There has always been a close relationship between the sciences of optics and vision. The reason is, of course, that the ultimate consumer of the products resulting from optical transformation has traditionally been the human visual system. So it is no surprise that names like Newton, Thomas Young, Brewster, Airy, Helmholtz, and Rayleigh loom as large in the history of vision as they do in the history of optics. After all, the natural history of optical phenomena would include the properties of the final detector, which until relatively recently was always the human eye.

One sometimes forgets how fast the scientific scene has changed in this century. As recently as the late 1920’s, when the nucleus was being studied in Rutherford’s laboratory in Cambridge, detection of α particles was by human vision; thus part of the study of atomic particles was to figure out how well the human eye could do as a scintillation counter. Chariton & Lea, in a paper on this topic in 1929, came to the conclusion that 17 quanta were required to elicit visual sensation. Moreover, they added this significant thought: “The definition of the limit contains a large ele-
ment of arbitrariness caused in part by the possibility of probability fluctuations in the small number of quanta forming the flash.”

It was only a few years later that Selig Hecht was able to show that the basis of the human absolute visual threshold was the absorption of a single photon in each of a handful of retinal receptors, and that the probability distribution of a subject’s “I saw it” responses to very dim light flashes matched the cumulative Poisson distribution predicted by the shot effect. These developments were part of a real increase in depth and understanding of the human visual system and its operation. We learned how summation zones in the retina were automatically adjusted with light-level changes so as to optimize quantum catch in dim light but resolution at higher light levels. Local processing was discovered, which comes up with difference rather than absolute signals. Sharpening position or wavelength information is the result, though with occasional loss of global information.

Many visual illusions and trompe l’oeil effects came to be understood as mandatory side effects of clever channeling of information for maximizing responsivity. Experiments were often of considerable subtlety and did more than merely add to the body of performance specifications of the human observer. By careful procedures and manipulation of parameters, it could be ascertained where the information processing occurred: receptive or neural layers of the retina; eye or visual cortex; instantaneous comparisons or memory storage. In turn this has set the stage for scientific breakthrough along two complementary directions:

(1) The connectivity, impulse formation, and interaction between individual elements of the nervous system.

(2) Channeling of information, laying down and retrieval of memory and decision-making processes in the human brain.

A surprising proportion of the current research in those areas is centered around the visual apparatus.

The eye itself has always been an interesting organ for the optical physicist. Here are some reasons why.

**Optical Quality** The eye has a receiving surface that takes care of the curvature of the field of the imaging system (or, if you like, vice versa). For smaller apertures, the optics are diffraction limited. In the human, this occurs up to a diameter of 2mm, but the falcon (Figure 1) has visual acuity that suggests that its eye is diffraction limited for a 5-mm pupil. The receptors themselves are directionally sensitive, with their acceptance lobes pointed to the center of the pupil. Acceptance lobes for bright-light receptors (cones) are narrower than those for dim-light receptors (rods).

**Color Vision** The ultimate color detection is done by three pigments, each in one kind of receptor. The receptors intermingle in the retina, keep their color signals separate, but interact for brightness signals. Wavelength-detection sensitivity minimizes the effect of chromatic aberration.

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The subsequent history of this facet of physiological optics would not sound at all unfamiliar to an optical engineer. The visual system has been compared with an ideal, noise-limited detector. The concept of quantum efficiency has been applied to the eye, and this has led to the postulate of temporal and spatial windows over which detection is in fact noise limited. Deviations from such ideal performance have been described as increases in internal noise, or ascribed to hypothesized neural quanta, refractive compartments, or internal gain changes.

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Focus and Aperture Control  The pupil is a variable-size aperture controlled reflexly to open up when a lot of light is needed and to close at high-intensity levels to keep down light scatter. The ciliary muscle controls the shape of the eye’s internal lens and in this way the focus position. The input for this system is highly sophisticated and depends on many perceptual factors. However, the physical process of ocular accommodation begins to fail in early middle-age, and this makes bifocal and trifocal (and perhaps one day varifocal) spectacle lenses so ubiquitous.

The visual organs of other species are an unending source of discovery. Pecten (a mollusk) has a catadioptric system (Figure 2). The back surface of the eye acts as a reflector and the retina is situated in the middle of the eye. Tiered retinas exist in some animals. In some spiders there are eyes with three retinas layered one behind the other. If nothing else, they are positioned correctly for chromatic differences in focus. Some fishes move their receptors so that, depending on the light level, either the rods or the cones catch the light. Many other species move screening pigments between the receptors when there is a lot of light.

In the water, the cornea loses much of its power; many fish eyes therefore have extremely effective lenses, with internal gradients of refractive index that prove to give a great deal of refractive power. One species has even developed a bifocal eye, one cornea for seeing above water, the other below.

The student of comparative anatomy and physiology of the eye cannot go far these days without a detailed knowledge of light guides. Many species have visual receptors whose diameter is of the order of a wavelength, and the indications are that waveguide characteristics of these receptors play a functional role.

Our own eyes are not sensitive to polarization, but those of bees and ants, for example, are. The amazing navigational feats of many animals have been found to have their origin in detection of polarization of the sky, which is surprisingly high (70 per cent or more). The ultrastructural property of their receptive cells provides polarizing and analyzing mechanisms. In fact, the whole area of sub-cellular assembly of biological materials is unbelievably interesting and wide open. Membranes and layers, disks and tubes abound in electron-microscopic pictures of visual cells. It will require a great deal of optical insight to demonstrate how the functional properties of cells (transparency, refraction, reflection, dichroism, polarization, scatter, selective absorption, etc.) arise out of the optical characteristics of these components (Figure 3). In fact, the only feature of incident light that has so far not been found to be detected by any eye is coherence, but then this capability has not really been looked for yet!

Figure 2. Pecten, a mollusk, has an eye with a catadioptric imaging system. (After M. F. Land; photograph courtesy of T. H. Waterman.)

These days even the basic scientist, let alone the applied researcher and technologist, looks toward
specific human problems. How and where is there further room for the application of optics to help the human eye and vision?

The basic procedures now used in testing and correcting human eyes were available at least at the turn of the century. Spherical, cylindrical and prismatic lenses, Snellen test letters, the ophthalmoscope, retinoscope, and kerometer all have been used for at least a century, and in principle do not look so very much different now from the way they did then. It is possible to view this situation in two ways. You can regard the current technology, extant and to be moving-film photography. Instrumentation for the evaluation of ocular motility has benefited greatly and can continue to benefit from the utilization of the variety of new optical components that found their way into military hardware long ago. While the principle of automatic refraction was enunciated a generation ago, only quite recently have devices been perfected that yield excellent measures of a patient’s refractive status in a few seconds. On-line devices interacting with the patient’s nervous system, which are now barely glimmers in the inventors’ eyes, may readily open up as yet uncharted regions of patient evaluation. Such systems should not be regarded as a substitute for the examiner, but as extensions of his abilities beyond the limits that happen to have been set by his senses.

Another example: examination of the eye for early signs of disease utilizes almost exclusively the human senses of sight and touch. But even the most experienced observer has limits to his sensitivity in the wavelength spectrum and to comparisons within and between various sensory capabilities. X-ray radiology is a spectacular example of what can happen when the human senses are supplemented. There are vast unexplored regions here. We have no idea what diagnostic signs of incipient or current malfunction (not only ocular but also circulatory, metabolic, hormonal) will be uncovered by innovative utilization of optical technology, extant and to be developed.

And a final thought: the rehabilitation of the severely visually handicapped poses formidable technological problems challenging the ingenuity of our most inventive scientists and engineers. Many of them are soluble and society seems poised to underwrite moves in this direction. Who will provide the impetus?

Figure 3. Transparency, reflection, dichroism, polarization, scatter, and selective absorption in biological tissue arise out of optical properties of subcellular tissue.

As effective as the old-fashioned, man-based procedures for evaluating the eye and vision are, it is precisely their basis in the capability of the human observer that provides the starting point of work on the next generation of testing devices: extension into dimensions that may be just as important as the current ones but that have so far not been easily accessible to the human observer. An example: we find it difficult to observe the speed of eye movements, probably because our perceptual apparatus has been deliberately blunted in the bandwidth of our own eye movements. In fact, the dynamics of human eye movements are unique in the realm of description of human visual behavior in that the beginning was not made until the twentieth century; it had to await the advent of non-coherent sources in examining visual functions?