( \frac{f_1}{f_2 f_e} \right)^2 \quad (16)$$

and the retinal illuminance is

$$E_R = \frac{\Phi}{S_R} = L_s A_p \left( \frac{f_1}{f_2 f_3} \right)^2 \quad (17)$$

Note that, as in Eq. (13),  $[A_{p1}(f_1/f_2)^2]$  is the size of the image of the aperture  $A_{p1}$  when measured at the exit pupil ( $A_{p0}$ ). Thus, even in this more complex case we find that the retinal illuminance is dependent only on the source luminance, the pupillary area measured at  $P_0$ , and the focal length of the eye.

## Advantages of Maxwellian Viewing: Example Revisited

The strength of a maxwellian view system is that properties of the target (focus, size, shape) can be controlled independently from retinal illuminance. If the source is larger than the limiting pupil, then the maximum retinal illuminance is the luminance of the source, scaled only by the exit pupil and eye size [Eqs. (13) and (17)]. The retinal illuminance is controlled by pupillary stops, and the target size, shape, and focus are controlled by retinal stops. Additionally, focus can be controlled independently of retinal illuminance and image size.

If we use the 60-W frosted bulb that we used in the example of newtonian viewing as a source in a maxwellian view optical system we find that we can produce the same maximum retinal illuminance for a given pupil size [Eqs. (5) and (13)]. However, with the maxwellian view system relatively inexpensive, achromat lenses will allow us to generate a field size greater than 20 deg. In addition, we can dispense with the frosted bulb (which was needed in free viewing to give a homogeneously illuminated target) and use an unfrosted tungsten halogen bulb to produce in excess of 1 million td.

## Controlling the Spatial Content of a Stimulus

The spatial frequency content of a retinal image is usually measured in cycles per degree (of visual angle). The frequencies present in the retinal image are those present in the target, cut off by the limiting aperture of the pupillary stop—either the eye's pupil or an artificial pupil in a pupillary plane *between the target and the eye*.<sup>25</sup> Apertures placed on the source side of the target do nothing to the spatial frequency content of the retinal image, leaving the pupil of the eye controlling the image, not the artificial pupil. (For a more detailed treatment of the effects of pupils on the spatial content of images see Refs. 6–10. For a discussion of the spatial resolving power of the eye's optics see Chaps. 1 and 4 in this volume of the *Handbook*).

## Positioning the Subject

One of the practical disadvantages in using maxwellian view systems is the need to position the eye's pupil at the focal point of the maxwellian lens ( $L_1$  in Fig. 2c) and to maintain its position during an experimental session. One technique for stabilizing the position of the eye is to make a wax impression of the subject's teeth (a bite bar). By attaching the bite bar to a mechanism that can be accurately positioned in three dimensions (such as a milling machine stage) the eye can be aligned to the optical system and, once aligned, the eye position is maintained by having the subject bite loosely on the bite bar. Alignment of the eye can be achieved either by observing the eye, as described at the end of this chapter, or by using the subject to guide the alignment process as described in the following paragraphs.

The first step in alignment is to position the eye at the proper distance from lens  $L_1$ . This can be accomplished by noting that, when the eye's pupil is at the plane of the source image, slight movements of the head from side to side cause the target to dim uniformly. If the eye's pupil is not at the proper distance from lens  $L_1$  then moving the head from side to side causes the target to be occluded first on one side, then the other. By systematically varying the distance of the eye from lens  $L_1$ , the proper distance of the eye can be determined. It is then necessary to precisely center the eye's pupil on the optical axis of the apparatus. There are several approaches to centering the eye.

1. The physical center of the pupil can be located by moving the translation stage such that the pupil occludes the target first on one side, then on the other. The center of these two positions is then the center (in one dimension) of the pupil. The process is then repeated for vertical translations.
2. The entry position that produces the optimum image quality of the target can be determined. One variant is to use a target that generates strong chromatic aberration (for instance, a red target on a blue background). The head can then be moved to minimize and center the chromatic fringes.<sup>11</sup> This process defines the achromatic axis of the eye.
3. The eye can be positioned to maximize the brightness of the target, which centers the Stiles-Crawford maximum in the pupil with respect to the exit pupil of the instrument.
4. A set of stimuli can be generated that enter the eye from different pupil positions. If the eye is centered, then all stimuli will be seen. If the eye is not centered, then the pupil occludes one of the pupil entry positions and part of the stimulus array disappears. In this case, the subject merely has to keep his or her head positioned such that all stimuli are visible.

## 5.6 BUILDING AN OPTICAL SYSTEM

### Alternating Source Planes and Retinal Planes in a Controlled Manner

The separation of retinal and pupil conjugate planes in a maxwellian view system allows precise control over the spatial and temporal properties of the visual stimulus. By placing the light source conjugate to the pupil of the eye, every point on the source projects to every point in the retinal image

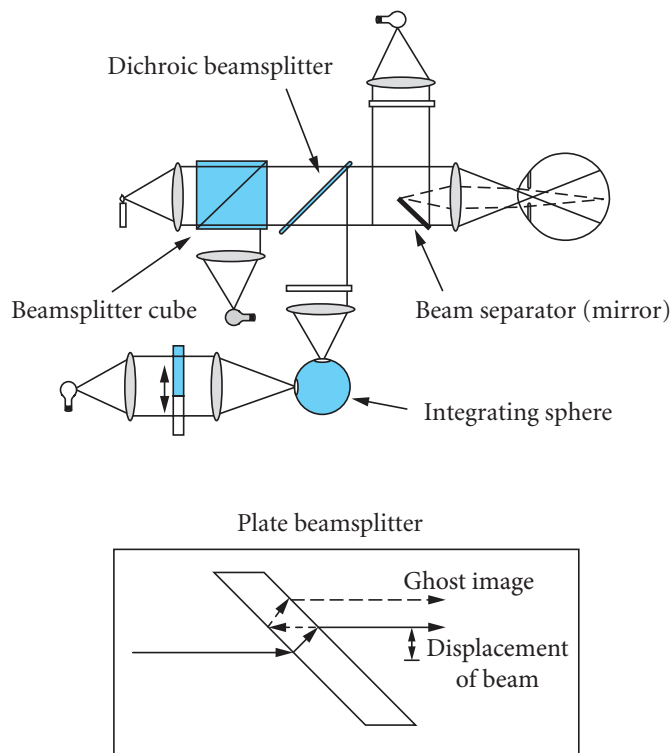


and vice versa. Thus, to control the whole retinal image, such as turning a light on and off, manipulation of a pupil conjugate plane is optimal. To control the shape of the retinal image without altering the entry pupil characteristics, variation at the retinal conjugate planes is required. However, there is an exception to this rule. Light from the edges of the image traverse the pupil conjugate plane at a higher angle than light from the center of the image. For small fields (<15-deg diameter) the angular dependence is minimal, but for larger fields it can be significant and filters should be placed in a collimated light path.

## Combining Lights in an Optical System

To control aspects of the visual stimulus independently, different light sources and targets, each with its own set of filters and shutters, can be combined. We will call these separate “channels.” Three different techniques allow for combining optical channels, beamsplitters, beam separators or reflective apertures, and diffusers. All three methods are demonstrated in Fig. 3.

**Beamsplitters** A beamsplitter both transmits and reflects a fraction of the incident light. Any surface with an index of refraction change can be a beamsplitter. In vision we generally use either a cube or a plate beamsplitter. By locating the beamsplitter in a collimated portion of the optical system (Fig. 3), but away from a retinal conjugate plane, two channels can be combined. For channels with different spectral compositions the beamsplitter can be dichroic, reflecting some wavelengths and transmitting others, usually by interference effects. Plate beamsplitters have the disadvantage

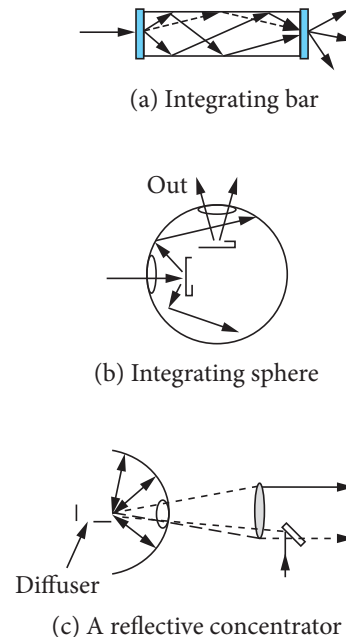


**FIGURE 3** Techniques for combining light from different light sources or optical paths. The inset illustrates potential problems that need to be considered when using a plate style of beamsplitter. These problems are eliminated by the use of a cube beamsplitter or wedge beamsplitter.

that there are secondary reflections, slightly displaced (inset, Fig. 3) from the main beam. In an image-carrying beam this produces “ghost” images, slightly displaced from the main image. The displacement decreases with decreasing thickness. A pellicle is simply a plate beamsplitter with negligible thickness. A wedge beamsplitter displaces a ghost image a long way, and Liebman has used this to design a tapered beamsplitter with no secondary reflections.<sup>12</sup> Unlike plate beamsplitters, the beamsplitter cube has the advantage that there is no lateral displacement of an image.

**Beam Separators (or Reflective Apertures)** A beam separator combines two optical channels into one, while keeping the light spatially distinct. For instance, a mirror placed halfway across the aperture at 45 deg combines two channels at 90 deg to each other. Such a separator in a retinal conjugate plane is imaged at the retina to produce a bipartite field (Fig. 3). The mirror must be oriented to hide the bevel from the subject and must have a high-quality edge. A transparent plate evenly silvered in a pattern and optically sandwiched between right angle prisms is a convenient beam separator with good edges.

**Diffusers, Integrating Spheres, and Optical Fibers** Diffusers also mix light. Diffusers are used when either the spatial uniformity of the final beam or thorough spatial mixing of light sources is important. The direction of light remitted from the diffuser is independent of the incident light, which simplifies the combination of sources. Both integrating spheres and integrating bars have been used to combine lights (Fig. 4a and b, respectively). Diffusers have been widely used in the construction of colorimeters.<sup>2</sup> In the La Jolla colorimeter<sup>13</sup> light is passed through a filter assembly with three monochromatic filters assembled edge to edge. Moving the filter assembly across the light path changes the relative proportions of the light impinging on each filter, which changes the average color of the light. An integrating sphere then completely mixes the colors producing a variable chromaticity light source without the spatial inhomogeneity of the filters. The major disadvantages of using diffusers are light loss, the need for careful optical baffling (since any light impinging on the diffuser gets mixed into the system) and the gradual deterioration of the diffuser due to dirt and dust. While the light loss from an



**FIGURE 4** An example of different types of beam combiners based on diffusers. In general it is critical that high-efficiency diffusing materials be used in all of these techniques.

integrating sphere is ideally very low, slight decreases in the efficiency of the diffusing surfaces cause large losses in the output. Collection of light from a simple diffuser can be increased by the use of a spherical mirror<sup>14</sup> (Fig. 4c). Similarly, a noncoherent fiber-optic bundle can be used to mix lights.

Mixing coherent light sources with diffusers requires movement to minimize interference (speckle) effects. Either liquid diffusers<sup>15</sup> which work by Brownian motion or moving diffusers<sup>16</sup> can be used.

## Lenses

Lens orientation affects any optical system. For instance, the most curved surface of a lens should be toward the more collimated light. This makes both sides of the lens share the work of refraction and decreases aberrations. Achromats reduce both spherical and chromatic aberrations (they have three or more refracting surfaces) and are typically designed to form a collimated beam.

Typically, the goal in aligning an optical system is to place all lenses upon a common optical axis, oriented such that a ray of light traversing that axis is not deviated. A simple prescription is

1. Define the system axis using pinholes, pointers, or a laser beam, with all lenses removed. In a multichannel optical system it is often easiest to start from the position of the eye's pupil ( $P_0$ ).
2. Introduce mirrors, beamsplitters, and other nonrefractive optics in their proper positions, being careful to keep the beam at the same height. A technique for ensuring a constant height, such as a movable pinhole, also helps.
3. Starting at the alignment source, set each lens, one at a time, such that its Boys points lie on the system axis. The Boys points are the focused reflections from the various curved surfaces of lenses (see Ref. 17 for a detailed discussion of using Boys points for alignment). When using a laser they are the "bull's eye" interference patterns. Lateral translation of the lens moves the first (brightest) Boys point and rotation moves the second, so convergence is rapid.
4. To determine the position of a lens along the optical axis, a photographic loop (a magnifying lens) and a target grid (graph paper) can be used. By placing the graph paper at a known location such as at the exit pupil, and then looking with the photographic loop into the system (turn off the laser first!) the exact position of the next pupil conjugate point can be determined. To position a lens to collimate light from a source, place a mirror in the collimated beam, reflecting the light back into the lens. When the lens is placed at one focal length from the source, the mirror causes the source to be imaged back onto itself (autocollimation).

## Field Quality

The uniformity of the illumination of the retinal image is controlled by the size and emission characteristics of the source and by the uniformity of illumination of the target. Ideally, a source emits uniformly into all angles subtended by the collection lens (lens  $L_2$  in Fig. 2). LEDs do not meet this requirement and produce inhomogeneous illumination unless the light is further diffused. Tungsten-halogen sources with coiled-coil filaments uniformly illuminate the collecting lens and can produce uniform retinal images. Problems arise if a retinal conjugate is placed too close to a pupil conjugate plane. This occurs most often when the target is placed at the end of a long collimated portion of the optical path. In this case, the structure of the source becomes visible at the retinal plane. In general, collimation lengths should be kept to less than roughly twice the focal length of the collimating lens. It is also important to control the pupillary conjugate points; in some cases multiple pupil conjugate apertures can help.<sup>18</sup>

## Controlling Wavelength

Spectral composition of a light source can be varied either by absorbing the unwanted light (in a filter), or by redirecting it (by either interference or refraction). Table 1 presents techniques for controlling wavelength. Interference filters can have blocking filters that absorb wavelengths outside the specified transmission band. However, a blocking of  $10^{-3}$  may not be sufficient for the human visual

**TABLE 1** Controlling Wavelength

Technique	Properties	Advantages	Disadvantages/Comments
Absorption filters: aka dye, film, gel, or pigment filters	Available in both gels and glass forms. Generally broadband.	Can be extremely stable over time. Wide range of colors available. Reasonably priced.	Broadband, can be damaged by too much light, as encountered with lasers and focused beams. Most fluoresce.
Narrowband interference	Half-width about 10 nm, usually bonded to an absorption filter for blocking distant wavelengths.	Convenient, readily available, and moderately priced.	If not fully sealed, humidity can cause long-term degradation. Wavelength depends on angle of incidence. Need good blockers.
Broadband interference (see also dichroic beam splitters)	Half-width 40–100 nm.	Same as narrowband interference filters, less need for blocking filters.	
Grating monochromators	Tunable, bandwidth can be set by slits.	Can have low stray light.	Must match aperture of system to the interior grating to minimize stray light. Expensive.
Prism monochromators	Produces a spectrum by refraction.	High throughput.	Bulky.
Interference wedges (spatially varying interference filters)	Allow continuous change of wavelength by changing the position of light incidence.	Small, easy to use.	Some have more leakage than a monochromator, may not be adequately blocked for higher-order transmission. Must be placed at a pupil conjugate point to avoid chromatic wedging on the retina.
Special sources (Na, Cd, etc.)	Discharge sources that produce a few exactly specified spectral lines.	Many lines are available. Very pure wavelengths. Larger aperture sources are available.	Mostly replaced by lasers which are stable, cheap, and easier to use but are point sources (see Table 5).

system. For instance, a narrow 670-nm filter may transmit only  $10^{-3}$  of the intensity at 555 nm, but the human visual system is about 30 times as sensitive to 555 nm as to 670 nm and can integrate over the entire visible spectrum. Thus, the visual effectiveness of the “blocked” light can be considerable. Monochromatic and narrowband light sources and lasers can also be used both to provide a specific wavelength and to calibrate the wavelength scale of monochromators.

Wavelength selection filters are best placed in a collimated beam to avoid changing the passband to shorter wavelengths. This shift is asymmetric, and the maximum transmission changes as the angle of incidence decreases from 90 deg.<sup>2</sup> Differently colored lights can be combined using broadband interference filters (dichroic filters) placed at an angle, but using narrowband filters designed for normal incidence at 45 deg can introduce unwanted polarization properties.<sup>2</sup> Filters designed for use at 45 deg are readily available.

## Turning the Field On and Off

Light from an optical channel can be clocked entirely by a shutter. Shutters should generally be located at a pupil conjugate plane. At this position the source is focused to a small area and thus a smaller, faster shutter can be used. In addition, manipulation of a pupil plane changes the retinal image uniformly (see above). Parameters of interest are the speed, repetition rate (and duty cycle), and the transmission of the shutter in both its open and closed states. Table 2 summarizes details on common types of shutters. Shutters that work by means of polarization generally need to be placed in a collimated beam, and their extinction (transmission when off) and maximum transmission are wavelength-dependent.

## Controlling Intensity

The visual system operates over about 11 log units of luminance (11 orders of magnitude, or  $10^{11}$ ), and within this range can make discriminations of 0.1 percent or better. This level of visual capability requires a two-stage control of retinal illuminance. The overall retinal illuminance is set by

**TABLE 2** Types of Shutters

Shutter	Speed	Size of Aperture (mm)	T off/T on	Comments
Mechanical shutter	ms	1 mm and up	0	Larger apertures are slower. Most designs cannot run in a continuous mode, but these are ideal for low duty-cycle use.
Galvanometers	ms	A few mm for high speeds	0	Operating at high rates requires fairly careful driver design but they can be used to excellent effect and are commercially available with drivers. Can be run continuously.
Choppers	kHz	Variable	0	For continuous on-off flicker choppers are ideal. They have no attenuation when open and no transmission when closed. Small, feedback-controlled devices are available off the shelf. Stepper motors with vanes mounted on the shaft can also be used.
Acousto-optic modulator (AOM)	$\mu$ s	<2 mm	$\sim 10^{-3}$	AOMs have small aperture and high $f$ -number and thus work best for lasers. They are inherently chromatic and orientation-sensitive. Polarization effects can be important.
LCD shutters	ms	A few cm	$\sim 10^{-2}$	Speeds are increasing rapidly, works by polarization. Maximum transmission is less than 50 percent. Use in collimated beam.
LCD displays	$\mu$ s	Work as video screens; individual pixels can be $\mu$ m.	$\sim 10^{-2}$	Work by polarization. Speed is increasing with development of displays for computer use.
Kerr cells	ps	cm	$\sim 10^{-2}$	Require high voltages, work by polarization.

discrete neutral density filters, while smaller steps are set by either a variable density filter or an electronic system. Due to limited precision in most measuring instruments, it is hard to calibrate an individual filter with a density greater than 3.0.

**Varying the Intensity of the Field** The intensity of a channel can be varied by using fixed or variable filters, or by controlling the radiance of the source. For simple, relatively slow (1/min) changes in retinal illuminance, neutral density filters are appropriate. For faster changes, modulators or direct variation of the source radiance are typically required.

**Filters** Neutral density filters either have a uniform attenuation across their spatial extent (fixed filters) or vary in their attenuation characteristics depending on the spatial location (variable filters or “wedges”). Absorbing filters should be used in a collimated beam to avoid different path lengths through the filter. Wedges are used at a pupil conjugate plane to avoid imaging the density gradient on the retina. Fixed filters are typically used to set fixed parameters (such as the average luminance), variable filters to control the brightness continuously (for instance, in an increment threshold test). Table 3 presents some types of neutral density filters.

**Modulators** Passing linearly polarized light through a rotating polarizer produces sinusoidal modulation of the transmitted light. Careful optical design allows generation of an excellent variable modulation, flicker stimulus.<sup>19,20</sup> Acousto-optic modulators (AOM) can be used to vary a light rapidly, but have only a small aperture. Mechanical methods have also been used for temporally modulating a target.<sup>21–23</sup> For the most part, mechanical modulators and moving polarizers have been replaced by direct control of light sources by high-speed shutters and by video systems (see Chap. 22 in this volume of the *Handbook*).

**TABLE 3** Neutral Density Filters

Method	Advantages	Disadvantages	Other Comments
Metal film neutral density filters	Readily available, stable, spectral neutrality is good.	Must be cleaned with care, pinholes can cause a problem. Interreflections between filters can cause deviations from density obtained when calibrated alone.	Silver and inconel are most common. Tilt to keep reflections out of the system.
Multilayer dielectric filters	Easier to clean.	Expensive, chromatic.	
Metal film “wedges”	Same as metal film filters.	Same as metal film filters.	Tilt to aim reflections out of the system. Use in a pupil conjugate plane to avoid spatial variation of image.
Absorbing gel filters	Less expensive, easily available at good photography stores.	They become brittle with age. Somewhat chromatic. Damaged by intense light.	Keep dry and away from a hot lamp. Use in a collimated light path.
Sector disk and mechanical devices (cams, variable slits, etc.)	Spectrally flat.	Must be used in a pupil plane to get desired results.	Use in a pupil conjugate (or in a uniform beam before an integrating sphere). Variable slits can be a simple, inexpensive way to control intensity.
Photographic film or film wedges	Cheap, easily made by flashing a film and developing.	Spectral neutrality will be poor in relation to commercial filters. Must be calibrated. Stability over time will depend on the film base used.	Best used with monochromatic light.



*Varying the Source* Varying the radiance of the light source is fast, and is particularly straightforward with electro-optical sources such as LEDs and diode lasers. However, control of the source is not limited to these devices and can be used with thermal sources (incandescent bulbs), xenon arcs, and fluorescent lights as well. There are four major problems to be overcome when directly varying a light source: (1) nonlinear current versus radiance characteristics, (2) changes in the current-radiance relation over time, (3) temporal hysteresis in the current-radiance relation, and (4) changes in the wavelength distribution of the source with changes in current.

For instance, LEDs have been considered ideal light sources by some investigators, yet they show the same deviations from ideal behavior common to other sources<sup>24–29</sup> (see Chap. 15, “Artificial Sources,” by Anthony LaRocca, Chap. 17, “Light-Emitting Diodes,” by Roland H. Haity, M. George Craford, and Robert M. Weissman, and Chap. 18, “High-Brightness Visible LEDs,” by Winston V. Schoenfeld in Vol. II). The current/radiance relation of LEDs depends on the internal temperature of the device. Thus, the relation changes with both the measurable *temperature* (due to both the environment and to the time average current) and with the immediate current history (for instance, it was just driven at a high current). Finally, the temperature also affects the probability of electronic transitions in the semiconductor, which can change the *wavelength* emitted. For LEDs used in visual work this wavelength dependence has been measured to be on the order of a 1.6-nm change in dominant wavelength with variation of the duty cycle for an ultrabright red LED.<sup>26</sup> Thermal sources, such as a tungsten-halogen bulb, undergo especially large changes in spectral output with changes in current. With these sources, only a narrow spectral band should be used if the source is controlled. In addition, the thermal inertia of an incandescent source precludes rapid modulation, although slow modulation (~1 Hz) can be achieved. Even fluorescent sources which have been widely used in some areas of research show significant changes in spectral output with time.<sup>30</sup>

While heat sinks can help to stabilize the response characteristics of many devices, linear control still requires careful driver design. Drivers can use either an analog or binary design. Analog drivers control the source radiance by varying the current, while digital drivers turn the source either on or off, with the average radiance set by the proportion of time that the source is on (the duty cycle). An advantage of the binary scheme is that transistors dissipate less power in the on and off states than in intermediate states.

There are four major approaches to linearization:

1. Calibrate the current-luminance relation and build a driver with the inverse nonlinearity. For simple applications this technique is adequate. However, for demanding applications the driver becomes complex and the demands for stability in the driver raise new problems.
2. Calibrate the current-luminance relation and use an inverse nonlinearity in computer memory (a lookup table). This technique is quick and easy to implement. A static lookup table will not compensate for dynamic nonlinearities (hysteresis) but a variation of this approach, known as *delta modulation*, will. With delta modulation a linear detector is used to precalibrate the output of a binary driver to produce the desired waveform. By later playing back the binary sequence, the waveform can be re-created exactly. Thus, delta modulation can be used to compensate for all source nonlinearities except for changes in wavelength. The disadvantage is that the waveform must be precalibrated.
3. Vary the ratio of the on and off time periods (the duty cycle) of the source using a binary driver. With a fixed cycle time, the on time can be varied (pulse-width modulation or PWM). PWM works fairly well, but is sensitive to capacitance and nonlinear switching effects that can alter the waveform for either short on or off periods. A similar approach is to use fixed (short) pulses and vary the frequency of the pulses (pulse-frequency modulation or PFM). This approach has the advantage that every pulse is identical, thus capacitance and switching effects are minimized. PFM has been used to control the luminance of LEDs<sup>27</sup> and AOMs<sup>16</sup> linearly over a 1000:1 luminance range.
4. Detect the light with a linear photodetector and use feedback within the driver to linearize the output. By using a PIN photodiode in photovoltaic mode (see Chap. 24, “Photodetectors,” by Paul R. Norton in Vol. II), it is possible to construct a very linear circuit.<sup>28,31</sup> Light feedback can be used with either analog or binary drivers.

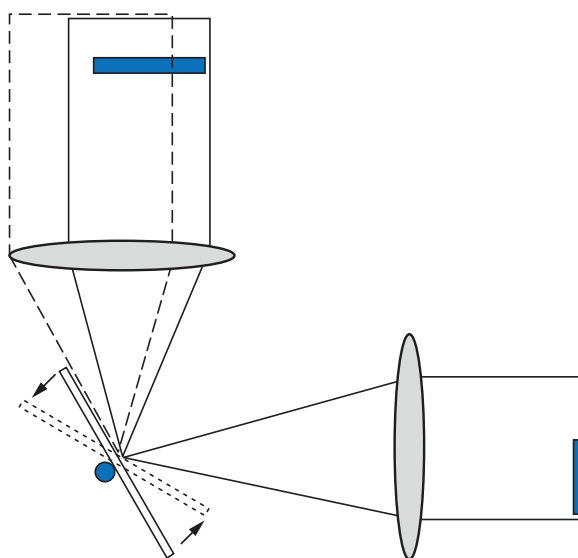
## Generating Complex Temporal and Spatial Patterns

Any type of light source or visual stimulus, from video monitors to street scenes, can be integrated into an optical system, giving improved control of luminance and pupil position. Thus, almost anything can be used as a target. Stimuli can be moved without varying the position of light entry in the eye's pupil by (1) translating a target in the retinal plane, (2) using a cathode ray tube (CRT) or a liquid crystal display (LCD) in a retinal conjugate plane, or (3) rotating a mirror in a pupil conjugate plane.<sup>22</sup>

Rotating a mirror in a pupil conjugate plane changes the angle at which light enters the eye, but not the pupil entry position. This technique has been used for generating motion and counterphase gratings<sup>21</sup> and for decreasing the apparent inhomogeneity of a stimulus by moving the image at a rate above flicker fusion. Galvanometers are commonly used to generate the motion (Fig. 5).

**Video Monitors and CRTs** The combination of a video display with a maxwellian view optical system allows the experimenter the advantages of precise control of the pupil, use of a broad spectral range of backgrounds (provided by the traditional optics), and the fine spatial control available in a video system. The video monitor or CRT is placed at a retinal conjugate plane and the other optical channels are added to it. By passing the combined light path through an aperture at a pupil conjugate plane it is possible to control the pupil size for the video system, insert achromatizing lenses, and the like (see Fig. 8 later in the chapter).

**Liquid Crystal Displays** One type of video display that is of increasing utility is the liquid crystal display (LCD) (Chap. 22). LCDs, unlike video monitors, work by transmission or reflection; they are not self-luminous. Thus, while the wavelength composition of a monitor is determined by the characteristics of its phosphors, the LCD can be used with *any* light source. LCD displays work by changing the polarization state of local regions of the display (pixels). The pattern of pixels is controlled by a video signal or a computer. Like most polarization devices, the extinction ratio is wavelength-dependent and the proportion of light transmitted in the off state may be relatively high. With color versions of the newer active matrix LCDs it is possible to pass three wavelengths of monochromatic light through the color LCD and have a spatially controlled, high-intensity display with the maximum possible gamut. In this case the LCD is placed at a retinal conjugate plane.



**FIGURE 5** A movable mirror located in a pupil conjugate plane allows motion of the retinal image without moving the pupil conjugate images.



## Calibration

There are several approaches to calibrating the retinal illuminance of a maxwellian view system. All depend on either a standard source of known luminance (a reference source) or a calibrated, linear<sup>31,32</sup> photodetector. In the past, calibration typically depended on referring the illuminance of an optical system to a carefully maintained standard light or by measuring the luminance of a diffuser. Well-calibrated photometers and radiometers are now readily available, and we will cover techniques based on using these (the reader is referred to Westheimer<sup>3</sup> for other approaches). We assume that all of the light arriving at the exit pupil of the instrument enters the eye and that the exit pupil can be adequately approximated as circular with a radius of  $r$ .

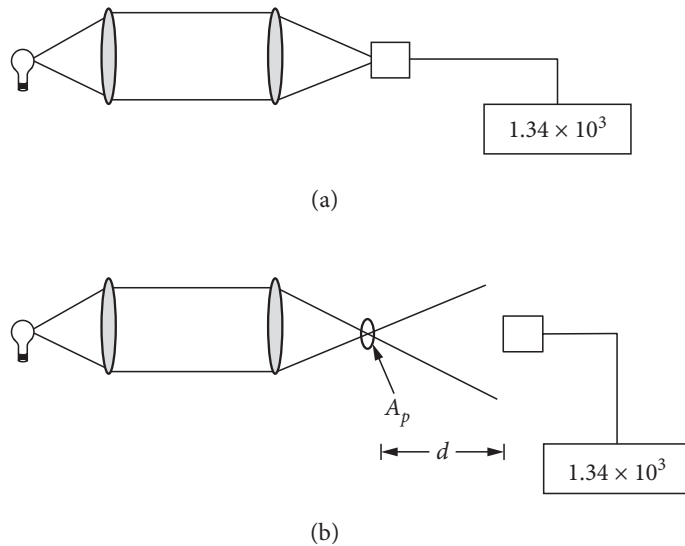
**Measurement of Power at Exit Pupil** With the first technique (Fig. 6a) a calibrated detector is placed at the exit pupil of the maxwellian view device. First, the total luminous power at the exit pupil is measured. Next, the retinal area illuminated is computed from the geometry of the stimulus [Eq. (12)]. From these two quantities the retinal illuminance can be computed. This calculation specifically assumes that all of the power is uniformly distributed across the retinal image. Conversion of retinal illuminance from  $\text{lm}/\text{m}^2$  to trolands is achieved using Eq. (6).

**Measurement of the Illuminance on a Detector** In this technique the illuminance falling on a detector at a fixed distance from the exit pupil is measured (Fig. 6b; also see Ref. 33). A circular source of luminance  $L$  and radius  $r$  produces an illuminance  $E$  on a detector at distance  $d^2$ . If we assume that the source dimensions affect the calibration negligibly ( $r < d/10$ ;  $r < f_e/10$ ), then

$$E = \frac{L\pi r^2}{(d^2)} \quad (18)$$

We want to relate  $E$  as measured by the detector to  $E_R$ , the retinal illuminance, which is

$$E_R = \frac{L\pi r^2}{(f_e)^2} \quad (19)$$



**FIGURE 6** Techniques for calibrating an optical system. (a) Measure the luminous power of the exit pupil and assume that it is uniformly distributed in the retinal image. (b) Measure the illuminance produced by an exit pupil of radius  $r$  at a detector located at distance  $d$  from the exit pupil.

Combining Eqs. (18) and (19) we have

$$E_R = \frac{(d)^2}{(f_e)^2} E \quad (20)$$

If the radius of the exit pupil ( $r_p$ ) cannot be ignored then we need to account for its properties as a light source. If the exit pupil is circular and can be approximated as a lambertian emitter, then the illumination on the detector [Eq. (18)] is

$$E = \frac{L\pi r^2}{(r_p^2 + d^2)} \quad (21)$$

(Ref. 2, Chap. 56, Table I(4.4)). Likewise, the retinal illuminance [Eq. (20)] is

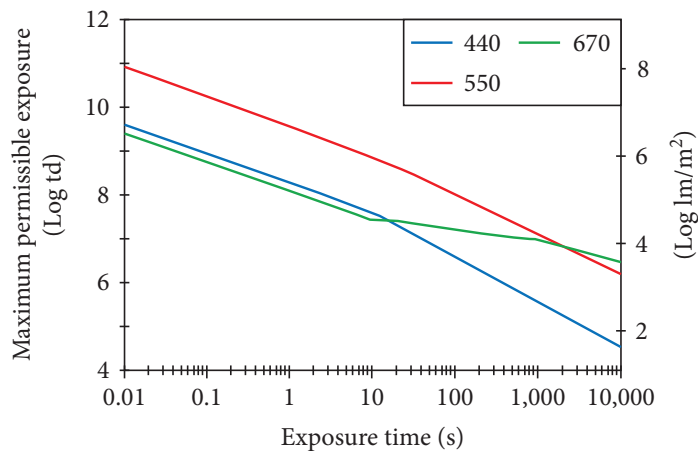
$$E_R = \frac{(r_p^2 + d^2)}{(r_p^2 + (f_e)^2)} E \quad (22)$$

The troland value of  $E_R$  can be computed from Eq. (16).

## 5.7 LIGHT EXPOSURE AND OCULAR SAFETY

There are two main mechanisms by which light can damage the eye. The first is simply by heating: too much radiation burns the retina. The second mechanism is photochemical. Light, especially short-wavelength light, causes photochemical oxidation. The by-products of this oxidation are toxic to the retina (see Chap. 7).

Figure 7 shows the relation of the danger thresholds as defined by the ANSI 136 standard,<sup>34</sup> expressed in tds and lumens/m<sup>2</sup>, for a 440-, a 550-, and a 670-nm light. These thresholds are for field sizes greater than 1 deg. The damage threshold for visible light is quite high, and thus lights capable of producing damage are intensely unpleasant. However, care should be taken to exclude IR and UV light. Most



**FIGURE 7** The maximum permissible retinal illuminance at different exposure times for 440 nm (blue line), 550 nm (red line), and 670 nm (green line) lights and extended fields according to the ANSI standards.

light sources emit considerable radiant energy in the infrared, and sources such as xenon arcs can emit ultraviolet radiation. Failures of blocking filters in these spectral regions may be visually undetectable. For safety it is advisable to have separate blocking filters to exclude unwanted radiation. It should also be noted that when using coherent light sources speckle can cause large focal variations in the retinal illuminance and the safety limits should be lowered by a factor of between 10 and 100 times.<sup>35</sup> Point sources and lasers have different safety standards that take into account the motion of the eye.

## 5.8 LIGHT SOURCES

Common light sources are presented in Table 4 and lasers are presented in Table 5 and in Chap. 15. Wyszecki and Stiles<sup>2</sup> present detailed discussions of light sources. The considerations for deciding on a light source are stability and uniformity of the luminous area, intrinsic luminosity of the source, and the spectral distribution of light from the source. Light sources of various types are discussed in Chaps. 15 to 23 in Vol. II.

## 5.9 COHERENT RADIATION

Coherent light sources can be used for generation of interference fringes,<sup>36</sup> a common use of lasers in vision research.<sup>8-10</sup> Light from the laser is directed into two similar channels. The light from the two channels arrives at the pupil of the eye separated by some distance  $d$ . Light spreading from the two beams then overlaps on the retina and creates an interference pattern in the intersection zone. The spacing of the interference pattern is controlled by the angle at which the beams intersect at the retina. The orientation of the pattern is controlled by the relative orientation of the two pupils. However, HeNe and easily controlled solid-state visible lasers are also excellent general-purpose light sources. The major drawback to their use is speckle.

### Generation of Speckle Fields

Speckle arises when coherent light is reflected from an optically rough surface. The surface roughness causes variations in the path length between the retina and adjacent areas on the surface. This variation causes phase differences from point to point in the retinal image. The spatial frequency of

**TABLE 4** Common Light Sources

Type	Properties	Comments
Tungsten	Broadband, thermal emitter.	Available in a number of filament and power choices, hotter bulbs are short-lived.
Tungsten-halogen	Broadband, thermal emitter.	Inclusion of halogen regeneration cycle allows tungsten-halogen to run hotter (more blue light and a higher luminance) at a longer rated life than tungsten. If running at below the rated wattage the bulbs can be inverted to extend the lifetime.
Xenon arcs	Nearly flat spectrum, high luminance, some emission lines are present.	UV light can create ozone which must be vented. Tendency for the arc to move relative to the electrodes, causing movement of the exit pupil in maxwellian view systems. Luminous area is fairly small.
Fluorescent tube	Broad spectral output with superimposed emission lines. Easily obtainable, efficient.	Can be modulated rapidly. But there may be problems with compound phosphors (see Ref. 28).
Light-emitting diodes (LEDs)	Small, cheap, efficient light sources. Easily controlled.	Can be modulated rapidly, come in a variety of wavelength and power ranges (see Chap. 13).

**TABLE 5** Types of Lasers

Type	Most Common Visible Wavelengths	Comments	Typical Power	Typical Noise %
Argon	514, 488, (other lines are available, depending upon the design). 444 nm	Power of each wavelength varies with particular laser design and cost. Most common wavelengths are 514 nm and 488 nm. Fairly expensive, have some high-frequency noise (>300 kHz) that may be important in scanning or short exposure applications.	5 mW–5 W	1
HeCd			0.5–50 mW	3
HeNe	543, 594, 632.8, also have orange lines.	Most common and least expensive gas laser. The 632.8-nm designs are easily available, inexpensive, and long-lived. Other wavelengths have many of the same advantages but power and beam options are limited and cost is higher. Expensive, tend to be unstable, large.	0.1–20 mW	0.5
Krypton Dye lasers	588, 677. Variable.	Expensive, need to be pumped by another laser. Require costly and toxic dyes to operate, not particularly stable.	50 mW–5 W 50 mW–5 W	3 Depends on pump laser.
Slab diode lasers	~630 nm, ~670 nm, ~690 nm, some in blue.	Development is very rapid with new wavelengths and power options. The beam geometry is not ideal but they have great potential as light sources. Can be easily controlled using standard electronic techniques as are common with LEDs. Have high impedance and are easily damaged by static electricity. Rapid developments at shorter wavelengths. These are under rapid development. They are solid-state lasers but have superior efficiency and beam properties as compared to slab lasers. Low impedance. Readily available, solid-state designs. Expensive.	0.2–100 mW	1 percent or better if temperature stabilized.
VCSELs vertical cavity lasers (microlasers)	Infrared.		1 mW	
Frequency doubled YAG	532 nm.		5–50 mW	<1 percent.
Tunable solid-state and solid dye lasers	Variable, pumped by lasers.	An area of rapid development. By using materials that fluoresce, and tuning the laser cavity, the output wavelength can be varied while maintaining excellent beam qualities.	mW–W	Depends on pump laser.

speckle depends on pupil size, since the size of those adjacent areas is smaller for bigger pupils. Thus, for a very small pupil, speckles will be large. Speckle has been used to develop optometers,<sup>37–39</sup> and to generate a pattern on the retina in the presence of poor optic media.<sup>40,41</sup> However, when using lasers as general-purpose light sources, speckle needs to be minimized or eliminated. There are three ways to despeckle a source: *spatial filtering*, *temporal despeckling*, and *raster scanning*.

In spatial filtering<sup>10</sup> the light remains spatially coherent. A light source is imaged onto a pinhole which diffracts the light so that a spherical wave emerges from the pinhole. A lens is then used to collimate the light, resulting in a plane wave. Filtering should be restricted to those experiments that require the use of coherent light. The introduction of dust or even structure in the anterior segment of the eye can introduce undesirable diffraction effects.

Temporal despeckling<sup>14,15</sup> uses the temporal integration of the visual system to blur the speckle field. Since speckle arises as a result of surface irregularities at a very small scale, a small amount of motion can decrease speckle contrast considerably.

Scanning moves a diffraction-limited spot of light across the retina to create a visual pattern. Typically, the pattern is a raster pattern, like that of a television, and the stimulus is generated by temporal variation in the intensity of the beam.<sup>42–44</sup> Since at any one time only a single, diffraction-limited, retinal region is illuminated, then there is no opportunity for speckle.

## 5.10 DETECTORS

Detectors are used for measuring the light produced by an optical system. They can generally be characterized by their quantum sensitivity, their spectral response curve, and the temporal amplitude spectrum of their noise (see Ref. 45 and Chap. 24, “Photodetectors,” by Paul R. Norton and Chap. 27, “Signal Detection and Analysis,” by John R. Willison in Vol. II). For most purposes detectors can be treated as detecting all light power incident upon their active area, but there are limitations that make it advisable to use them for normally incident light whenever possible.<sup>46</sup> Table 6 presents the most common detectors (also see Chaps. 24 to 28 in Vol. II). At low light levels photomultiplier tubes (PMT)<sup>47</sup> or an avalanche photodiodes (APD)<sup>48</sup> can be used in a photon-counting mode (Chap. 26, “High-Speed Photodetectors,” by John E. Bowers and Yih G. Wey in Vol. II).

## 5.11 PUTTING IT TOGETHER

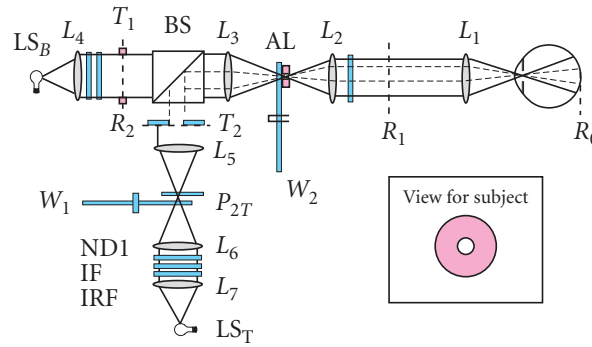
This section briefly describes construction of more complex maxwellian view systems. The goal is simply to help the researcher get started building an optical device by presenting real examples.

### A Two-Channel Maxwellian View Apparatus

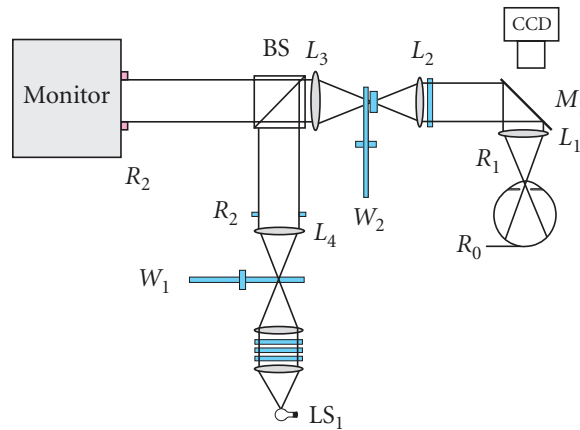
We first consider a simple two-channel maxwellian view device (Fig. 8a) for measuring the detectability of a small circular target on a large circular background. The background is provided via the straight optical channel. It has a light source  $LS_B$  followed by a lens  $L_4$  that collimates the light from the source. A field stop (target  $T_1$ ) controls the size of the background field. Adjacent to the target is a beamsplitter, followed by another lens  $L_3$ .  $L_3$  creates a source image where we place a 2.0-log-unit circular neutral density wedge, a 2-mm (diameter) stop (artificial pupil) and an achromatizing lens AL. An achromatizing lens minimizes the effects of the chromatic aberrations of the eye.<sup>49–51</sup> The artificial pupil will be imaged at 1:1 in the pupil of the eye, thus providing a limiting pupil. Lenses  $L_2$  and  $L_1$  relay the artificial pupil to the pupil of the eye. The test channel is derived from the second light source  $LS_T$ . Light is collimated by  $L_7$ , passed through a heat-rejecting filter IRF, interference filter  $IF_1$ , and a neutral density filter  $ND_1$ . An image of  $LS_T$  is then formed at  $P_{2T}$  by  $L_6$ . In this plane we set an electromechanical shutter and a neutral density wedge. We then collimate

**TABLE 6** Detectors

Detector	Sensitivity	Speed	Problems/Limitations
Photomultipliers	Best in the blue, extended multialkali cathodes extend sensitivity into the red and near IR. Many designs have very low noise.	Fast, MHz, capable of photon counting.	Low sensitivity in the red and infrared, can be damaged by high light levels, though recovery can be aided by leaving in the dark for a long time (months). Fragile. Require high voltage (kV).
Avalanche photodiodes	Have the silicon sensitivity curve, peaking in the near IR. Higher quantum efficiency than PMTs.	Fast MHz, capable of photon counting, better quantum efficiency than a PMT, but higher noise level.	Noise increases rapidly at avalanche voltage, light can affect the breakdown point. Higher noise level than PMTs, but the higher quantum sensitivity makes them better for video rate imaging. Small sensitive area.
CCDs, CIDs	Very linear, easy to use, sensitivity peaks in the near IR. These have a high quantum efficiency.	Variable, depending upon implementation, integrate between readings (kHz).	Blooming and charge spread can affect spatial properties at high radiances. <sup>52</sup> CIDs are resistant to blooming.
PIN silicon photodiodes	Easy to use, sensitivity peaks in the near IR.	With care they can be operated at high rates (MHz); however, in most photometers the circuitry is specifically designed for low-noise, lower-frequency operation.	
Thermal (bolometers)	Measures energy, thus flat spectral responsivity.	Very slow <10 Hz.	The only real use for these devices in vision research is for calibration of the spectral sensitivity of another detector. In general, it is better to have the detector calibrated against an NIST standard by a manufacturer.
See also photoresistors, vacuum photodiodes, and phototransistors	Seldom used.		



(a) Two channel increment threshold apparatus



(b) Using a video display in a maxwellian view and monitoring eye position

**FIGURE 8** (a) An example of a two-channel increment threshold maxwellian view device. Two light sources are used ( $LS_B$  and  $LS_T$ ) to form a background and a test channel respectively. The two channels are combined using a beamsplitter (BS). The intensity of the test field is controlled by a circular neutral density wedge  $W_1$ , and the intensity of both channels is controlled using wedge  $W_2$ . Additional details are provided in the text. (b) A similar apparatus, except now a video monitor is superimposed on a background derived from source  $LS_1$ . An infrared sensitive CCD camera is used to monitor the pupil through the back of a dichroic beamsplitter plate ( $M_1$ ) which reflects visible light and transmits infrared light (cold mirror). Infrared illumination of the eye is provided by infrared LEDs (not shown).

the light with lens  $L_5$ , pass it through an aperture  $T_2$  that creates the target, and combine it with the background light at the beamsplitter. In some cases it may be desirable to obtain both the test and background light from a single light source. This is readily achieved by the addition of mirrors and avoids the possibility that slight fluctuations in the sources might produce variability in the ratio of the target and background illuminances. When appropriate, use a single light source for multiple optical channels.



A similar optical design allows full spatial control of the stimulus by incorporating a video monitor (Fig. 8*b*) or an LCD (not shown). In general, the retinal image of the monitor will need to be minified. As shown, the size of the retinal image of the monitor is set by the ratio of the focal length of lenses  $L_1$ ,  $L_2$ , and  $L_3$  [Eq. (14)]. The main advantages of the hybrid system over free-viewing the monitor are the ability to control the pupil precisely, the ability to add spectrally pure backgrounds (and, if only low contrasts are needed, the background can be quite bright), and the ability to align an achromatizing lens precisely and to monitor the eye position. We show a simple monitoring system, where the eye is monitored by a CCD camera, through the back side of a “cold mirror” (M1). A cold mirror is a dichroic beamsplitter that reflects visible light and transmits infrared radiation. IR-emitting LEDs are used to illuminate the eye diffusely. Using the full aperture of the lens  $L_1$  means that the depth of focus will be small, and the eye can be precisely positioned (or monitored) in three dimensions. The resolution of the camera can be relatively low.

To use an LCD in transmission mode rather than a video monitor we can simply introduce the display at the retinal conjugate plane ( $R_2$ ) in Fig. 8*a*. Again, it will be desirable to decrease the magnification of the LCD on the retina by choosing  $L_3$  to have a longer focal length than lenses  $L_1$  and  $L_2$ .

## An Interferometer

We next describe a research interferometer that was built using modern electro-optical components.<sup>10</sup> To study the spatial sampling of the photoreceptor matrix of the eye, this instrument needed to have the following properties: (1) generation of spatial patterns on the retina with a frequency content above that imaged by the optics of the eye, (2) rapid and precise control of the modulation (contrast) and frequency (spacing) of the spatial patterns, (3) minimization of speckle, and (4) control of the two entrance pupils of the interferometer to displace them symmetrically about the center of the eye’s pupil. We outline below how these objectives were achieved. The researcher should refer to the original paper for a more detailed account.

Interference can be used to generate diffraction patterns on the surface of the retina. Two coherently related sources are imaged in the plane of the eye’s pupil (Fig. 9*a*). The spacing of the resulting diffraction pattern depends on the separation of the two sources in the eye’s pupil, and the orientation of the pattern depends on the relative position of the two sources. Williams<sup>10</sup> (see also Refs. 8 and 9 for other examples) constructed a modified Mach-Zender interferometer<sup>52</sup> (Fig. 9*b*) that satisfies the requirements outlined above.

Modulation of the interference pattern is controlled using AOMs. Each of the beams is either on or off, with a 50 percent duty cycle. If both beams are on at the same time (in phase), the interference pattern is seen at full contrast. If one is off when the other is on (counterphase), then there is no interference pattern. Intermediate phases of the two beams will cause intermediate contrasts of the interference pattern (Fig. 9*c*). Thus, both beams are always operated in the same state (avoiding luminance artifacts due to temporal nonlinearities), and all control of modulation is electronic. The use of an all-electronic design allows precise control of contrast without audible cues to the subject. Spatial masking from speckle is minimized by placing spatial filters in a pupil conjugate plane. The spacing of the interference pattern is controlled by a rotatable cube. Each beam traverses the cube in opposite directions (Fig. 9*d*). As the cube is rotated the beams, and thus the images in the eye’s pupil, are displaced symmetrically.

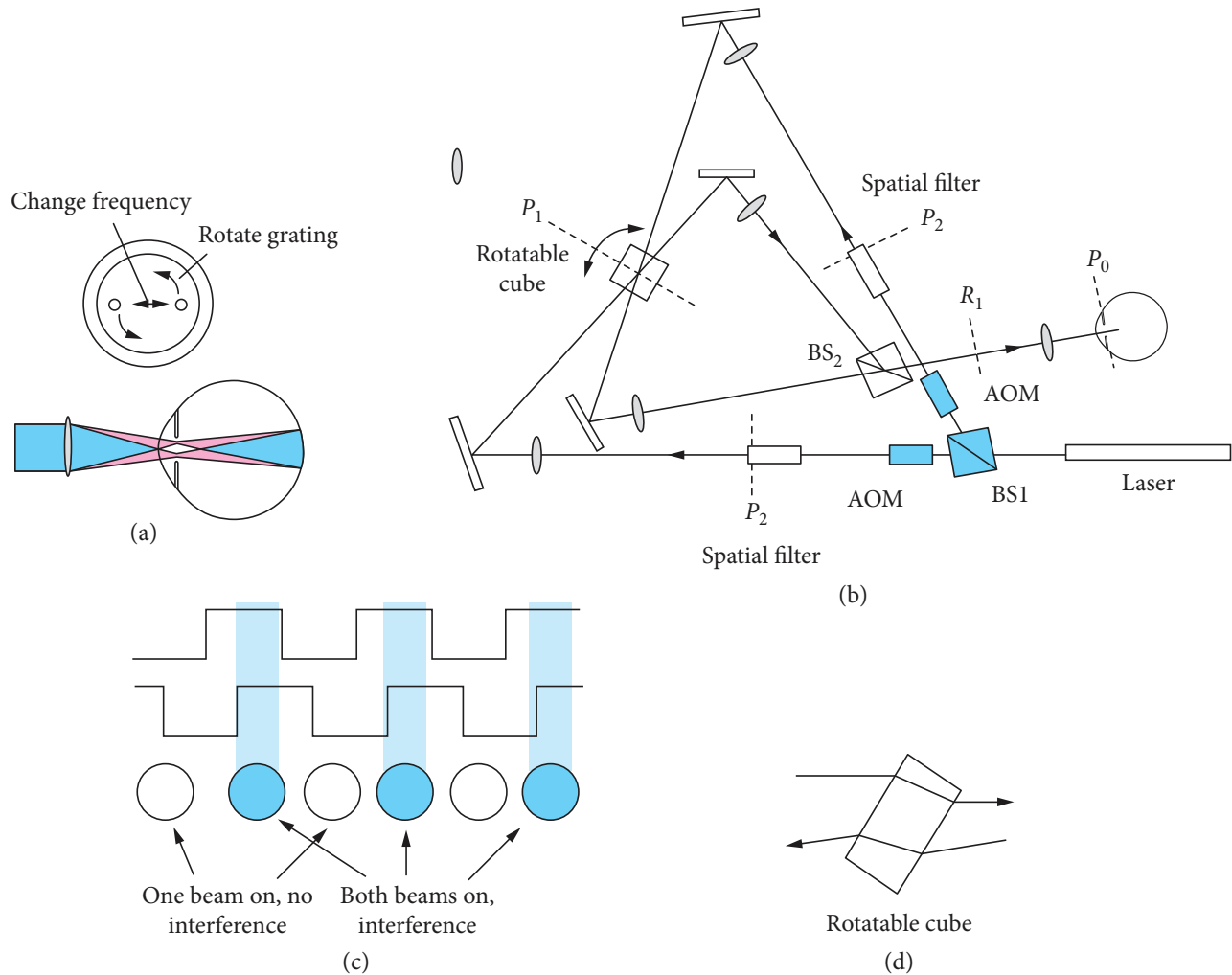
## 5.12 CONCLUSIONS

We have covered only some of the basics of stimulus generation. We urge the interested reader to look elsewhere in this *Handbook*. In addition, the following references are good general sources for this topic.

## 5.13 ACKNOWLEDGMENTS

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**FIGURE 9** An example of a modern interferometer for vision research. (Modified from Ref. 10.) (a) Factors controlling the spacing and orientation of the interference pattern on the retina. Increasing the distance between the entry pupils decreases the spacing of the pattern (increases the spatial frequency in cycles per deg). It is also possible to change the orientation of the interference pattern by rotating the two entry pupil in the plane of the eye's pupil. (b) A schematic of William's interferometer. This is a modified Mach-Zender interferometer and includes acousto-optic modulators (AOM) to control the modulation of the interference pattern, spatial filters to reduce speckle, a rotatable cube to control spacing and beamsplitters to separate the two beams (BS1) and to recombine them (BS2). (For additional details see Ref. 10.) (c) Contrast of the interference pattern is controlled by electronically varying the phase of the signals from the two AOMs. Each AOM is square wave modulated. The interference pattern is produced only when both beams are on at the same time. Thus, varying the relative phase of the two beams varies the proportion of the time when both are on, and thus the contrast. (d) The spacing of the beams in the plane of the eye's pupil is varied by rotating a deviation plate. The two beams propagate through the glass plate in opposite directions. Thus, as the plate is rotated, the beams are displaced equal but opposite amounts, resulting in symmetric deviations of the beams about the center of the eye's pupil. The actual apparatus uses an anti-reflection coated cube.

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