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History of physiological optics in the twentieth century

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Contents

1.1	Status at the beginning of the century	3
1.2	The foundations	3
1.3	Structural optics of the eye	4
1.3.1	Eye dimension and axial length	4
1.3.2	Cornea	4
1.3.3	The crystalline lens	4
1.3.4	Transmission of the ocular media	5
1.3.5	Retinal optics	5
1.4	The retinal image	5
1.4.1	Aberrations of the eye	5
1.4.2	Quality of the retinal image	5
1.4.3	Optical transfer function	6
1.4.4	Strehl ratio	6
1.4.5	Stray light	6
1.5	Ophthalmic instrumentation	7
1.5.1	Ophthalmoscopy	7
1.5.2	Optometers and automatic objective refractometers	7
1.6	Spurt at the end of the twentieth century	7
	References	8

1.1 STATUS AT THE BEGINNING OF THE CENTURY

Physiological Optics, as confirmed by its central manifestation, Helmholtz's three-volume handbook, was understood at the time to be synonymous with the current *Vision Science*. But nomenclature has to go along with the explosive expansion of scientific knowledge. Hence the more optical components are now subsumed under *Visual Optics*, and even here further subdivision is needed. Optical imagery in the living eye is continually conditioned on factors arising from being embedded in motor apparatuses, specifically those controlling the pupil aperture and the ciliary muscle. Hence a division into *structural visual optics*, relating to the image-forming properties of the static normal eye, and *functional visual optics*, which would fold in accommodative and aperture size factors, seems indicated. Though it is not recognized as a distinct discipline, one can identify a branch of research as *histological optics*. Insofar as it transmits light unimpeded, eye tissue, such as the cornea and the crystalline lens, needs to have unusual biological structure. This became more evident and constituted a challenge around the middle of the century when electron microscopy began to reveal the subcellular makeup of corneal and lenticular layers.

The pioneering study by David Maurice (1957) on the cornea was influential here.

The final biological stage of light capture resides in the receptors. Starting with an observation by Ernst Brücke in the 1840s, there have been consistent attempts to assign to them special light-gathering properties. The directional sensitivity and wave guide nature of retinal receptors has been an active area now for the last 80 years. It may be noted parenthetically that the optics of invertebrate eyes, left out of consideration in this review, has deservedly been given much attention (Exner 1891, Snyder and Menzel 1975, Land and Nilsson 2002).

1.2 THE FOUNDATIONS

The eye's image-forming properties were well understood in the middle of the eighteenth century as shown in the classic treatise by Robert Smith (1689–1768) (Smith 1738). Through the efforts of astronomers, for example, Bessel, Seidel, and Airy (1801–1892), optics as a discipline was thoroughly established in the nineteenth century. Maxwell's (1831–1879) electromagnetic theory took command of the subject in 1861 and has never needed superseding. The giants of physiological optics, Thomas Young (1773–1839), Jan Purkinje (1787–1869), Listing (1808–1882), and

Helmholtz (1821–1894), laid and cemented the foundations, and ophthalmologists Donders (1818–1889), Landolt (1846–1926), and Snellen (1834–1908) developed clinical applications. Thus, a century ago, at the time of the beginning of the First World War, a student had available comprehensive compendia containing the available knowledge, specifically Helmholtz's *Physiological Optics* in the new edition updated in particular by Gullstrand (1862–1930), the *Graefe-Saemisch Handbuch der Augenheilkunde* in its many volumes and several editions, followed in the next couple of decades by important chapters in Vol XII of Bethe et al., *Handbuch der normalen und pathologischen Physiologie* (1932) and in *Abderhalden's Handbuch* (1920), and in Vol 1 of Duke-Elder's *Textbook of Ophthalmology* (1932). When the author entered optometry school in 1940, the assigned textbook, the second edition of Emsley's *Visual Optics* (Emsley 1939), contained a treatment of the subject that would rival current accounts and in some respects exceed their scope. By that time, too, quantum theory insofar as its characterization of the photon was concerned had solid footing and quite soon thereafter gripped the vision community when used to underpin our understanding of the absolute visual threshold (Hecht et al. 1942). The vision community has been well served by the authoritative treatment of the subject by Yves LeGrand (1908–1986) in various versions of his textbook (LeGrand 1949), a model of clarity.

Exhaustive literature surveys of vision science up to the beginning of the twentieth century had been provided in the encyclopedic scholarship displayed in the appendixes by A. Koenig to the second edition of Helmholtz's *Physiological Optics* (almost 8000 references up to 1894) and F. Hofmann in his *Graefe-Saemisch Handbuch* chapters (almost 1500 references on spatial vision alone) and by A. Tschermak in the voluminous footnotes of his chapters in *Bethe et al. Handbuch* (Tschermak 1931).

As will be seen, developments in visual optics during the second half of the twentieth century required an expanded view beyond geometrical optics and the simple application of diffraction theory in Airy's disk, yet the foundations for it were well in place. Abbe (1873) and Rayleigh (1896) in their treatment of microscope resolution used a framework that contained, almost explicitly, all the elements that were to become mainstream in the Fourier theory of optics that has since become dominant. Though it was more of academic than practical interest at the time, the theory applicable to coherent light (and what is more challenging, partially coherent light) was put on the table by van Cittert (1934), and so were the celebrated polynomials of Zernike (1934).

The upswing in the growth of optics, specifically as it plays a role in vision, in the middle of the twentieth century thus had their origin elsewhere. Most prominently, it was the harnessing of scientific and industrial resources in the conduct of the Second World War that ended in 1945. The scientific community virtually unanimously rallied behind the war effort, contributing insight and inventiveness to a heady mixture that also included technological innovation and industrial prowess. After the war, this continued in university and some corporate laboratories, blossoming into a research enterprise of unprecedented magnitude and productivity. The sequence into cybernetics (Wiener 1948), information theory (Shannon and Weaver 1949), and the linear systems approach (Trimmer 1950) and control theory was seamless and

so was the progress toward labs equipped with oscilloscopes, photomultipliers, digital computers, transistor devices, in time followed by lasers, LCD, and deformable mirrors. For decades, vision laboratories thrived on “war surplus” lenses, mirrors, prisms, and filters. Light that was once generated by candles, and had its intensity controlled by the inverse square law and its duration by episcotister disks, was produced by lamps with specific filaments and then by high-pressure mercury arcs with wavelength range restricted by narrowband interference filters and intensity adjusted by neutral density wedges. To achieve high retinal illuminance, the filaments were imaged in the pupil in Maxwellian view well before its optical subtleties had been realized (Westheimer 1966).

1.3 STRUCTURAL OPTICS OF THE EYE

1.3.1 EYE DIMENSION AND AXIAL LENGTH

The ingenious method of measuring the eye's axial length by utilizing x-ray phosphores (Goldmann and Hagen 1942) soon gave way to sonography that in the form of corneal pachometry (Molinari 1982) is in clinical use and now has become a reliable means of evaluating the refractive needs associated with cataract extraction (Hoffer 1981).

1.3.2 CORNEA

Because it is the principal source of the eye's refractive power and because, unlike the other refractive surfaces, it is immediately accessible, the cornea has always attracted much attention. Gullstrand in his appendix to the Third Edition of Helmholtz went into much detail about the shape of the corneal surface and the various means of measuring it. Keratometry and keratometry formed a strong chapter in *Abderhalden's Handbuch*. As contact lenses became ubiquitous and their fitting needed good information of the corneal surface on which they rested and whose optical properties they largely preempted, rapid and accurate measurements of corneal curvature could be performed in the clinic by cleverly designed electro-optical apparatuses, the subject of continued attention and technical innovation (Fowler and Dave 1994). Polarization effects, which can be made visible, have been ascribed to the cornea (Stanworth and Naylor 1950).

1.3.3 THE CRYSTALLINE LENS

The anterior and posterior surfaces of the crystalline lens are of critical relevance in how the eye accommodates, that is, changes focus under neural control by contraction of the ciliary muscle. E.F. Fincham (1937a), in part using optical means, made the major contribution to this topic in his monograph. It became clear early in the optical modeling of the eye that the anterior and posterior curvature of the lens could not fully account for its total refractive power for a biologically realistic refractive index, and giving the eye a solid interior core was not supported by evidence. Hence the proposition that a remarkable proportion of its total refractive power is provided by a refractive index gradient had gained acceptance by the time Gullstrand wrote his 1911 appendix. More recent approaches show just how challenging a topic this is (Campbell 1984, Pierscionek and Chan 1989).

1.3.4 TRANSMISSION OF THE OCULAR MEDIA

For a variety of reasons, the transmissivity of the ocular media has been of interest, more recently because of concern for possible damage from exposure to intense sources. For decades the data accepted as authoritative came from the study by Ludvigh and McCarthy (1938). It formed the basis for the confirmation that the energy exchange at absolute visual threshold involved only a handful of photons (Hecht et al. 1942). Wavelength dependency of light absorption in the media became an issue in the characterization of retinal photopigments, one of the most important research enterprises of vision science in the middle of the twentieth century (Rushton 1959, Wald 1964).

1.3.5 RETINAL OPTICS

In the vertebrate, before it reaches the receptors, light has to traverse several retinal layers that therefore have to be essentially transparent, not necessarily a quality automatically associated with active neural tissue. Haidinger's brushes, an entoptic phenomenon, have their origin in retinal optical structure (Naylor and Stanworth 1954). Myelination of the ganglion cell axons, helpful in enhancing velocity of action potentials, does not start till they exit the eyeball at the optic disk. The vascular tree of Purkinje, a prominent feature of the fundus, is somehow compensated for and made visible only by special tricks. The central region of the retina in the primate is suffused by a pigment, selectively absorbing light of some wavelengths. It seems to have a role in Haidinger's brushes (Bone and Landrun 1984, Mission 1993), but whether it is the origin of the entoptic phenomenon known as Maxwell's spot (Maxwell 1890/1965, p. 278) has been subject of an interesting debate (Polyak 1941, Walls and Mathews 1952). Of great significance are its possible protective properties (Snodderly 1995).

Optics becomes critical however, in the operation of receptor cells, whose diameter is of the order of the wavelength of light. A start was made in the 1840s by Ernst Brücke, at the time Helmholtz's fellow student in Johannes Müller's Institute in Berlin, who made the observation that rodlike retinal receptor cells acted like light guides. He seems not to have published it; all we have is Helmholtz's (1866) report and the comment that light once it had entered a receptor and impinged on the cylindrical boundary separating media of high from low refractive index would undergo total reflection and proceed further along the receptor and not leave it.

Receptor optics became mainstream with the discovery of the retinal directional sensitivity by Stiles and Crawford (1933) and the conjecture by Toraldo (1949) of retinal cones being wave guides. This set into motion extensive research activity, still ongoing. The state of the subject is well captured in the contributions to Enoch and Tobey's *Vertebrate Receptor Optics* (1981).

Whereas rods and their rhodopsin photopigment had been fully identified with scotopic vision, the same could not be said about cones and the cone pigments till the 1960s. Before that, because there was no firsthand knowledge of the phototransduction that underlies color vision, the possibility remained open that there was only a single cone pigment and that wavelength analysis came about through an intracellular filtering process, as indeed is the case with oil drops in birds (Walls 1942). Of historical

interest, therefore, is the attempt by Ingelstam (1956) to show that the ultramicroscopic structure of receptors, which had just been discovered, might allow wavelength-dependent differential energy concentration. Most of these conjectures were laid to rest by Brindley and Rushton's (1959) demonstration that to the human observer colors looked the same whether light entered the retina from the front or the back. The effect of the concentration of photopigments on their absorption spectrum—called self-screening—must, however, be considered in color vision theory (Brindley 1960) and probably plays a role in the Stiles–Crawford effect of the second kind (Stiles 1939), color changes associated with direction of incident light.

1.4 THE RETINAL IMAGE

1.4.1 ABERRATIONS OF THE EYE

A theoretical approach to the monochromatic aberrations in an optical system requires adequate knowledge of the optical parameters, position and curvature of the surfaces, and refractive index of the media. Because the precision needed to estimate image quality by ray tracing was lacking, this topic of visual optics was largely unattended until it was, so to speak, turned upside down quite recently by nulling out the aberrations. There was a brief flurry of activity centered on spherical aberration, when it was fingered to account for night myopia (Koomen et al. 1951), of practical importance during the Second World War. The enlarged pupil in the scotopic state allows light to enter into the eye through regions manifesting spherical aberration, but the more likely explanation of accommodation activity in empty fields (Otero and Aguilar 1951) won out. In a curious interlude, a quite adequate experimental determination of the eye's spherical aberration (Ivanoff 1953) was marred by inclusion of a point derived from the wrong supposition that the eye was always focused precisely on the target plane. When this is corrected (Westheimer 1955), outlines of spherical aberration across the pupil looked regular.

Because it needs to be factored into the stimulus situation in color vision research, vision researchers throughout the twentieth century remained aware of the eye's chromatic aberration (Hartridge 1918, Ames and Proctor 1921). Axial chromatic aberration (Wald and Griffin 1947) was mostly seen consonant with that of eye media with the dispersion of water. To obviate possible effects of chromatic aberration in color vision research, an "achromatizing lens" with the reverse of the eye's chromatic aberration was designed (Bedford and Wyszecki 1957). During the same period, the role of lateral chromatic aberration of the eye in engendering spurious stereoscopic disparity was given due consideration (Vos 1960), but some inadequacies in the explanation remain.

1.4.2 QUALITY OF THE RETINAL IMAGE

Helmholtz was fully aware that the central issue and best descriptor in the specification of the quality of the retinal image is the light distribution at a sharp target edge, though it took a little while for the realization that the point-spread function is even more basic. The most influential contributor at the beginning

of the century was Hamilton Hartridge (1922), and it is hard to imagine anyone doing better at a time before the idea of direct measurement took hold. Assuming that the shape of the point-spread function was Gaussian and making rather good guesses of the parameter, Fry and Cobb (1935) were able to achieve some synthesis between image light spread and thresholds for simple line targets.

In retrospect, the direction of future development was clearly foreshadowed by exceedingly insightful indirect approaches to retinal image quality by LeGrand (1935) using interference and Shlaer (1937) employing what is tantamount to Abbe's theory of microscope resolution. But, at the start of my career in vision science just after the Second World War, these were not adequately understood or appreciated.

In their place, the interest was in direct measurements, first in an approachable if not particularly informative animal preparation, the excised steer eye, expeditiously brought from the abattoir to the lab, as Jay Enoch, one of the collaborators explained to me (Boynton et al. 1954). Needless to say, light spread was very extensive, making one the researchers wonder why, if the image is so bad, visual acuity is so good (DeMott 1959). As the research during the remainder of the century, and continuing to the present, has made clear, such a proposition was ill-posed—the need instead was to pursue the question of how good, in the end, the retinal image might actually be, with all the experimental prowess that can be marshaled.

The most interesting and productive laboratory of the time was at the Institut d'Optique in Paris where Arnulf and his students were in daily contact with the change in approach to the theory of optics that began with Duffieux's (1946) paperback. To call the turn to Fourier optics revolutionary would be an exaggeration, because it is implicit in the resolution formulations of Rayleigh and Abbe and *Fourier's Lehrsatz* is explicitly used on p. 185 of Born (1933). In the single most significant paper in the subject of retinal imagery of the twentieth century, Françoise Flamant (1955) used the principle of the ophthalmoscope to measure the width of the reflected image of a narrow slit. Being familiar with the theorem that convolution becomes multiplication in the Fourier domain, she undid the double convolution due to the light traversing the eye media twice by taking the square root of its Fourier transform. Needless to say, Flamant's results were much closer to the human optics than those on the excised steer eye. In a sequence of more and more sophisticated experiments using photomultiplier tubes in place of Flamant's grainy photographic film (Westheimer and Campbell 1962, Campbell and Gubisch 1966), objective data were accumulated on the optical image quality of the normal human eye that proved quite compatible with psychophysical ones employing the principle of interference fringes (Westheimer 1960, Campbell and Green 1965). Conjectures on hypothetical image sharpening mechanisms with their improbable information-theoretical basis could be discounted (Gubisch 1967).

1.4.3 OPTICAL TRANSFER FUNCTION

Nowhere is the complementarity of the traditional spatial and the modern spatial-frequency descriptions of imagery more evident than in counterposing the image light spread and the optical transfer functions. They are Fourier transforms of each other

and therefore have their x-axes point in opposite directions: light spread over extensive regions tends toward infinite distances in the image plane but toward zero (the DC point) in the spatial-frequency spectrum. In principle, the diffraction image of a point source with a round pupil never stays at zero intensity, though its central lobe, the Airy disk, has a well-defined diameter. But the spatial-frequency spectrum has a distinct cutoff point beyond which there is no representation of grating targets. When this became understood and increasingly popular from the middle of the twentieth century on, the resolution limit of optical devices was better appreciated and could be related to the electrical circuits to which they were increasingly being coupled. Yet the fundamental distinction always needs pointing out: on the one hand, a firm cutoff spatial frequency in optical imagery and, on the other, the sloping transfer function, in principle never quite reaching zero transmission in electronics.

The eye's actual optical transfer function exemplified by the original one provided in the Campbell and Green study of 1965 included the effect of aberrations and the pupil diameter, but still needed extension to include not only amplitude but also phase, discarded in the power spectrum. For many years, from the seminal paper by Schade (1956) and the widely quoted data of van Nes and Bouman (1967) on, the majority of interpretations of the modulation transfer function of the whole visual system failed to stress that it lacked phase information and hence did not allow a unique description of light spread from the power spectrum. It took almost a couple of decades from the first enunciation of the Fourier theory of vision till the explicit demonstration that phase was more important than amplitude (Piotrovsky and Campbell 1982). Yet it has been shown by Hopkins (1955) and Steel (1956) that defocus manifests itself prominently in the phase of the optical transfer function.

1.4.4 STREHL RATIO

Attempts at capturing image quality in a single number go back to Strehl (1895), a high school teacher with an abiding interest in telescope design, who suggested the ratio of the height of the actual point-spread function at its center to that of the diffraction image, generally the Airy disk, defined by the instrument's aperture and the wavelength of light. It was conservatively estimated at 0.2 (Gubisch 1967) in a good eye, but in practice may be much less, because even a miniscule level of stray light (see below) at outlying image distances, covering as it does large retinal areas, would be integrated in the constant volume of light involved in computing the Strehl ratio. Areal summation of light probably makes a low value of the Strehl ratio not as severe a visual handicap as it may appear.

1.4.5 STRAY LIGHT

Whereas the shape of the central lobe of the point-spread function is an important factor in visual acuity, its long tail plays a role in a different visual phenomenon, glare. The veiling effect of bright sources in quite remote retinal areas can have deleterious influence on some visual tasks and early on in the twentieth century attempts were made to distinguish between optical and physiological causes (Holladay 1927, Stiles and Crawford 1937). This required the estimation of the retinal illuminance distribution caused by light scatter in the eye, which also, depending on the

wavelength and the red reflectance of the fundus, could act as an integrating sphere. The visual system has been used as a null detector to calibrate the threshold-raising effect of a uniform field of known luminance against that of distant outer zones of bright glare sources. This has yielded useful contributions to our knowledge of the quality of the retinal image (Fry and Alpern 1953, Vos 1962).

1.5 OPHTHALMIC INSTRUMENTATION

1.5.1 OPHTHALMOSCOPY

The introduction of the ophthalmoscope by Helmholtz led to an unsurpassed blossoming in the diagnosis of eye diseases and, when the optical industry was ready at the turn of the twentieth century, to the development of high-performing instruments. Successively versions were self-luminous, reflex-free, and stereoscopic. The Thorner design made by Busch was pitted against the Gullstrand version made by Zeiss.

1.5.2 OPTOMETERS AND AUTOMATIC OBJECTIVE REFRACTOMETERS

In order to clearly visualize the fundus in ophthalmoscopy, the patient's refractive error needs to be compensated. Schmidt-Rimpler in 1877 used this phenomenon to obtain an objective measure of the refractive error. Since then there have been many versions of what are called *optometers* or *refractometers* or *refractionometers*. E.F. Fincham's design of a *Coincidence Optometer* is perhaps the highlight of this trend (Fincham 1937b) early in the century. They depended on an observer detecting either the sharpness of an image or, as in Fincham's instrument, the alignment of two lines each carried by a separate beam through a different region of the eye's pupil.

The automatic recording infrared optometer of Campbell and Robson (1959) put an end to an era when records of the eye's accommodative changes were secured by cinematography of the Purkinje image from the anterior surface of the lens (Allen 1949) and the emphasis shifted to using light reflected from the fundus.

With the advent of modern optical and electronic components, automated objective refractometers became compact and user-friendly and by the turn of the twenty-first century had established themselves firmly in the eye clinic. Documentation of this development can be found elsewhere.

1.6 SPURT AT THE END OF THE TWENTIETH CENTURY

The narrative so far, covering developments in physiological optics narrowly defined to include the optical properties of human eye in the major portion of twentieth century, was informed by the author's personal experience: undergraduate training based on the state of knowledge prior to the outbreak of the Second World War, his active involvement in the discipline over the rest of the century, and his personal acquaintance with all the major participants in the story.

Much of the groundwork was laid in the British Isles by Smith and Porterfield in the eighteenth century and by Thomas Young,

J.C. Maxwell, Lord Rayleigh, Airy, and others in the nineteenth century and preserved in ophthalmological (Duke-Elder 1932) and optometric texts (Laurence 1926, Emsley 1939). Specifically deserving of mention as upholding and furthering the tradition in the twentieth century are E.F. Fincham (1893–1963) and Arthur G. Bennett (1912–1994).

On the continent, where Kepler, Descartes, and Scheiner had earlier clarified the image-forming properties of the eye, the work of the giants, Gauss and Listing (1808–1882), Purkinje, and Helmholtz, soon percolated down to the clinic and then to productive collaboration with optical industry. Von Graefe (1828–1870), Donders, Landolt, Snellen, and Gullstrand held on and maintained the tradition, and so did, at least in the realm of scholarship, Moritz von Rohr (1868–1940) and Armin von Tschermak (1870–1952) in the next generation. Emblematic of what followed is Max Born (1882–1970) and his magisterial textbook *Optik*. Removed in 1933 from their native habitat, they reemerged in another, more welcoming language and environment and with immensely augmented success and influence. *Principles of Optics* by Born and Wolf is now in its seventh edition.

Important laboratories in the middle of the twentieth century were located in the Netherlands, sparked by Maarten Bouman (1919–2011), and at the Istituto Nazionale di Ottica in Arcetri-Florence under the auspices of the Ronchi family. In Paris at the Institut d'Optique, where Marechal and others (Fleury et al. 1949) dug deeply into the fundamentals of image formation, diffraction, Fourier filtering, and apodization (Dossier 1954), Albert Arnulf (1898–1984) led a group of investigators who in the 1950s were unmatched in the point of attack and skill in physiological optics experiments. Fergus Campbell once told me that whenever he started a research project, he found that Arnulf had been there before. Cambridge, England, had been the site of Thomas Young's major discovery. In the middle of the twentieth century, it saw an extraordinary blossoming of vision research and, as the host of innumerable students and visitors, predominantly from the United States, had a lasting international impact. Of the several centers in the United States, mention should be made of the Dartmouth Eye Institute (Burian 1948) where collaboration with a research arm of the American Optical Company resulted in the design of ophthalmic diagnostic and corrective devices. The work of scientists Paul Boeder and Kenneth N. Ogle (1902–1968), later at the Mayo Clinic, helped give it an optical basis. In the same period, vision research in general, and often physiological-optical in substance, was prominent at Columbia University, where Selig Hecht (1882–1947) in Biophysics and C.H. Graham (1906–1971) in Psychology operated well-supported laboratories and their many students spread a research culture characterized by up-to-date methodology and experimental rigor. The same applied to Lorrin Riggs (1912–2008) at the Psychology Department of Brown University and Glenn A. Fry (1908–1996) at the Ohio State University School of Optometry.

The dramatic transformation that took place in the last third of the twentieth century had its origin less in any theoretical or conceptual changes than in the prodigious advances in the materials from which optical and electronic components are constructed: optical fibers, crystals, transistors, integrated

circuits, CRTs, LEDs, LCDs, and the list goes on. Right from its inception a couple of centuries ago, the study of the eye's image-forming properties has always been a prologue and necessary preliminary to vision as a perceptual process, it is what would now be called the front end. Adherent of idealist or materialist philosophy alike, the student of physiological optics was interested in the rules imposed by the laws of physics on what reaches the brain. Expressing electromagnetic disturbance distributions in Fourier—rather than position—space was not a revolutionary step, but generating such disturbance with lasers, orders of magnitude higher in intensity and coherence than other light sources, was. Quantitative change in sufficient measure, so F. Engels interpreted G.F. Hegel, becomes a qualitative one. When the intensity and coherence of light sources, the sensitivity of light detection, its temporal and spatial resolution, the storage capacity for the resultant signals, and the speed and power of analysis increase by a factor of 10^3 , in some cases even 10^6 , the character of the whole enterprise changes. This has been the case within a single generation for the entire armamentarium used by the vision scientists in his—now, of course, his or her—laboratory. Unimagined ease of generating visual stimuli with devices controlled by fast and powerful computers with virtually unlimited memory has relegated to the historical dust heap the metal and wood—more recently even the electronic—shops of just 50 years ago. Flexible and versatile optical components made of novel materials are allowing experimental forays that Selig Hecht, let alone Helmholtz or Lord Rayleigh, could not have dreamt of. The evidence of this development is provided in the following chapters, detailing stunning advances, yet built on the strong knowledge base erected over the course of many previous generations and solidified by the twentieth-century scientific work sketched here.

REFERENCES

- Abbe, E. Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung. *Arch Mikroskop Anatomie* 9 (1873): 413–468.
- Abderhalden, E. (Ed.). *Handbuch der biologischen Arbeitsmethoden*. Berlin, Germany: Urban & Schwarzenberg, 1920.
- Allen, M.J. An objective high speed photographic technique for simultaneously recording changes in accommodation and convergence. *Am J Optom Arch Am Acad Optom* 26 (1949): 279–289.
- Ames, A. and C.A. Proctor. Dioptrics of the eye. *J Opt Soc Am* 5 (1921): 22–84.
- Bedford, R.E. and G. Wyszecki. Axial chromatic aberration of the human eye. *J Opt Soc Am* 47 (1957): 565.
- Brindley, G.S. *Physiology of the Retina and Visual Pathway*, 1st edn. London, U.K.: Edward Arnold, 1960.
- Brindley, G.S. and W.A.H. Rushton. The colour of monochromatic light when passed into the human retina from behind. *J Physiol* 147 (1959): 204–208.
- Bone, R.A. and J.T. Landrum. Macular pigment in Henle fiber membranes: A model for Haidinger's brushes. *Vision Res* 24 (1984): 103–108.
- Born, M. *Optik*. Berlin, Germany: J. Springer, 1933.
- Boynton, R.M., J.M. Enoch, and W.R. Bush. Physical measures of stray light in excised eyes. *J Opt Soc Am* 44 (1954): 879–886.
- Burian, H.M. The history of the Darmouth Eye Institute. *AMA Arch Ophthalmol* 40 (1948): 163–175.
- Campbell, F.W. and D.G. Green. Optical and retinal factors affecting visual resolution. *J Physiol* 181 (1965): 576–593.
- Campbell, F.W. and R.W. Gubisch. Optical quality of the human eye. *J Physiol* 186 (1966): 558–578.
- Campbell, F.W. and J.G. Robson. High-speed infrared optometer. *J Opt Soc Am* 49 (1959): 268–272.
- Campbell, M.C. Measurement of refractive index in an intact crystalline lens. *Vision Res* 24(1984): 409–415.
- DeMott, D.W. Direct measures of the retinal image. *J Opt Soc Am* 49 (1959): 571–579.
- Dossier, B. Recherches sur l'Apodisation des Images Optiques. *Revue d'Optique* 33 (1954): 257–267.
- Duffieux, P.M. *L'intégrale de Fourier et ses applications à l'optique*. Imprimeries Oberthur, Rennes, France, 1946.
- Duke-Elder, W.S. *Text-Book of Ophthalmology*, Vol. I. London, U.K.: Henry Kimpton, 1932.
- Emsley, H.H. *Visual Optics*, 2nd edn. London, U.K.: Hatton Press, 1939.
- Enoch, J.M. and F.L. Tobey. *Vertebrate Photoreceptor Optics*. Berlin, Germany: Springer-Verlag, 1981.
- Exner, S. *Die Physiologie der Facettirten Augen*. Leipzig, Germany: Deuticke, 1891.
- Fincham, E.F. The mechanism of accommodation. *Br J Ophthalmol* (1937a), Monograph Supplement VIII.
- Fincham, E.F. The coincidence optometer. *Proc Phys Soc* 49 (1937b): 456–468.
- Flamant, F. Étude de la répartition de lumière dans l'image rétinienne d'une fente. *Revue d'Optique* 34 (1955): 433–459.
- Fleury, P., A. Maréchal, and C. Anglade. (Eds.). *La Théorie des Images Optiques, Colloques Internationaux du CNRS*. Paris, France: Éditions de la Revue d'Optique, 1949.
- Fowler, C.W. and T.N. Dave. Review of past and present techniques of measuring corneal topography. *Ophthalm Physiol Opt* 14 (1994): 49–58.
- Fry, G.A. The image-forming mechanism of the eye. In *Handbook of Physiology*, Vol. 1, J. Field (Ed.). Washington, DC: American Physiological Society, 1959, pp. 647–670, XXVII.
- Fry, G.A. and M. Alpern. The effect of a peripheral glare source upon the apparent brightness of an object. *J Opt Soc Am A* 43 (1953): 189–195.
- Fry, G.A. and P.W. Cobb. A new method for determining the blurredness of the retinal image. *Trans Am Acad Ophthalmol Otolaryngol* (1935): 432–448.
- Goldmann, H. and R. Hagen. Zur direkten Messung der Totalbrechkraft des lebenden menschlichen Auges. *Ophthalmol Basel* 104 (1942): 15–22.
- Goodman, J.W. *Introduction to Fourier Optics*. San Francisco, CA: McGraw-Hill, 1968.
- Gubisch, R. Optical performance of the human eye. *J Opt Soc Am A* 57 (1967): 407–415.
- Gullstrand, A. Appendix to Part I. In *Handbuch der Physiologischen Optik*, H.V. Helmholtz (Ed.). Hamburg, Germany: Voss, 1909.
- Hartridge, H. Chromatic aberration and the resolving power of the eye. *J Physiol* 52 (1918): 175–246.
- Hartridge, H. Visual acuity and the resolving power of the eye. *J Physiol* 57 (1922): 52–67.
- Hecht, S., S. Shlaer, and M.H. Pirenne. Energy, quanta and vision. *J Gen Physiol* 25 (1942): 819–840.
- Helmholtz, H.V. *Handbuch der Physiologischen Optik*, 3rd edn. Hamburg, Germany: Voss, 1909.
- Hoffer, K.J. Accuracy of ultrasound intraocular lens calculation. *AMA Arch Ophthalmol* 99 (1981): 1819–1823.
- Hofmann, F.B. Die Lehre vom Raumsinn. In *Handbuch der gesamten Augenheilkunde*, Vol. 1, A. Graefe and T. Saemisch (Eds.). Berlin, Germany: Julius Springer, 1920, pp. 1–213.
- Holladay, L.L. Action of a light source in the field of view in lowering visibility. *J Opt Soc Am* 14 (1927): 1–15.

- Hopkins, H.H. The frequency response of a defocused optical system. *Proc R Soc (Lond) A* 231 (1955): 91–103.
- Ingelstam, E. Possible interpretation of the ultrastructure of retinal receptors including an electromagnetic theory of the primary mechanism of colour vision. In *Problems in Contemporary Optics. Proceedings of the Florence Meeting*, September 10–15, 1954. Firenze, Italy: Istituto Nazionale di Ottica, 1956, pp. 640–667.
- Ivanoff, A. *Les Aberrations de L’Oeil*. Paris, France: Revue d’Optique, 1953.
- Koomen, M., R. Scolnik, and R. Tousey. A study of night myopia. *J Opt Soc Am* 41 (1951): 80–83.
- Land, M.F. and D.E. Nilsson. *Animal Eyes*. New York: Oxford University Press, 2002.
- Laurence, L. *Visual Optics and Sight Testing*, 3rd edn. London, U.K.: School of Optics, 1926.
- Le Grand, Y. Sur la mesure de l’acuité visuelle au moyen de franges d’interférence. *Compte rendus de l’Académie des Sciences* 200 (1935): 490–491.
- Le Grand, Y. *Optique Physiologique*. Paris, France: Editions de la revue d’optique, 1949.
- Ludvig, E. and E.F. McCarthy. Absorption of visible light by the refractive media of the human eye. *AMA Arch Ophthalmol* 20 (1938): 37–51.
- Maurice, D.M. The structure and transparency of the cornea. *J Physiol* 136 (1957): 263–286.
- Maxwell, J.C. *The Scientific Papers of James Clerk Maxwell*. New York: Dover, 1890/1965, Vol. II.
- Misson, G.P. The form and behaviour of Haidinger’s brushes. *Ophthalm Physiol Opt* 13 (1993): 392–396.
- Molinari, J.F. A review of pachometry. *Am J Optom Physiol Opt* 59 (1982): 912–917.
- Naylor, E.J. and A. Stanworth. The measurement of the Haidinger effect. *J Physiol* 123 (1954): 30–1P.
- Otero, J.M. and M. Aguilar. Accommodation and night myopia. *J Opt Soc Am* 41 (1951): 1061–1062.
- Pierscionek, B.K. and D.Y. Chan. Refractive index gradient of human lenses. *Optom Vis Sci* 66 (1989): 822–829.
- Piotrowski, L.N. and F.W. Campbell. A demonstration of the visual importance and flexibility of spatial-frequency amplitude and phase. *Perception* 11 (1982): 337–346.
- Polyak, S.L. *The Retina*. Chicago, IL: University of Chicago Press, 1941.
- Purkinje, J. *Beobachtungen und Versuche zur Physiologie der Sinne*. Prague, Czech Republic: Calve, 1823.
- Rayleigh, L. On the theory of optical images, with special reference to the microscope. *Philos Mag* 42 (1896): 167–195.
- Rushton, W.A.H. Visual pigments in man and animals and their relation to seeing. *Prog Biophys Biophys Chem* 9 (1959): 240–283.
- Schade, O.H. Optical and photoelectric analog of the eye. *J Opt Soc Am* 46 (1956): 721–739.
- Shannon, C.E. and W. Weaver. *The Mathematical Theory of Communication*. Urbana, IL: U. Illinois Press, 1949.
- Shlaer, S. The relation between visual acuity and illumination. *J Gen Physiol* 21 (1937): 167–188.
- Snodderly, D.M. Evidence for protection against age-related macular degeneration by carotenoids and antioxidant vitamins. *Am J Clin Nutr* 62 (1995): 1448S–1461S.
- Snyder, A.W. and R. Menzel. (Eds.). *Photoreceptor Optics*. New York: Springer-Verlag, 1975.
- Southall, J.P.C. (Ed.). *Helmholtz’s Treatise on Physiological Optics*. New York: Dover, 1924/1962.
- Stanworth, A. and E.J. Naylor. The polarization optics of the isolated cornea. *Br J Ophthalmol* 34 (1950): 201–211.
- Steel, W.H. The defocused image of sinusoidal gratings. *Opt Acta* 3 (1956): 49–55.
- Stiles, W.S. The directional sensitivity of the retina and the spectral sensitivities of the rods and cones. *Proc R Soc Lond B Biol Sci* 127 (1939): 64–105.
- Stiles, W.S. and B.H. Crawford. The luminous efficiency of rays entering the eye pupil at different points. *Proc R Soc (Lond) B* 112 (1933): 428–450.
- Stiles, W.S. and B.H. Crawford. The effect of light glaring source on extrafoveal vision. *Proc R Soc (Lond) B* 122 (1937): 255–280.
- Strehl, K. Aplanatische und fehlerhaft Abbildung im Fernrohr. *Zeitschrift für Instrumentenkunde* 15 (1895): 362–370.
- Toraldi di Francia, G. Retina cones as dielectric antennas. *J Opt Soc Am* 39 (1949): 324.
- Trimmer, J.D. *The Response of Physical Systems*. New York: John Wiley, 1950.
- Tschermak, A. Optischer Raumsinn. In *Handbuch der normalen und pathologischen Physiologie*, A. Bethe et al. (Eds.). Berlin, Germany: Julius Springer, 1931.
- van Cittert, P.H. Die Wahrscheinliche Schwingungsverteilung in einer von einer Lichtquelle direkt oder mittels einer Linse beleuchteten Ebene. *Physica* 1(1934): 201–210.
- van Nes, F.E. and M.A. Bouman. Spatial modulation transfer in the human eye. *J Opt Soc Am* 57 (1967): 401–406.
- Vos, J.J. Some aspects of color stereoscopy. *J Opt Soc Am* 50 (1960): 785–790.
- Vos, J.J. *On Mechanisms of Glare*. Utrecht, the Netherlands: University of Utrecht, 1962.
- Wald, G. The receptors of human color vision. *Science* 145 (1964): 1007–1016.
- Wald, G. and D.R. Griffin. The change in refractive power of the human eye in dim and bright light. *J Opt Soc Am* 37 (1947): 321–336.
- Walls, G.L. The vertebrate eye and its adaptive radiation. Detroit, MI: Cranbrook Institute, 1942.
- Walls, G.L. and R.W. Mathews. New means of studying color blindness and normal foveal color vision. *Univ Calif Publ Psychol* 7 (1952): 1–172.
- Westheimer, G. Spherical aberration of the eye. *Opt Acta* 2 (1955): 151.
- Westheimer, G. Modulation thresholds for sinusoidal light distributions on the retina. *J Physiol Lond* 152 (1960): 67–74.
- Westheimer, G. and F.W. Campbell. Light distribution in the image formed by the living human eye. *J Opt Soc Am* 52 (1962): 1040–1045.
- Westheimer, G. The Maxwellian view. *Vision Res* 6 (1966): 669–682.
- Westheimer, G. Optical properties of vertebrate eyes. In *Handbook of Sensory Physiology*, Vol. VII/2, M.G.F. Fuortes (Eds.). Berlin, Germany: Springer-Verlag, 1972, pp. 449–482.
- Wiener, N. *Cybernetics: Or, Control and Communication in the Animal and the Machine*. Cambridge, MA: Technology Press, 1948.
- Zernike, F. Beugungstheorie des Schneidenverfahrens und Seiner Verbesserten Form, der Phasenkontrastmethode. *Physica* 1 (1934): 689–704.