Specifying the Visual Stimulus

John M. Foley
UC Santa Barbara

Light is the stuff that activates the visual system. Although light is very familiar, its nature remains mysterious. Sometimes it acts like a wave, spreading out in all directions from wherever it is. At other times, it acts like a stream of tiny packets of energy, called photons, which travel in straight lines except when deflected. For most practical purposes, the latter description is adequate.

Ordinarily the lens of the eye will bend the path of light so that all the photons that came from the same point on the stimulus will land at the same place on the retina. We say that the lens forms an image of the object on the retina (Fig. 1). There is one particular point in the eye (the nodal point) such that photons aimed at it pass through undeflected. We can find the image of any point on the stimulus simply by drawing a straight line from the point on the stimulus to the nodal point and extending it to the retina. The nodal point is approximately 7 mm behind the front of the eye.

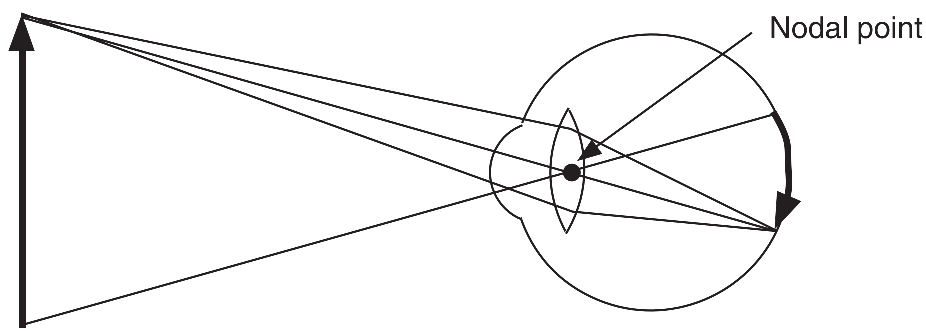


Figure 1. Image formation in the eye.

In vision research it is essential to specify the stimuli used. A visual stimulus has a shape, orientation, direction, distance, size, energy spectrum, overall intensity, and duration.

Shape

A circular stimulus is very common in many kinds of visual work. Squares and rectangles are also common. When this is the case, the shape can simply be named, although the size, e.g. the diameter of a circle or height and width of a rectangle, must be specified. More complex shapes must be described, but a picture is preferable.

Orientation

In most work stimuli are presented in a vertical plane that is parallel to the vertical plane that passes through the nodal points of the eyes. This is called a frontal or frontoparallel plane (Fig. 2). Any other plane is specified by its angle with respect to this plane (the *slant*), and the direction of the slant (called the *tilt*). For many stimuli (e.g., a line) there is also an orientation within the plane that must be specified. A line or a letter may be upright or rotated at some angle relative to upright.

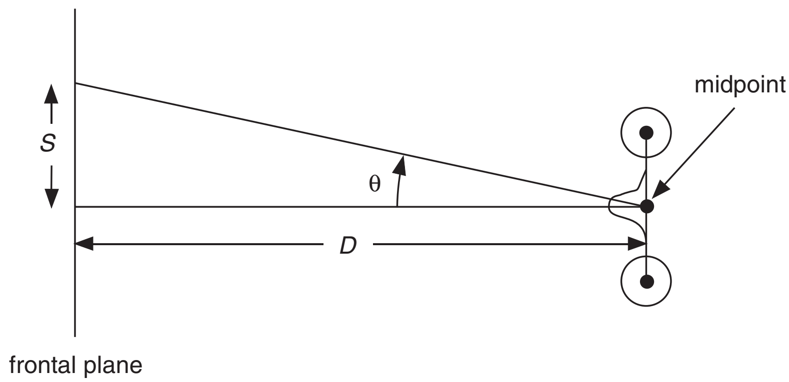


Figure 2. Frontoparallel plane and visual angle.

Direction

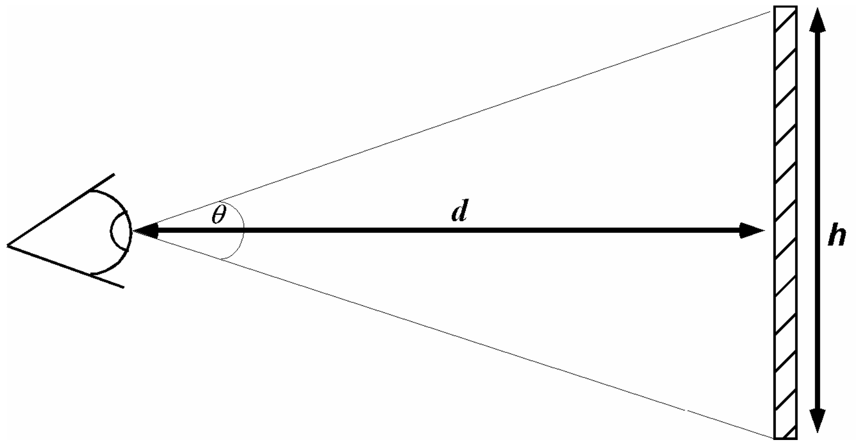
In most experiments either the stimulus or the fixation point or both are straight in front of the observer or straight in front of the viewing eye. The direction of a second stimulus is specified by the angle between the line extending straight ahead and a line from the center of the stimulus to the midpoint between the eyes (called the Cyclopean eye) or, in monocular viewing, from the nodal point of the viewing eye. This is the angle θ such that $\tan\theta = S/D$ (Fig. 2). If the stimulus is displaced both horizontally and vertically from straight ahead, two angles are given, e.g., “The stimulus was 5 deg to the left and 3 deg above the fixation point.

Distance

In scientific work, distances are generally given in metric units (1 inch = 2.54 cm). Distance is measured from the nodal points, although for distances greater than 20 cm, the error introduced by measuring from the corneas becomes negligible. Distance is sometimes specified as perpendicular distance to the frontal plane containing the stimulus, and sometimes as radial distance to the stimulus.

Size

It is the size of the image in the eye, rather than the size of the object, which is most important in vision. For this reason, size is almost always specified in terms of visual angle. Since the distance from the nodal point to the retina remains relatively fixed, visual angle is approximately proportional to retinal image size. The computation of visual angle here is the same as the case of direction. As long as the stimulus is approximately straight ahead and not too large, the formula $\tan\theta = S/D$ can be used, where *S* is size (e.g., in cm) and *D* is distance (in the same units). However, a slightly more exact formulation is shown in the following diagram:



In the diagram above, the thing on the left is supposed to be an eye, looking at an object of height *h*, at a distance *d*. The object subtends an angle, *θ*, which is called the visual angle. This calculation assumes that the object is presented in the frontal plane, and centered about the line of sight.

First, measure the height (or width etc.) of the object (*h*), and the distance from the center of the object to the eye (*d*) in the same units (e.g., centimeters). Now, notice that there is a right-angled triangle formed by the eye, the center of the object, and the top of the object. The angle next to the eye for this triangle will be exactly half of the visual angle of the whole stimulus. According to trigonometry, the tangent of this angle will be equal to the length of the opposite side (half of *h*), divided by the length of the adjacent side (*d*). This can be written as:

$$\tan\frac{\theta}{2} = \frac{(h/2)}{d}$$

which can be rewritten as:

$$\theta = 2\tan^{-1}\frac{h}{2d}.$$

If you do this on your calculator, make sure your calculator is set do perform calculations in degrees. The other unit used for angles that your calculator may use is radians, where π radians are equal to 180 degrees. 1 radian = 57.3 deg.

If the stimulus is circular, the visual angle of its diameter is given. If it is rectangular, both the visual angle of its width and the visual angle of its height are given. With alphanumeric stimuli, often the visual angle of the height of a particular letter (e.g., the small "x") is given.

One can give the solid angle subtended by a rectangular stimulus by multiplying its width by its height. For example, a stimulus that is .05 radians wide by .12 radians high subtends .05 × .12 = .006 square radians or steradians, as they are usually called.

Steradian measure is used primarily with reference to the specification of intensity (see below).

Energy Spectrum

Light comes in different kinds. These are perceived by us as having different colors. Kinds of light are usually specified in terms of their wavelength. Light consists of electromagnetic radiation having wavelengths of approximately 400-700 nanometers (1 nm = 10^{-9} m). A typical visual stimulus will contain light of a wide range of wavelengths. Lights that appear white usually contain all visible wavelengths. Lights that appear colored usually have a smaller range of wavelengths. To measure the energy spectrum of a stimulus, it is necessary to separate out small ranges of wavelength and measure the energy in each. This requires expensive equipment. It is usually unnecessary because the spectrum produced by many kinds of light source is already known at least approximately, and exact knowledge of the spectrum is often not essential. It is customary simply to specify the kind of light source used in the experiment. The spectrum often varies with the current to the bulb. This is one reason why neutral density filters rather than current changes are used to vary intensity.

Overall Intensity

Overall intensity is the most complicated dimension of the visual stimulus. There are several different kinds of measures and several different units of each. The most important of these are presented in Table 1. Of them, the most commonly used in visual research are measures of luminance. To understand what luminance is, we must first consider radiometric quantities and then photometric quantities.

Light measurement involves an emitting or reflecting surface whose intensity is to be measured and a receiving surface on which some of the light falls. We will assume that the receiving surface is perpendicular to the direction of the emitting surface and that the emitting surface is uniform in light output.

The basic unit is radiant flux. To measure radiant flux, a device called a radiometer is placed in front of a light source. This device measures the amount of light energy that falls on a sensitive surface on the instrument per unit time. Common units of radiant flux are watts or ergs/sec. If the radiant flux is divided by the area of the sensitive surface, this quantity is called irradiance, and its unit is watts/m^2. If irradiance is in turn divided by the solid angle subtended by the light source at the radiometer, the quantity is radiance, and its unit is watts/m^2/steradian. Radiance is a measure of the intensity of the source. As long as the air is clear, its value will not depend on how far away we measure from. The reason for this is that as the radiometer is moved away from the source, less light will reach it, i.e., irradiance will decrease. However, the visual angle subtended by the source at the radiometer decreases at exactly the same rate, leaving radiance constant. Radiance is a perfectly good measure of light intensity. However, because people are not equally sensitive to different wavelengths, lights of equal radiance can appear very different in brightness. Visual scientists consequently have defined a new measure of intensity called luminance that has the property that lights of equal luminance appear approximately equally bright.

Actually, three new quantities were defined which correspond quite closely with radiant flux, irradiance, and radiance. These are luminous flux, illuminance, and luminance. They are called photometric quantities. First, let us consider luminous flux. To compute luminous flux, we have to measure the energy in each small band of wavelengths separately, that is, to determine the energy spectrum. Then, the radiant flux in each narrow wavelength band is multiplied by the visibility of these wavelengths. The visibility $V(\lambda)$ of any wavelength λ is a number which is a kind of average of the sensitivity of the human eye to that wavelength in relation to other wavelengths. It is the ratio of radiant flux at 550 nm (the wavelength to which we are most sensitive) to the radiant flux at λ such that lights of 550 nm and λ would be matched in brightness (or matched with respect to an equivalent perceptual criterion),

$$V(\lambda) = \frac{P_c(550)}{P_c(\lambda)},$$

where P_c is the radiant flux at criterion. Therefore, when $V(\lambda)$ is multiplied by the radiant flux of a stimulus, the product will be constant for narrow wavelength bands of equal brightness. We multiply by 680 to get the luminous flux for a single wavelength band. Multiplication by 680 simply makes the unit a convenient size. To compute the luminous flux of the entire stimulus, we add together or integrate the luminous flux over all the narrow wavelength bands. The unit of luminous flux is the lumen. To get illuminance, we divide by the area of the sensitive surface. To get luminance, we divide again by the solid angle subtended by the emitting surface at the radiometer. It sounds pretty difficult to do.

Fortunately, there are easier ways. The first to be developed was photometric measurement. The basic idea behind it is known as Abney's Law. It says that lights of equal luminance will look equally bright. This "law" is actually wrong, but it is accurate enough for many practical purposes. If lights of equal luminance look equally bright, then all that is necessary is to match the brightness of a light of known luminance to the unknown light. The luminance of the unknown light is simply the luminance of the known light that matches it. No multiplication or integration is necessary. Even the radiometer can be dispensed with.

A still easier way to measure luminance is to use a photometer. A photometer is a device with a photoelectric receiving surface that has sensitivity characteristics similar to the visibility curve. What this means is that a radiometer can be constructed which, in effect, multiplies the energy at each wavelength by its visibility before adding up the energy. Such instruments can be calibrated directly in luminance units.

Unfortunately, there are several different units of luminance. In recent years one of these, candelas/square meter (cd/m^2) has become the most commonly used in vision research. Some American and English photometers, however, are calibrated in footlamberts (ftL), where 1 ftL = 3.426 cd/m^2.

This is not quite the end of the story because still another photometric unit has been defined which is used frequently enough to merit its inclusion here. If we are interested in how much light reaches the retina, we have to take pupil size into account. For a constant luminance, the larger the pupil the larger will be the amount of light reaching the retina. Accordingly a quantity called retinal illuminance has been defined as the product of the luminance times the area of the pupil. The common unit is the troland (td), where 1 td equals 1 cd/m^2 viewed through a pupil with an area of 1 mm^2. That is, the number of trolands is the luminance in cd/m^2 multiplied by the pupil area in mm^2.

Light intensity is usually varied by means of neutral density filters. These transmit the same proportion of the light that reaches them at all wavelengths. Neutral density filters are specified in terms of their density, *D*, where

$$D = \log_{10} \frac{1}{T},$$

where *T* is the proportion of light transmitted through the filter. If more than one filter is placed in the light path, the total density is the sum of the individual densities.

Radiometric Measurement				Photometric Measurement			
Quantity	*Symbol*	*Definition*	*Units*	*Quantity*	*Symbol*	*Definition*	*Units*
Radiant Flux	*P*	$P=\frac{\text{Energy}}{\text{Time}}$	Watts	Luminous Flux	*F*	$F=680\int V(\lambda)P(\lambda)d\lambda$	Lumens
Irradiance	*E*	$E=\frac{P}{A_i}$	Watts/m^2	Illuminance	*I*	$I=\frac{F}{A_i}$	Lumens/m^2 Lumens/ft^2 (foot-candles)
Radiance	*R*	$R=\frac{E}{\omega_e}$	Watts/m^2/ster.	Luminance	*L*	$L=\frac{I}{\omega_e}$	cd/m^2 (where 1 cd = 1 Lum/ster.) Foot Lamberts (1 ftL = 3.426 cd/m^2)
				Retinal Illuminance	*T*	$T=LA_p$	Trolands

Table 1. Quantities and units used in specifying light intensity. A_i is the area of the irradiated surface. ω_e is the solid angle subtended by the emitting source. A_p is the area of the pupil in mm^2. For the definition of retinal illuminance in trolands, *L* is the luminance in cd/m^2. Note that *R*, *L*, and *T* are independent of the distance from the source.

Duration

The duration of visual stimuli is generally specified in seconds or milliseconds (1 msec = .001 sec). It is generally determined by a timer that either opens and closes a shutter or turns the light on and off. Or, with computer displays, it is determined based on the video frame rate and the number of video frames displayed.