Arnulf Oppelt (Ed.)

Imaging Systems for Medical Diagnostics

Fundamentals, Technical Solutions and Applications for Systems Applying Ionizing Radiation, Nuclear Magnetic Resonance and Ultrasound

SIEMENS

Arnulf Oppelt

Imaging Systems for Medical Diagnostics

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Foreword

Twenty-five years ago, in 1980, the first edition of 'imaging systems for medical diagnostics' appeared as a German paperback. This was a time when computed tomography with X-rays had just made its way into clinical routine and when real time ultrasound replaced static B-scanners. Magnetic resonance imaging, single photon and positron emission tomography were still in their infancy. The rapid development of these methods has led to two further editions, the last having appeared in 1995. An English translation of the second edition came out in 1990.

Why is it time now for a new edition? Imaging technology has made tremendous progress. All imaging modalities are now capable of generating three dimensional information of the human body. In order to make this information accessible, sophisticated digital image processing is required. Methods for the exact spatiotemporal superposition of information from different modalities have to be applied. The drastically increasing importance of information technology is further emphasized by the need for a uniform platform with an identical user interface for all modalities. *Syngo* has been a pioneer in this field. Ultimately, information technology enables the optimization of clinical workflow and thus helps increase the quality of care while at the same time reducing cost.

A new edition of 'imaging systems for medical diagnostics', therefore, can no longer restrict itself to the physical basics and to the actual technology of imaging instruments. Because of their increasing significance, applications of image and information processing and distribution have to be included. Nevertheless, the importance of the physical principles of modern imaging systems persists, which has led to the well-known extraordinary technical solutions. The desire to convey this variety of technical knowledge explains the significant increase in the volume of the book.

In keeping with increasing internationalization not only in medical science but in all areas, this new edition appears only in English. The authors are active specialists in project management and development in the medical industry who drafted their contributions concurrently with their professional duties and were motivated by their devotion to the arena. A unique compendium of modern medical imaging technology has emerged which is useful for all parties, technically interested physicians as well as students, technicians, engineers and physicists.

Dr. Hermann Requardt
Executive Vice President, Siemens Medical Solutions

Preface

This book is intended to give an overview on medical imaging from the technical side. It starts by recapitulating the biological facts of the human visual system, presents the physics of the imaging process, portrays current technical designs and concludes with the last developments of software technology. It is composed of five parts: The first part is dedicated to images, how they are processed in the human eye, how they can be subjectively characterized, how they can be displayed and fused when obtained from different modalities, and how one can use them to navigate. The second part is devoted to the physics of the different imaging methods, applying X-rays and γ-rays, ultrasound or nuclear magnetic resonance. The third part gives an outline on system theory and image reconstruction. The fourth part deals with the technology of actual imaging instrumentation revealing some of their design secrets. Finally, the fifth part is devoted to the handling, evaluation and distribution of medical images. A uniform user interface, computer assisted detection of lesions and integration into the hospital workflow are becoming increasingly important matters.

To compile such a plentitude of information into a single volume is a challenging task. It is expected that the reader is familiar with basic mathematics and the fundamentals of Fourier transform theory. The editor wishes to thank the 85 authors and co-authors who have contributed with their professional knowledge for their cooperation. Thanks also go to the publisher for his patient willingness to respond to the suggestions of the editor and to bring the sometimes bumpy English manuscripts into readable form. In particular, the tremendous dedication of the publishing editor Gerhard Seitfudem warrants special mention. Finally, this book would not have been possible without the continuous encouragement and support of the members of the board of Siemens Medical Solutions.

May the 4th edition (i.e. 2nd edition in English) of 'imaging for medical diagnostics' be accepted as a handbook suited as well for students interested in biomedical engineering as for their teachers, for developers and experts, and for everyone interested in current medical technology.

Arnulf Oppelt

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Part I – Principles of Image Processing

1 Physiology of vision

1.1 General considerations regarding sensory physiology

Over the last few decades much progress has been made in the area of imaging systems for use in medical diagnostics. New techniques, for example magnetic resonance tomography, have been developed, opening up new avenues in diagnosis. However, enormous improvements have also been made in conventional techniques, e.g. those using X-rays, in particular by the application of microelectronics: the amount of radiation to which the patient is exposed has been drastically reduced, and the quality of the images considerably enhanced.

Today industry is able to produce imaging systems which are to a large extent technically compatible with the biological needs of the human eye. In order to give a full account of these systems, it therefore seems appropriate to begin by giving some idea of the function of the eye as a sense organ.

The sense organs allow the organism to perceive its constantly changing environment. Depending on the physical dimension of the environmental change, the various sense organs are specialized for quite specific, adequate stimuli. Different sensory perceptions [1.1], also known as sensory modalities, arise in this way.

The amount of information received by all the sensory organs together is immense. It has been estimated at around 10^9 bits/s [1.2]. This flood of information, cannot, how-

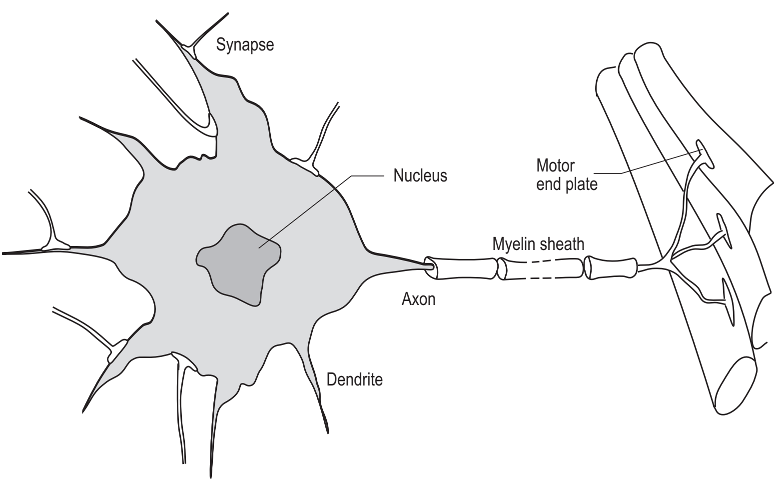


Figure 1.1 The neuron, the basic working unit of the central nervous system

ever, be transmitted by the nerves to the brain in its entirety. The nervous system therefore needs to select the most important information at any particular moment. This selection procedure cuts down the information received in the ratio of $10^7 : 1$. People vary greatly in the selection they make so that the same pattern of stimuli will be perceived and assessed differently from one person to another. In principle this information selection takes place in the nervous system by means of the excitation and inhibition of nerve cells. Thus the nervous system has the task of comparing information in terms of the degree of neural excitation and, where necessary, of passing it on to higher decision-making centers. In order to perform this task, the nervous system has two separate functional elements: nerve cell bodies for converting information and nerve fibers for stimulus conduction. Collections of nerve cells in the brain and in the spinal cord are known as gray matter and the fibers as white matter. The neuron is the basic working unit of the central nervous system (CNS). It consists of a cell body with several projections which increase its surface area, and a long fiber, the axon, which establishes the contacts (synaptic junctions) with other nerve cells. Figure 1.1 shows a diagram of such a neuron.

This method of transforming and transmitting information applies equally to all the sensory organs, including the *eye*. In this process, specific sensory perception is not generated by the nature of the impulse, but by the anatomy of the nerve connections between the relevant sensory organs and particular areas of the brain. Thus a distinction is made anatomically between a visual pathway, an auditory pathway, an olfactory pathway, a gustatory pathway and a pain pathway. Even the quality of sensory perception, which in the case of the eye constitutes the difference between color perception and light-dark perception, is governed by the finely-structured connections between individual nerve fibers and relevant sensory cells.

1.2 The eye

1.2.1 Adequate stimulusus

The eye is sensitive to certain electromagnetic waves. These waves can be divided up into various regions [1.3] which have quite different effects on the organism. As can be seen from fig. 1.2, the sensitivity range of the eye barely covers one octave (400 to 780 nm) of the electromagnetic spectrum. The frequency corresponds to the color (see fig. 1.17), the amplitude to the degree of brightness perceived.

In addition, the sense of vision can perceive objects in three dimensions. This is because of the parallactic shift of the image seen by the right eye relative to that seen by the left eye.

1.2.2 Anatomy

Like the camera, the eye has an optical imaging system. It consists of the cornea and the lens. In order to reduce chromatic aberration (color distortion), the lens is made

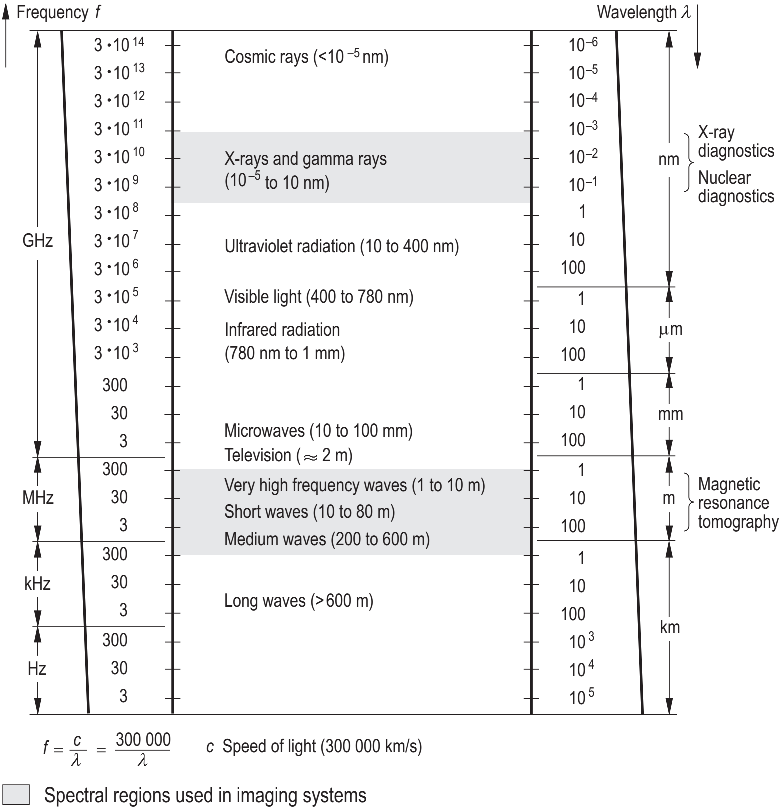


Figure 1.2 Regions of the electromagnetic spectrum

up of several layers, like an onion, each with a different refractive index. Anatomical details are shown in fig. 1.3 [1.4]. The space between the cornea and the lens (anterior chamber) is filled by the crystal-clear aqueous humor. The interior of the eye is occupied by the jelly-like vitreous body, which in common with all the other transparent parts of the eye does not contain any blood vessels, receiving nutrients by diffusion. Inside the sclera (the firm white outer membrane) lies the choroid (the brownish vascular membrane), followed by the retina. The retina contains the light-sensitive elements, the rods and the cones, which convert the electromagnetic waves into nerve impulses. The retina also contains nerve cells which carry out a preliminary processing of the information on the spot. This is also where the fibers of the optical nerve start. The lens is suspended in the ring-shaped muscle of the ciliary body. The iris, which covers the front of the lens, leaves only a small aperture (the pupil) open. Six muscles, stemming from the bone wall of the eye socket and attached to the outside of the sclera, are capable of moving and turning the eyeball in all directions.

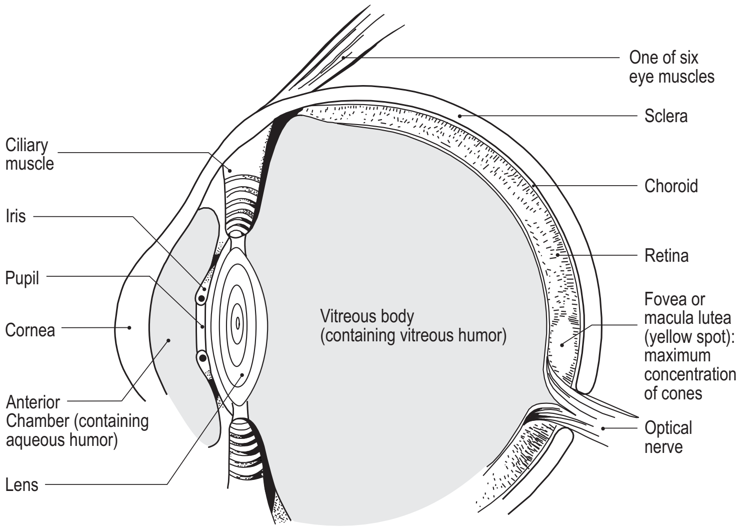


Figure 1.3 Anatomy of the eye

1.3 Functioning of the eye

1.3.1 The imaging mechanism

The projection of an image of the environment through the cornea onto the retina obeys the laws of geometrical optics [1.5, 1.1], as shown in fig. 1.4. The various optical media of the eye have the following refractive indices: cornea 1.38, aqueous humor 1.34, lens 1.44. Since the density of the eye roughly corresponds to that of water, the critical angle for total reflection can be calculated to be 48° 40'. In principle an image can be produced by the outer surface of the cornea alone. However, the lens in the eye permits light to be refracted to varying degrees, which in turn permits focusing on near and distant objects. The total refracting power of the healthy eye is about 48 diopters, and the capacity to vary this by means of the lens is known as the amplitude of accommodation. In young people the amplitude of accommodation is around 12 diopters; with increasing age (usually between 50 and 60) it approaches one diopter [1.6].

1.3.2 Aberrations in image production

As is generally the case in optics, the eye suffers from certain common lens aberrations. Spherical aberration, which leads to peripheral rays being more powerfully refracted than central rays resulting in a barrel-shaped distortion, is corrected to a large extent by the diaphragm action of the pupil. Chromatic aberration (color distortion), due to more powerful refraction of blue rays than red rays, is mitigated by the effect of the onion-like structure of the lens with its layers of different refractive index (the inner layers refract more powerfully than the outer layers). When colored objects are

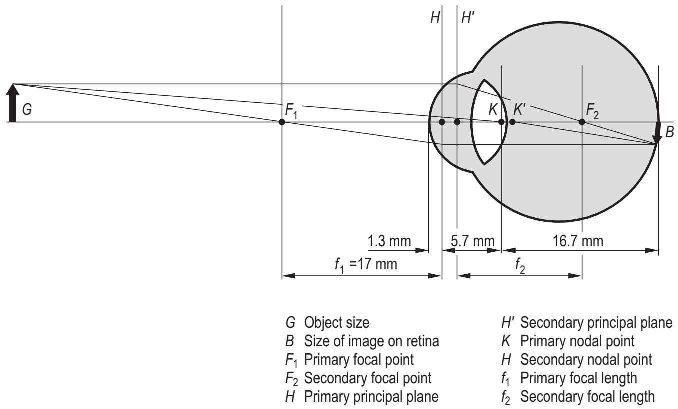


Figure 1.4 Geometrical optics of the eye

observed, difficulties in accommodation can occur if the object lies in a plane close to the eye, because the eye tries to accommodate in turn to the colors with shorter or longer wavelengths. When the object is further away, this effect does not arise because of the greater depth of field.

1.3.3 Eye defects

Figure 1.5 shows that a sharp image is formed on the retina of an eye with normal vision.

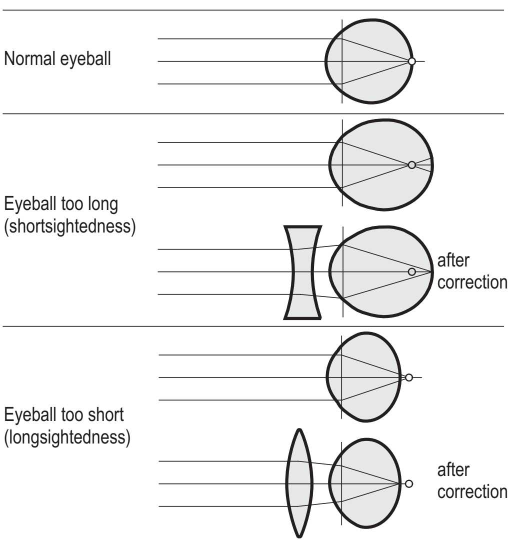


Figure 1.5
Visual defects produced when eyeball is too long or too short, and means of correction

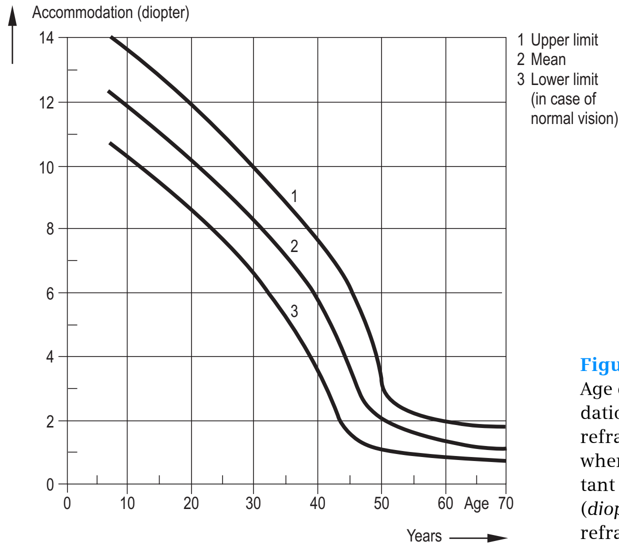


Figure 1.6
Age dependence of accommodation (difference between the refracting power of the lens when looking at near and distant objects) according to Graff (*diopter* = $1/m$ is the unit of the refractive power $1/f$ of a lens)

In the case of an eyeball which is too long (shortsighted) or too short (longsighted), the image is formed in a plane in front of or behind the retina. A sharp image can therefore only be achieved by means of correction with appropriate lenses (glasses or contact lenses). Apart from the decrease in amplitude of accommodation due to the loss of lens elasticity associated with increasing age (as illustrated in fig. 1.6), clouding of the lens or of the aqueous humor can cause sight to deteriorate.

1.3.4 The accommodation process

Focusing an image on the retina is achieved by changing the refractive power of the lens. This is done by contraction or relaxation of the ring-shaped ciliary muscle (see fig. 1.3) so that the lens is compressed or stretched radially. The process is controlled by the nerve cells of the oculomotor center in the brain which adjusts the refractive power of the lens until the size of the image reaches a minimum.

1.3.5 Eye movements

With the help of the eye muscles shown in fig. 1.7, the eye is moved until the image of the object to be observed is located at the point of maximum resolving power (smallest spatial resolution) on the retina (viz. the fovea: see fig. 1.3). As can be seen from fig. 1.10, this point has the highest cone density. The process is subject to continuous control, because the eye moves its optical axis in relation to the object observed until the number of stimulated cones reaches a maximum. As in any control process, there is permanent adjustment towards an optimum value, i.e. the axis of the eye is moving constantly to and fro. In order to maintain this maximum stimulation, the eye continually makes oscillatory movements (saccades) in all directions. Such movements are

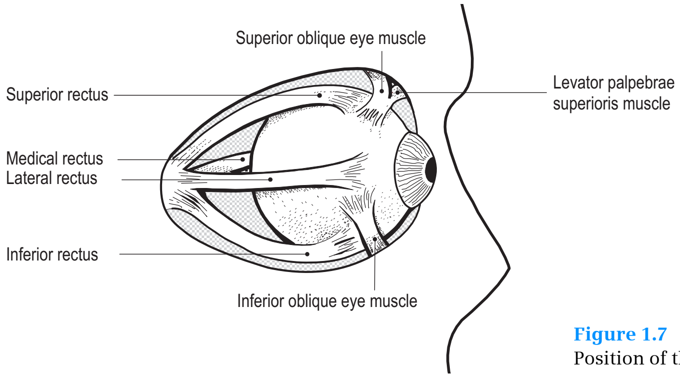


Figure 1.7
Position of the eye muscles

also carried out in a resting state (with the eyes open) at a frequency of approximately 10 Hz.

1.3.6 Depth of field

The eye's depth of field depends on the same parameters as does any ordinary optical apparatus. That is, it depends on the diameter of the pupil (aperture) and on the degree of accommodation (depth adjustment). As fig. 1.8 shows, in the case of medium

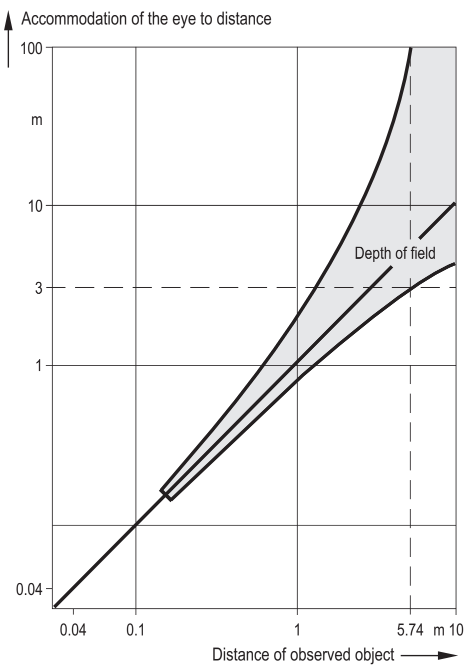


Figure 1.8
Depth of field of the human eye in relation to accommodation at medium pupil diameter. Accommodation to a distance of 5.74 m gives the ability to see in focus at distances between 3 m and infinity (fixed focus setting according to Ranke in [1.1])

pupil diameter and accommodation to a distance of 5.74 in, everything from 3 in to infinity is seen in focus [1.1].

1.4 Conversion of light into neural impulses

1.4.1 Anatomy of the retina

As fig. 1.3 shows, the retina lies on the inside of the rear half of the eyeball. It contains the photosensitive rods and cones as well as the nerve cells [1.4] which preprocess optical information. Figure 1.9 shows a diagram of a microscopic portion of the retina with all the optically active elements. From the diagram it is clear that the photosensitive outer segments of the rods and cones which contain the visual purple [1.7] are turned away from the light and are partially submerged in the pigment layer (not shown). This means that the effect of scattered light is reduced and that the sensitive elements are protected from overexposure to light by creeping into the pigment layer.

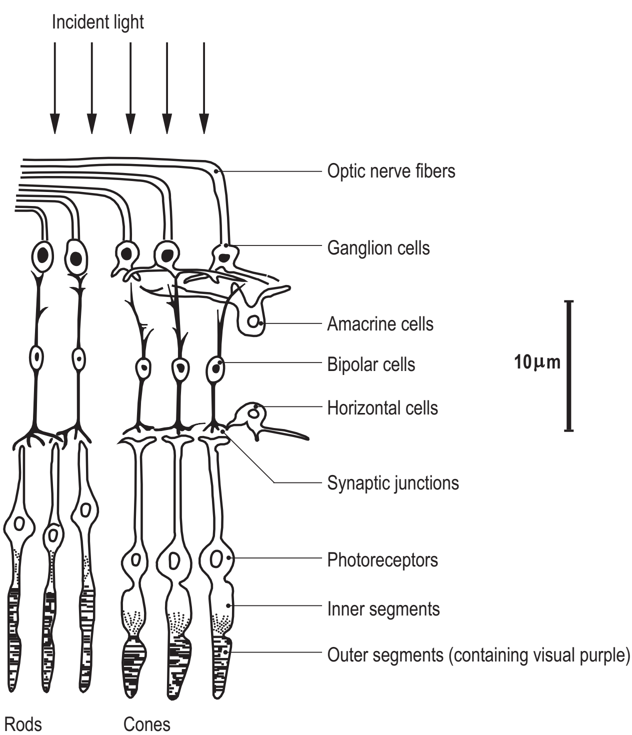


Figure 1.9
Diagrammatic representation of the structure and relative position of the active elements of the retina

The visual purple [1.8], a derivate from vitamin A, is stored in the outer segments of the cones; it is decomposed by the absorption of light, the cleavage molecules producing an impulse which is passed on by the photoreceptors to the bipolar cells via synaptic junctions. The connection of several photoreceptors to one bipolar cell forms the receptive field [1.9]. Every ray of light that hits one of the receptor cells in such a group stimulates the nerve cells connected to them in such a way that those at the edge have an inhibitory effect whilst those at the center have an excitatory effect (or more rarely, the other way round). With increasing light intensity, however, the activity changes in that the amount of inhibition becomes greater. In this way the difference between light (excitation) and dark (inhibition) is reinforced. The impulses travel from the bipolar cells via further synaptic junctions to the ganglion cells and optic nerve fibers, which transmit them to the brain.

1.4.2 Spatial resolution

Visual acuity

Two points are only recognized as being separate entities when the images on the retina are so far apart that an unstimulated cone or receptive field happens to be located between the two. The bigger the receptive elements, therefore, the greater will be the distance required between the two images in order for them still to be seen separately, and the spatial resolution of the eye will be correspondingly worse. In medicine

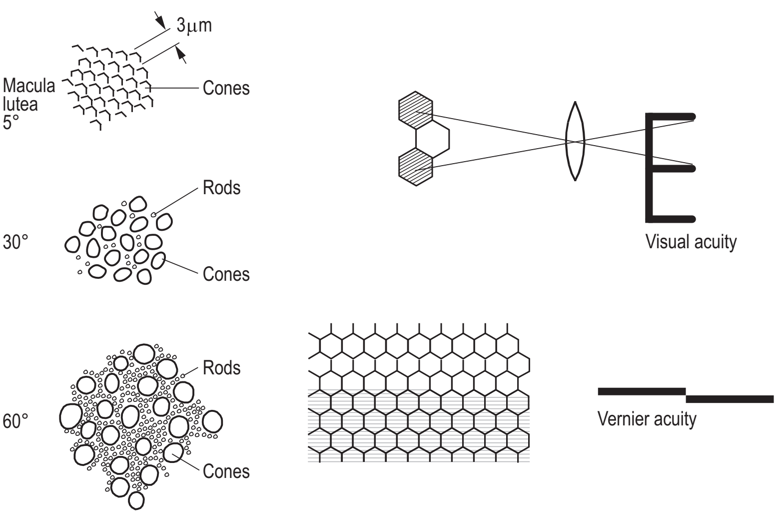


Figure 1.10
Diagram of the rods and cones at the fovea (macula lutea) and in sections of the retina separated by an arc of 30 and 60 degrees from the macula. In the macula lutea there are only cones; towards the periphery both rods and cones are found, with cones becoming progressively less numerous and rods more numerous. The diagram is copied from a microphotograph. Next to it are shown the mechanisms for visual acuity and Vernier acuity. See text for details.

this is called the visual acuity [1.1] and is related to the angle between two light rays which can still just be told apart. As is clear from fig. 1.10, the width of a cone in the macula lutea is about 3 µm, so that taking into account the laws governing image formation in the eye, there is a maximum possible visual acuity corresponding to 50 arc seconds. From fig. 1.10 it is also clear that the distance between cones in the outer regions of the retina increases giving the distribution of visual acuity over the retina shown. Only in a narrow range of 5°, corresponding to the extent of the macula lutea, can the maximal visual acuity therefore be achieved.

Vernier acuity

Whilst the visual acuity of the eye is already very high, an even greater resolving power is possible under certain conditions, namely when lines, rather than two points, have to be distinguished. As shown in fig. 1.10, the eye detects the break in a line due to a slightly offset continuation because the cones (or rather, the nerve cells connected to them) are all interlinked and can tell if on average more cones are being stimulated after the break (from the other half of the image) than before the break. By means of statistical evaluation of the distribution of the stimulated cones, the nervous system can recognize distances between lines which are even smaller than the distances detected in conditions of maximum visual acuity. This fact has long been known in engineering workshops and is used when reading the Vernier scale on measuring instruments, which has led to the name ‘Vernier acuity’. In summary it should be emphasized that the nature of the neural processing mechanisms means that visual acuity also depends on the shape of the object perceived.

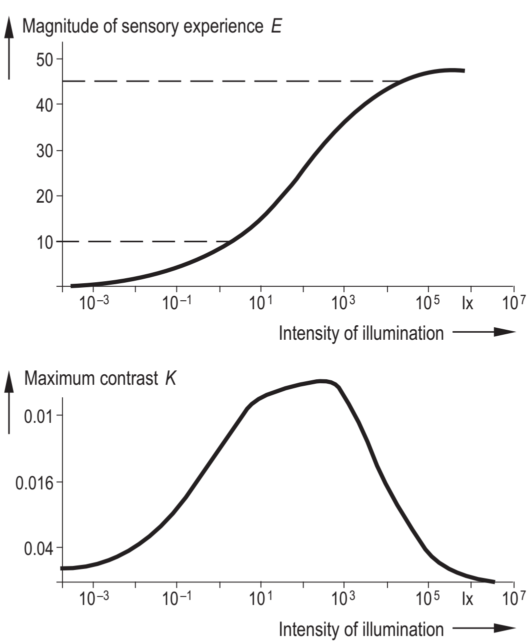
1.4.3 Contrast resolution

Differential sensitivity

In principle one might expect that a minimum increase in the brightness of an object exist which will produce a minimum increase in the magnitude of the eye’s sensory experience. This assumption has proved to be correct, with one qualification: the minimal increase in the magnitude of the sensory experience depends upon the level of background illumination at the time. According to the Weber-Fechner law, the magnitude of the sensitivity E increases logarithmically with the strength of stimulus R according to the equation

$$E = K \ln \frac{R}{R_0}$$

in which, according to Fechner [1.1], K is a constant and R the original stimulus intensity. If, following the practice in technical fields [1.10], the logarithmic value of the light intensity is plotted on the ordinate and the magnitude of the sensitivity is plotted on the abscissa, the graph shown in fig. 1.11a is obtained. At the point where the graph climbs most steeply, the contrast sensitivity is high; where the graph is flat, the contrast sensitivity is low. In the top area glare is said to occur whilst in the bottom area the stimulus is said to be below threshold. Fig. 1.11b shows the differential quotient, i.e. the contrast sensitivity.



a) The sensitivity $E = K \ln R/R_0$ is plotted as function of the intensity of illumination. The eye can distinguish about 50 equally spaced levels of sensitivity. Of these roughly 35 lie in the linear region.

b) This graph shows the actual sensitivity to the eye to contrast (differences in brightness). If the Weber-Fechner law were to hold exactly (rising straight line in **a)**) the curve (taken from Ranke [1.1]) would be parallel to the *x*-axis.

Figure 1.11
Sensory experience of the eye according to Weber-Fechner **(a)** and actually measured contrast sensitivity **(b)**

Glare

As explained in the last paragraph, the term glare [1.11] means the reduction to zero of the contrast sensitivity as a consequence of being exposed to such great light intensity that one no longer sees anything but ‘brightness’. This definition, however, fails to encompass all the phenomena and causes of glare. Glare also occurs locally, if next to a brightly lit portion of the retina the strongly stimulated cones there inhibit their weakly stimulated neighbors. In this way this area of the retina falls beneath the stimulus threshold and can no longer detect any differences in brightness. Such an effect is reinforced even more by the scattered light [1.12] emanating from a bright ray of light in the not completely clear media of the eye, especially of the vitreous body. This scattered light obscures the tiny differences in brightness of the weakly illuminated surroundings of a bright spot on the retina.

Simultaneous contrast

The mutual coupling of the rods and cones described previously, which is associated with a mutual promotion or inhibition of stimulation, is known as lateral enhancement or inhibition, as the case may be. It is the cause of the fact that a brightly illuminated spot on the retina inhibits the cells around it; by so doing the difference in brightness of the stimulus, and with it the sensory experience, is reinforced. The end

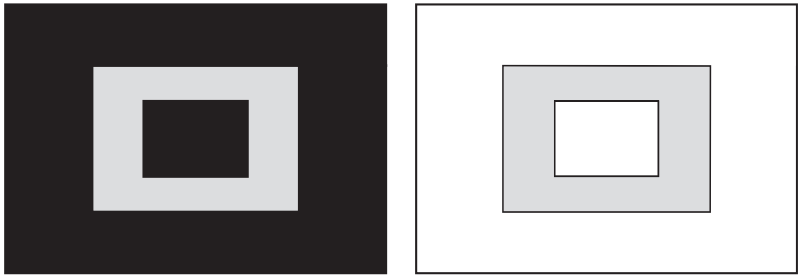


Figure 1.12
An example of simultaneous contrast. The same gray rectangle appears darker on a white background and lighter on a black background.

result is therefore always a neural enhancement in the perceived contrast, an effect which is demonstrated in fig. 1.12.

Successive contrast

Since in the case of pictures presented one after another the neural enhancement in the perceived contrast cannot occur because of the lack of inhibition, the contrast sensitivity is less than in the case of simultaneous contrast.

Contrast gradient (image definition)

The transition from a bright to a dark area of a picture normally takes place gradually so that a contrast gradient can be defined as the decrease in brightness over the appropriate distance in the image. Should this distance reach dimensions comparable to those of the diameter of a cone, it will lie beneath visual acuity and the physical contrast gradient can be ignored. In such a case it is only the physiological mechanisms for the perception of contrast which are involved, so that any further improvement in definition using technical means does not make sense. Besides these considerations, the problems mentioned in connection with glare play an important role, especially when the change in the level of brightness is very large.

1.4.4 Adaptation

Spatial resolution, the detection of contrast and the perception of definition, i.e. the mechanisms which are necessary for producing image quality, are extremely dependent on the eye's adjustment to brightness, known as adaptation [1.13]. This process can be described as follows: when bright light hits the eye, the visual purple in the cones is decomposed. The breakdown products give rise to stimulation. At the same time, however, the visual purple is reconstituted at a quite specific rate and is once more available for the visual process. When illumination starts, the breakdown process predominates, so that there is intense stimulation. With the onset of the reconstitution processes, a situation of equilibrium develops in which breakdown and reconstitution are exactly in balance. The breakdown products available at this stage are