

accuracy. It turns out that the best solution is for the response to be at the boundary of that threshold which requires the least effort for detection, and this occurs when the response is slightly less than the stimulus. Thus, the steady-state response is seen to “lag” the stimulus, rather than being exactly equal to the stimulus. Examples of deadspace in the oculomotor system are the DOF<sup>9</sup> for accommodation and Panum’s fusional area (PFA)<sup>121</sup> for vergence.

## Eye Movement Measurement Techniques

### Stimulus arrangement and typical experimental protocol

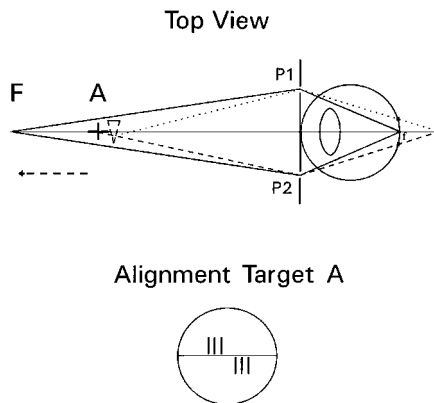
Both free- and instrument-space experimental protocols have been used by experimenters.<sup>76</sup> The free-space environment represents the normal visual scene where all the cues such as blur, disparity, overlap, perspective and shading are available to the observer. Moreover, the accommodative and vergence stimuli, based on the reciprocal of the distance of the target from the corneal plane of the observer, are equal or congruent. On the other hand, in the instrument-space environment, many of the cues are purposely removed, so that only blur and/or disparity cues are available to the observer. Moreover, the accommodative and vergence stimuli can be dissociated to provide non-congruent stimuli and a means to “dry dissect”<sup>158</sup> the oculomotor systems.

### Accommodation measurement

#### *Static*

The static accommodative response can be measured using a Hartinger coincidence optometer. Its operation is based on the Scheiner principle.<sup>54</sup> Consider the situation where the subject’s eye is focused at point F but also simultaneously sees the instrument alignment target A, consisting of three long vertical line segments, which is at a position indicated by the cross (Fig. 5). A prism is placed in front of the upper half, but not the lower half, of alignment target A. Thus, the rays emanating from the upper portion of target A (dotted

lines) are refracted by the prism and pass through pinhole P1, whereas the rays emanating from the lower half of target A (dashed lines) bypass the prism and traverse directly through pinhole P2. The pinholes result in a large DOF, so that the subject sees the alignment target A as sharp, and does not accommodate for it. Also, since target A is closer to the subject than the focused point F, the rays from A that pass through pinholes P1 and P2 will form two horizontally displaced images on the retina. Due to the prism placed in front of the upper half of target A, the subject sees two sets of short vertical line segments (one upper and one lower) which are displaced horizontally (see bottom illustration in Fig. 5). This technique of using pinholes to present two images of a target on the retina is called the Scheiner principle. As target A is moved closer to F (dashed arrow), the separation between the two images (and therefore the two sets of vertical line segments) is reduced. When A is at F, the two images will be vertically aligned. And, as A is moved beyond F, the two images will once again increase in separation but in the opposite direction. In the Hardinger coincidence optometer, the subject adjusts a dial that moves the alignment target until the images are aligned.



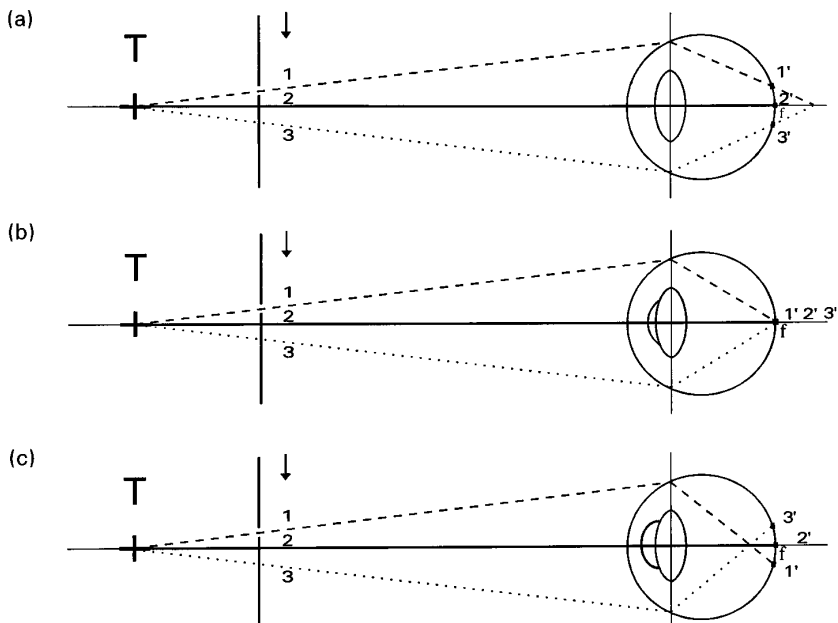
**Fig. 5** Scheiner principle and Hardinger optometer. Schematic top-view drawing showing subject focused at F and viewing alignment target A. A prism placed at the upper half (out of page) of target A results in two separate light beams that are projected through two pinholes. Two images are formed on the retina that are displaced horizontally, as shown in the alignment target below. When A is moved to coincide with F, the two images will be aligned vertically. A dial reading corresponding to position of A provides a measure of accommodative response.

dial position can be calibrated to provide a reading of the static accommodative response.

## *Dynamic*

The dynamic accommodative response can be measured using the infrared optometer.<sup>10,29</sup> Its principle of operation is based on the clinical retinoscope, which assesses refractive power of the eye. Figure 6 shows schematic diagrams of the side-view of the eye for the (a) under-, (b) equal-, and (c) over-accommodated conditions. In each diagram, a pinhole aperture in front of target T is swept sequentially in time from position 1, through 2, to 3. The angles of the rays in the diagrams are exaggerated for visual effect, but are meant to represent influence due to lens refraction. If the lens is under-accommodated (A), the target image on the retina will sweep through 1', 2' and 3' from *top to bottom*. However, if the lens is correctly accommodated (B), the target image will remain in one position on the retina. Moreover, if the lens is over-accommodated (C), the target will sweep through 1', 2' and 3' from *bottom to top*. In the dynamic optometer, instead of sweeping across the pinholes, the source is switch back and forth rapidly (150 Hz) between positions 1 and 3. Receiving photodetectors (not shown) that are optically conjugate to the retina will pick up the signals reflected from “top” and “bottom” of the retina. The phase difference of the detector signals provides the direction sense for driving a servomotor, which controls the optical power of the infrared light source, until the phase is zero. The amount and direction of displacement of the servomotor provides a quantitative measure of optical change, or accommodation, which is output as a voltage signal. The resolution of the optometer is typically 0.05 D and the bandwidth is 5 Hz.

Another device, called the SRW-5000 autorefractometer (Shin-Nippon, Japan), uses the grating focus principle. Optics within the device are moved rapidly back and forth by means of electronics to seek the highest contrast in the image of the retinal reflection of the target. This is done in three meridians (0, 45 and 90 deg) so that both spherical and cylinder (associated with astigmatism) corrections are available. The range of the autorefractometer is  $\pm 15$  D for the spherical reading and  $\pm 7$  D for the cylinder reading; the resolution is 0.12 D and the reading is provided automatically every 2 sec.



**Fig. 6** Retinoscopic principle. Schematic drawing of the side-view of the eye showing the rays of light from the target  $T$  through an aperture that is swept through positions 1 (dashed), 2 (solid) and 3 (dotted). (a) For under-accommodation, the target images ( $1'$ ,  $2'$  and  $3'$ ) on the retina move from top to bottom. (b) For correct accommodation, the target images on the retina remain stationary. (c) For over-accommodation, the target images on the retina move from bottom to top. The phase difference in the signals of photodetectors, located optically conjugate to the retina (not shown), provides a measure of the accommodative response.

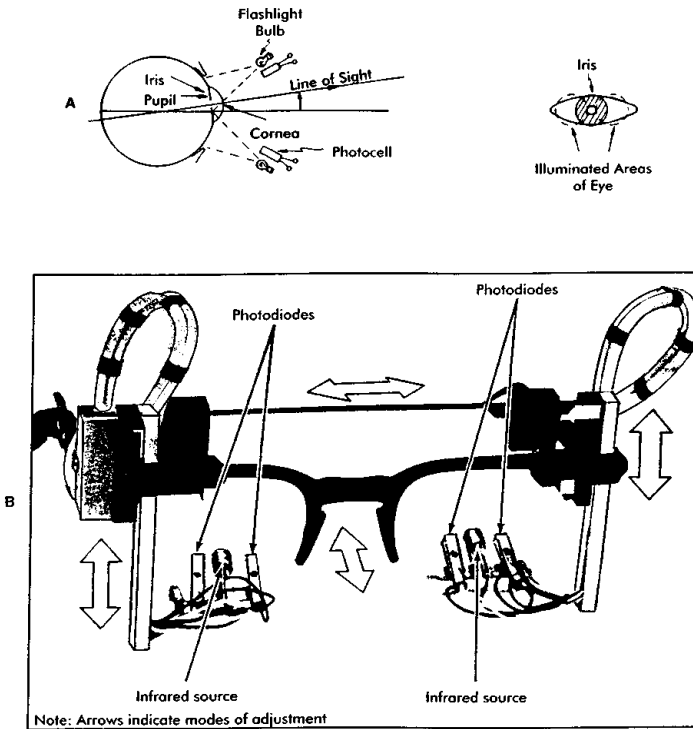
Moreover, the electronics can be adopted to provide dynamic accommodative response measurement with a bandwidth of 16 Hz.

## Dynamic vergence and saccadic eye movement measurement

Eye movements, or rotations of the eyes, in the horizontal dimension can be measured by illuminating a beam of infrared source that is mounted on spectacles at the limbus of the eye and detecting the amount of reflected light.

The limbus is the boundary between the white sclera and darker iris (as seen through the transparent cornea) portions of the eye. Suppose a detector is placed in front of the lateral limbus (i.e. the boundary between the white sclera and the dark iris) of the right eye. As the eye rotates leftward or rightward, more or less respectively, of the reflected infrared light will be received at the detector, thus providing a quantitative measure of the amount and direction of eye rotation. To reduce low frequency interference, the emitters are pulsed at 1 KHz, and to improve common-mode rejection, two infrared emitter-detector pairs are aimed at the lateral and medial limbus of each eye. The difference between lateral and medial detector signals is then bandpass-filtered at 1 KHz and demodulated to provide a signal proportional to the eye rotation (see Figs. 7A–C). A typical infrared eye movement monitor, such as the Skalar Model 6500, has a linear range of 25 deg, a resolution of 5 min of arc and a bandwidth of 200 Hz. This non-invasive device can be worn comfortably for a relatively long period of time (e.g. 1 to 2 hrs). Since a majority of eye movements occur in the horizontal plane and these movements have a negligible vertical component,<sup>27</sup> one-dimensional horizontal tracking is generally adequate. However, in other applications such as eye fixations on video displays, two-dimensional eye tracking is needed. This can be performed using the Iota Eyetrace Systems (Sweden) eye tracker.

Other eye movement measurement techniques also provide tracking in two dimensions. In the video-based helmet-mounted eye movement monitor system (ISCAN), a miniature infrared camera mounted on the helmet scans the eye. The electronic circuitry tracks the corneal reflection of a distant infrared source and also calculates the center of the pupil. Since the pupil center moves with both eye translation and rotation (whereas the reflection from the spherical corneal surface is influenced by translation but not by rotation), the difference between these two signals provides a measure of eye rotation. The video-based system has a linear range of  $\pm 30$  deg, resolution of 1 deg and bandwidth of 30 Hz.<sup>106</sup> However, since much higher bandwidths are needed for resolving fine dynamic features of saccade and vergence, it is inadequate for measuring dynamics of eye movements. Instead, the video-based system is more appropriate for assessing two-dimensional fixations. A two-dimensional system that has the needed higher bandwidth uses the scleral search coil technique.<sup>127</sup> In this technique, the subject is enclosed in a large box-shaped frame, which contains circular wound (Helmholtz) coils on either side for the horizontal



**Fig. 7** Infrared limbal eye tracker. (A) Light and photocell arrangement for infrared limbal tracking. (B) Spectacle-mounted infrared differential reflectivity device (reprinted from Ciuffreda and Tannen,<sup>24</sup> p. 199, with permission).

signal, and on the top and bottom for the vertical signal. The horizontal and vertical coils are driven at 50 and 75 KHz, respectively. The oscillating electromagnetic fields are picked up by a thin circular wire coil embedded in a contact lens worn by the subject. Thus, the eye coil simply acts as a transformer. When the eye coil rotates, there is an induced voltage that is proportional to the sum of the horizontal and vertical magnetic fluxes traversing in the coil. This voltage is amplified and the 50 and 75 KHz components are separated by phase-locked detectors to give the signals for horizontal and vertical components of eye rotation. For rotations of less than 30 deg, the output voltage is linearly related to eye angle to within 5%. The resolution can be as small as 1 sec of arc, and the bandwidth is up to 1 KHz.<sup>24</sup> However, this

invasive method requires that the eye be anesthetized and the recording can be performed for only about 20 min. Moreover, the eye coils are delicate and expensive.

For a detailed review of a variety of eye movement measurement devices, see Young and Sheena<sup>171</sup> and Ciuffreda and Tannen.<sup>24</sup>