

15 Virtual technologies aid in restoring sight to the blind

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Abstract. Virtual technologies, and the novel approaches taken in their design, promise to enable a new field of image processing applications often referred to as "Artificial Vision." In this chapter, we present the concepts encompassed under this terminology, introduce three areas of application—with strong emphasis on the rehabilitation of blind and visually impaired individuals—, summarize in general terms their current status, and sketch a road map for their developments in the foreseeable future.

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This chapter is based on an earlier paper by the same author and R.W. Massof, which appeared as the title article in [1], pp. 22-29; ©1996 IEEE; it has undergone major revisions for inclusion in this volume.

15.1 Three types of vision rehabilitation

Virtual technologies allow us to present information in novel ways: reducing the content in order to meet transmission capacity limits of the system or recipient; altering the mode of presentation in order to circumvent sensory deficits; and creating new representations that can be more easily understood.

Commonly, the information source used in virtual technologies is remote or intangible, often created and existing inside a computer only. When the objective is vision rehabilitation, the source of the information can still be a computer—data, text, or entertainment material presented through a user interface—, but more often consists of real objects and living beings, whose presentation requires capture into the information processing system used. Since the processing and presentation technologies are the same, regardless of the real versus virtual source of the information, we can apply many of the virtual technologies introduced in this book to the problems of vision rehabilitation.

It is helpful to distinguish three application modes in vision rehabilitation: *enhanced vision*, *prosthetic vision*, and *artificial vision*.

- *Enhanced vision* refers to visual impairment remedied by assistive devices that present image information to an individual's remaining seeing retina, after processing the raw image for maximum visibility by that individual.
- *Prosthetic vision* presents processed visual information to the individual's inner retina or visual pathways through electrical stimulation of surviving neurons.
- *Artificial vision* processes and interprets visual information, and may even make decisions, presenting the result to the individual through another sensory modality.

All three modes may reduce image information to symbolic or iconic form prior to presentation, but for enhanced and prosthetic vision this is not necessary

15.2 A glimpse of the future

"Meet Gregory Greenacres, an 81 year-old semi-retired businessman who used to make a comfortable living in the sale of cellular videophones, and who spent his weekends playing a mean round of golf, until a precipitous case of macular degeneration robbed him of his central eyesight four years ago. Following retina surgery that stopped the disease process but did not bring back the lost vision, his only driving was as a passenger in his wife's car; his reading was halting even with his portable vision enhancer; and his only sport was playing poker with his former golf buddies, using large-print cards and downing more Martinis than was good for his liver. Until last year, in the summer of 2020, when a smart visual prosthesis brought back the joys of central vision, plus a few gadgets his natural vision never provided: zoom and scan technology that automatically tracks the flight of his golf ball over hundreds of yards; and on-chip infrared reception of faxes and cellular videophone communications, with complete privacy guaranteed by an electronic feed into the prosthesis and the speech output directly into his digital hearing aid. Greg calls the device his "bionic eyes" because the image he sees respond instantly to his eye movements; his wife refers to it as his "robot visor" because of its sunshades look; the official name is macular opto-electronic prosthesis, or MOP. Several of Greg's friends have eagerly asked their eye doctors what the chances are that they will get macular degeneration, since the FDA has not yet approved the MOP for civilian application in normally-sighted people.

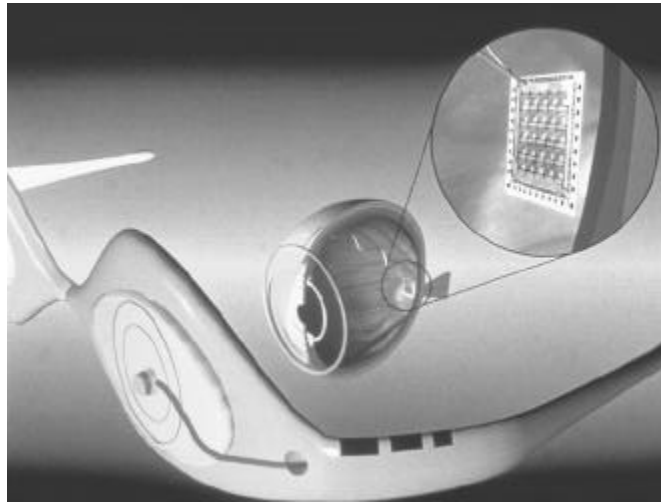


Figure 15.1. Schematic of visor and retinal chip. Greg's future "bionic eye" may consist of a visor and a belt pack, connected by a thin optical fiber. The visor contains a miniature wide-angle video camera near the temple arm, an eye position sensor, and an RF transmitter to an intraocular receiving antenna and decoder/stimulator chip replacing the defective light sensitive retinal cells. Image processing and control functions will be housed in the belt pack. In a more advanced version, the visor would be transparent, to provide a free view for Greg's healthy peripheral retina (Image courtesy of Dr Wentai Liu, North Carolina State Univ).

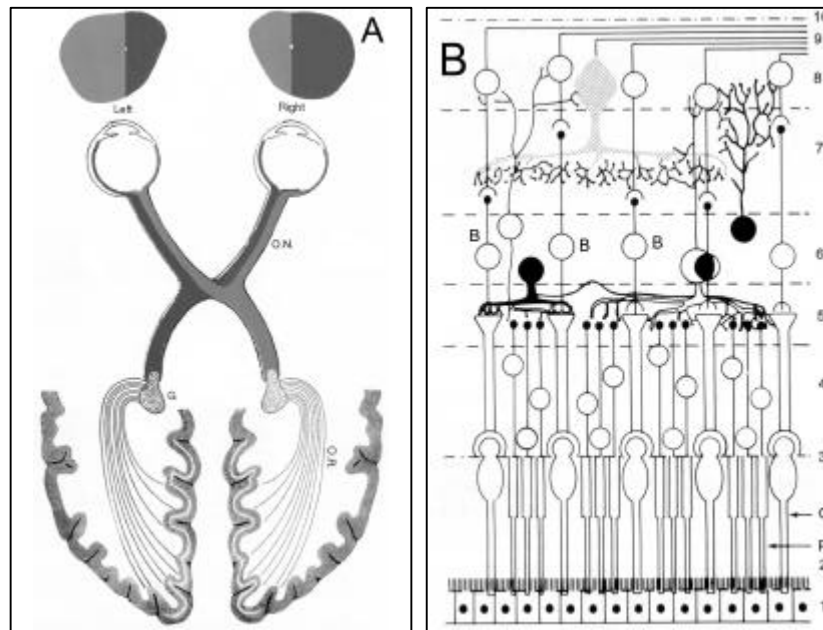


Figure 15.2 Schematic representation of the human visual pathway (A), and of the cell layers in the retina (B). Information from the two eyes (in A) is combined by partial crossing of the optic nerve (O.N.) fibers at the optic chiasm, so corresponding locations on the two retinas project to the same area in the visual cortex. Signals then travel through the lateral geniculate nucleus (G) and the optic radiations (O.R.) to the primary visual cortex, of which only a small portion is situated on the cerebral surface. Depending on the location of the lesion that causes blindness, a visual prosthesis can stimulate remaining cells at different locations along the pathway. Adapted from A. J. Bron, R. C. Tripathi & B. J. Tripathi, *Wolff's Anatomy of the Eye and Orbit*, Chapman and Hall Medical, New York, 1997, with permission. Light entering the retina (in B) passes through the nerve fiber (9), ganglion cell (8), inner nuclear (6)—containing bipolar cells (B)—, and outer nuclear (4) layers, before being absorbed in the outer segments of the rods (R) and cones (C). Reprinted from "Anatomy of the human eye, orbit & adnexa" by R. C. Tripathi & B. J. Tripathi, Ch. 1 in H. Davson, *The Eye, Vol. 1A, Vegetative Physiology and Biochemistry*, Academic Press, 1984, with permission.

Greg's doctors have told him that the restoration of his central vision has been made possible by a combination of video technology, image processing, and two stimulator chips inside his eyes that activate relay cells to the brain. A retired biologist friend of Greg's has explained to him that what looks like an almost normal image—albeit consisting of small dots—is produced by an elaborate series of image transformations mimicking what several layers of his retinal cells used to do, and that it took the synthesis of at least three research fields, each of which went back to well before the turn of the millennium, to generate the first prototype of the MOP, ten years ago. While Greg is interested in the background of his gadget, he has long since come to accept that much of the 2020s technology cannot be understood in terms of the physical and biological concepts he learned in college, back in the late 1960s. What he does know, however, is that several million elderly people like himself are regaining their independence, thanks to the MOP."

15.3 Normal vision

To clarify the emerging field of VR technology application to vision rehabilitation, it is helpful to briefly go over the properties of normal vision. For a better understanding of the challenges of vision enhancement and restoration, Appendix I lists the major disorders that lead to vision loss, and the ways in which impaired vision differs from normal vision.

The human visual system is a remarkable instrument, featuring two mobile image acquisition units (the eyes) placed at a remote location from the central processing circuitry (the visual cortex), as depicted in Figure 15.2. Nature has created a number of amazing engineering solutions. It solved the contradictory requirements of a wide viewing angle (at least 140° per eye) and high resolution (1 arcmin or better), to be transmitted over a limited capacity carrier (roughly 1 million fibers in each optic nerve), by changing the ratio of receptors to transmitting elements (retinal ganglion cells) from 1:1 in the center to 300:1 in the far periphery, resulting in a gradual shift in resolution and other system parameters. It solved the dynamic range problem of at least 1000 million-fold changes in ambient light by creating two photoreceptor systems (rods and cones), each equipped with an impressive gain control mechanism, and followed by further range compression in subsequent cell layers. It developed a crude form of spectroscopy by alternating, in the high-intensity receptor matrix, cones with different pigments, and by encoding in subsequent retinal layers signal differences between adjacent receptors. It created special classes of retinal ganglion cells to transmit information about rapid changes and edges. At the cortical level, it added an impressive array of feature extraction mechanisms that bring about such varied achievements as:

- attention being drawn, and gaze redirected, upon sudden movement in the peripheral field of an object too small to be perceived while stationary;
- resolving depth differences in tasks such as threading a needle, by virtue of combining signals from the two eyes, and distinguishing disparities with a precision less than one tenth of the size of photoreceptor; and
- detecting curvature, judging perpendicularity, and estimating alignment with a precision requiring combined input from tens or hundreds of photoreceptors over several degrees of visual field angle.

These mechanisms are not fail-safe, as we all know from optical illusions, but in natural visual environments they are remarkably robust. Even when the system breaks down under the attack of eye disease, it is remarkable how much destruction can be tolerated before severe vision loss occurs (see Appendix I). For vision rehabilitation purposes we may thus

be well advised to explore the possibilities of tying into any remaining part of the visual system rather than pinning all our hopes on completely artificial vision systems with or without sensory substitution at their output.

15.4 Vision restoration or artificial vision?

Delving into recent literature about "bionic eyes," especially in the popular science press [1], one cannot help but be impressed by the tools that are being arrayed for the development of artificial vision systems. It is tempting to conclude that intelligent machine vision systems are the way of the future, not only for robotic systems in areas such as quality control, surveillance, and telepresence, but also as support systems for the blind. One argument we will make in this chapter is that there is a large category of blind people whose vision has been severely impaired by diseases of the eye or visual pathways (see Appendix I), but whose remaining visual system has the capacity for functional rehabilitation, provided it is appropriately stimulated by a prosthetic device. Techniques such as simulated physiological preprocessing and signal transduction from electrodes to neurons will allow these systems to bypass degenerated retinal cells, or even the eye altogether. Experience gained with such systems may even lead to improvements in designs for machine vision systems, regardless of their application. A second argument to be made is that, even without prosthetic devices over the retina or cortex, vision enhancement hardware and image processing algorithms can be developed that will grant many individuals with low vision the tools for independence through their remaining visual function.

The World Health Organization defines the term "low vision" as best-corrected visual acuity in the better eye worse than 0.3 (6/20 or 20/67) [2], but in the USA low vision is defined only in functional terms: a person has low vision if (s)he is unable to perform ordinary visual tasks because of a visual condition that cannot be corrected through refraction—i.e., with glasses or contact lenses—, medically, or surgically [3]. In practice, this means that anyone with corrected visual acuity 20/40 or worse in the better eye, with impaired contrast sensitivity—e.g., less than 1.5 on the Pelli-Robson contrast letter chart; see Appendix I—, or with restricted visual fields *may* have low vision, if this vision loss limits his/her daily activities. In 1990, over 4 million people in the United States fell under this operational definition [4], and most of these were over 65 years old. With the expected increase in the number of elderly, this number is bound to rise over the next decades. Advances in medical science may limit the increase in the low vision population, yet it is unlikely that effective prevention of common eye disorders, or reversal of the ensuing vision loss by medical or surgical means, will become a reality in the next few decades.

Most individuals with low vision can compensate for their loss with relatively simple means such as optical magnifiers, improved illumination, and minor adaptations in their environment. Yet an estimated 1.5 million people in the USA cannot adequately perform some everyday visual tasks, even with assistive devices [5]. Over half of these qualify for the status of legal blindness under US law—corrected visual acuity 20/200 or less in the better eye, or visual field diameter less than 20°—, and approximately 100,000 are functionally blind, in the sense that they can make no practical use of their vision [4]. Assistive devices for the functionally blind make use of sensory substitution, such as touch (braille, long white cane) and hearing (books on tape, radio reading service, tapping with cane); additional substitution systems are under development (talking signs, vibrating obstacle detectors, etc.). For the purpose of this chapter, these systems play the role of *artificial vision*, since they replace vision by another sensory modality for further information processing.

The alternatives to these substitution systems are those that make use of the remaining visual system, either by enhancing the visual information and presenting it to the remaining retinal photoreceptors in the form of images (*vision enhancement*), or by converting the images into a pattern of electrical activity stimulating the higher order neurons in the retina or higher visual pathways (*prosthetic vision*).

15.5 Challenges to the developers

In the next sections we will look at specific challenges faced by the designers of vision rehabilitation and restoration systems. Some of these pertain equally to each type of system, while others are unique to prosthetics design in relation to properties of the blinded visual system, such as its limited information transfer capacity and the optimal location for the prosthesis-tissue interface.

15.5.1 Eye movements

The importance of eye movements to visual perception is often underestimated. Every time a normally-sighted person makes an eye movement, typically several times per second, the image on the retina undergoes a translation. This is equally true for a visually impaired persons making use of an enhanced vision system: they are observing a transformed image on a (virtual) projection screen, and eye movements across the screen will result in a shift of the retinal image. Such image shifts under eye movement control are very important: if an image remains stationary on the retina, it quickly starts fading.

For a person wearing a retinal or cortical visual prosthesis, with electrodes always activating the same locations, the situation may be different. If the camera is built into the eye, or is made to follow eye movements, the shift occurs just as in normal vision; however, if the camera is mounted on a visor or a tripod, an eye movement does not result in an image shift. The ensuing fading can be prevented by temporal modulation of the image (imposed movement or flicker) or by the movement of a head- or body-worn camera. It seems, therefore, that for early versions of prosthetic vision eye movements can be ignored, as long as a head-mounted camera or other image de-stabilizing technique is used.

Real-time simulations of pixelized prosthetic vision in normally-sighted observers, using a head-mounted camera and a video visor, have confirmed that the wearer learns to use head movements rather than eye movements to inspect the scene. Retinal images were not stabilized in these experiments, however, so evidence for the efficacy of camera movements for a visual prosthesis wearer is still lacking.

15.5.2 Wearer interface

Once an image has been captured, and preprocessing has been performed, a transducer will present the information to the user. Disregarding the option of sensory substitution, only two methods are available: enhanced vision, i.e., making use of surviving photoreceptors, and prosthetic vision, i.e., electrically stimulating retinal or higher neurons. If several options are available, how should a choice be made?

If the remaining vision is sufficient for tasks such as orientation and mobility, we may be able to use light input to the retina for most visual tasks by suitably "packaging" the information, as was suggested in some of the examples above. At present, training in special fixation techniques, such as eccentric viewing, scanning, and tracking, can help individuals

with visual field loss become more proficient at performing tasks that would normally require use of the field area they lack. In the future, such training could be simplified using eye movement monitoring and techniques such as biofeedback. Moreover, preprocessing features in an enhanced vision system may reduce the need for training, and allow even patients with severe vision loss to function adequately using visual information.

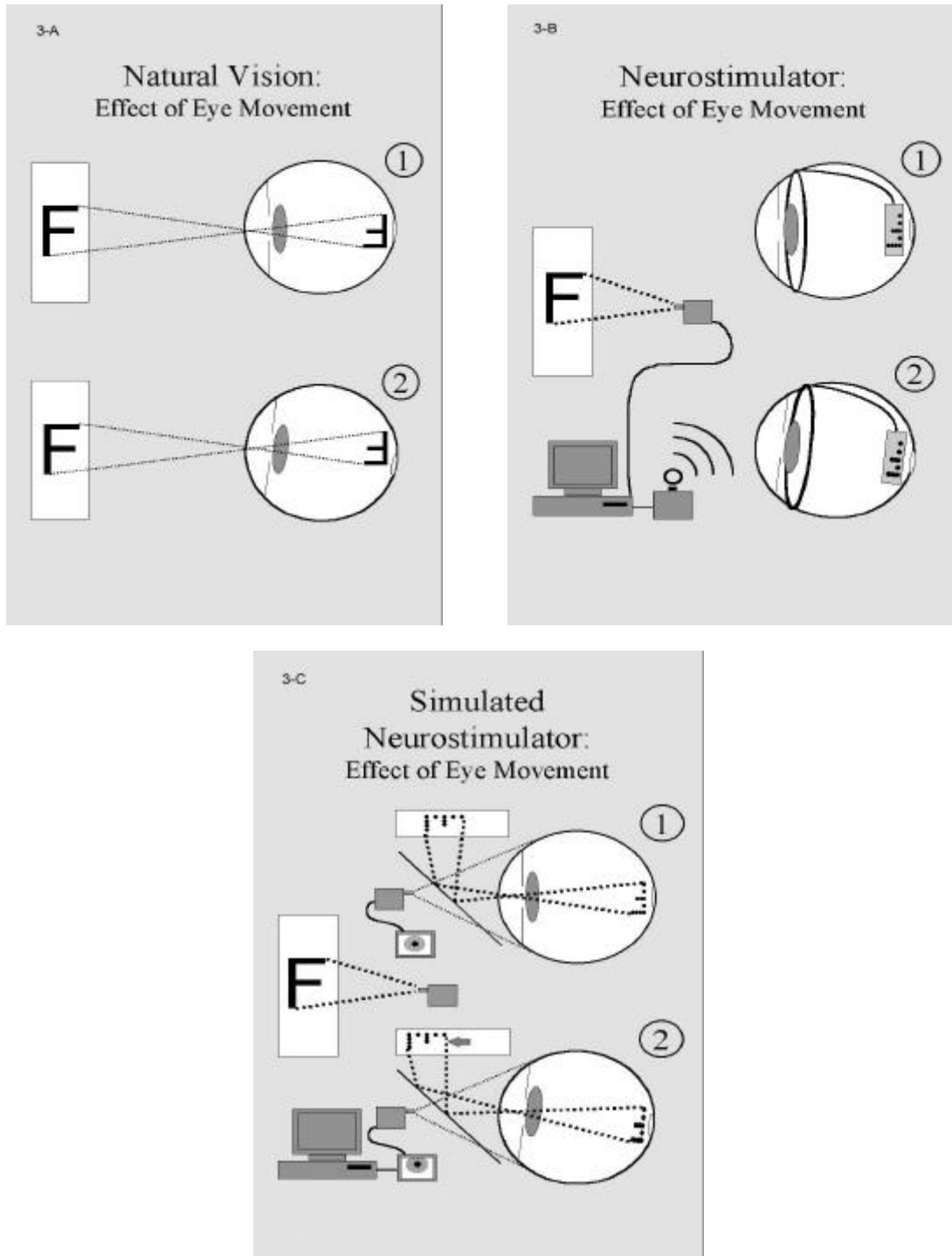


Figure 15.3 The effects of eye movements on the retinal stimulus in normal and (simulated) prosthetic vision. (A). In normal vision the retinal image shifts as the eye changes its direction of gaze. (B). In (simulated) prosthetic vision without eye movement compensation, the pixelized camera image is directly projected onto the electrode array or seeing retina, and does not shift in response to eye movements; the image is stabilized on the retina and will fade. (C). by building in an eye position sensor and shifting the pixelized image being displayed, the subject is provided with a natural response to eye movements.

If little or no vision remains, secondary neurons along the visual pathway can be stimulated electrically, as demonstrated by several groups (see 15.7.2). There is, however, a general question: what are the arguments to favor retina, optic nerve, or cortex, and within each, early vs late processing stages?

In answering this question, one should bear in mind the elaborate image processing performed at all levels of the visual system, in the retina, the lateral geniculate nucleus (a relay station in the mid-brain, between the eye and the cortex), and the visual cortex, and the feedback mechanisms at several levels: as prosthetic stimulation is applied at higher levels, the preprocessing complexity required to approximate "life-like" vision, increases rapidly. Also, neuronal circuits become more and more specialized as the signal travels up the visual pathway, and parallel representations of different aspects of the visual world are being generated. For example, a cortical neuron specialized to signal the presence of a red-green border 18° from fixation at 9:30 hours azimuth, running under a 45° angle, and moving towards fixation at 5° per second, may have neighbor cells that signal the same edge, but at a different resolution, or for a different stimulus aspect altogether. It is true that many of these cells, especially in the cortex, may be able to "re-learn", but it is not certain to what extent this capacity survives, especially late in life. Thus, there is a clear advantage to interfacing earlier along the pathway.

On the other hand, one may be forced to resort to a higher level interface if early levels of the system are too severely damaged to sustain stimulation, let alone reliably transmit information. Thus, for a person blind from trauma to the optic nerve, a cortical prosthesis offers the only realistic chance at vision restoration in the near future.

On a pragmatic note one should bear in mind that surgical placement of a prosthesis at one level may limit the chances of future intervention at a lower level, should a method of treatment at that level become available. Thus, a trade-off has to be managed, in general, and especially while prosthetic systems are still under development, it appears that the lowest viable level along the visual pathway should be chosen for the prosthesis interface.

15.5.3 *Learning ability*

In a person with scotomas in both eyes, enhanced vision uses remapping and other methods to concentrate information on the viable parts of the retina. This forces the visual system to perform more tasks in certain sections of the cortical projection areas, i.e., those connected to viable retina, while leaving other sections unused. In creating prosthetic vision, on the other hand, we force the visual system to process information in sections or entire areas that may have been unused for many years, if not from birth. This raises the question whether a "busy" cortical cell population can recruit the help of neighboring "idle" cell populations, whether cells in the busy population can learn new tasks, and whether cells that have never processed visual information can learn to do so.

Several things are known about the learning ability of cells in the visual system:

- If a cortical area has never sustained high resolution, as in cases where the fovea is not properly developed—e.g., congenital cataracts, albinism—, it may never learn to do so, even with high resolution transducers and extensive training: numerous and elaborate neuronal connections would be required to achieve this, and it is unlikely that these can form after the first months or years of life (the critical period). The same is true for binocularity, depth perception, and most other aspects of form vision [6].

- If a cortical area has never received any visual input (congenital blindness), it is unlikely that useful vision will develop beyond the critical period. However, it is unknown just how much is possible, and until what age.

On the other hand, there is some evidence that cortical cells may, in the absence of input signals from the retinal area they used to serve, form new connections and accept input from neighboring retinal areas [7]; this is one explanation sometimes given for distortions around scotomas. Providing new input from the original area of the visual field to these cells may lead to a conflict, perhaps even double vision. One may expect such conflicts to be resolved gradually, through re-learning.

One cannot predict the extent of functional visual recovery from those obtained in speech and motor rehabilitation following brain damage: some cortical areas may be capable of more recovery than others. On the other hand, as is known from cochlear implant research, recovery of earlier function is quite good, and learning new function goes on at least through several years of infant and toddler development [8]. We are only just beginning to apply new forms of stimulation to the visual system, and the system may turn out to be more malleable than has been thought until now.

15.6 A functional wish list

Enhanced, prosthetic, and artificial vision systems may be useful even if their performance does not match that of the intact human visual system. We should, however, make a wish list of specifications we consider essential, followed by those that are highly desirable, and those that can be included as a bonus with little extra effort.

Essential specifications

- *Dynamic range compression, e.g., luminance, contrast.* To allow operation at illumination levels from bright daylight to at least dim artificial lighting, an adaptive mechanism needs to be part of the system. By combining exposure timing and lens aperture, the automatic gain control systems in today's video cameras already approximate this requirement. Similarly, automatic compression or expansion of image (luminance or color) contrast to utilize the full dynamic range can be performed with currently available analog and digital techniques.
- *Enhancement of local contrast* (see Colour Plate 15.1). To make local contrast features more visible without driving areas of stronger contrast into saturation, differences must be enhanced only over short ranges. Such operations, more commonly known as edge enhancement can be performed with relatively small convolution kernels. While real-time spatial filtering at video rates in a belt-pack system is not yet possible today, it is likely to become available within a decade. In the longer run, new developments such as optical computing technology may allow complex filtering operations in true real-time. As we can see in Colour Plate 15.1, the undistorted image (A) may appear with reduced contrast and a washed-out area in the center to a patient with macular degeneration (B). Edge enhancement in part or all of the image (C) can help patients make optimal use of their remaining vision. Such image compensation techniques can be adjusted to individual patients' deficits.

- *Customization.* Whatever the capabilities and functions of the system, its most important requirement is adaptability to the needs and remaining visual capabilities of the user. Moreover, the extent to which certain features of the system are put to use may vary according to the task at hand. This means that the system has to be customized to a user as well as programmed to the task. Ideally, such tailoring should require only a few adjustments on the part of the laboratory or clinic dispensing the system, and should demand only limited training and minimal effort on the part of the user.

Desirable specifications

- *Eye position monitoring.* In more elaborate forms of enhanced and prosthetic vision, eye position monitoring and feedback become indispensable to accomplish several objectives:
 - *Image remapping.* To allow a visually impaired person maximum benefit from an enhanced vision system, the image has to be adapted to local properties of the retina, such as scotomas (blind areas), distortions, and poor acuity or contrast sensitivity. Thus the image enhancement algorithms require a map of the wearer's retinal function, and real-time eye position information: as the wearer shifts his/her gaze, the "region of interest" (ROI)—i.e., the section in the image where the enhancement is applied, or the section that is being presented to a the device wearer—has to shift with it. The eye position information controls the image processor. Several types of image transformations may be applied. If the person has field loss in both eyes, information (e.g., an approaching vehicle) might be "lost" in a scotoma, so the equipment must be able to *warp* (distort) the image, such that information from the scotoma is mapped onto seeing retina (see Colour Plate 15.2). In the photographs of Colour Plate 15.2, using an accurate map of the patient's scotomas, and a set of warp algorithms optimized for specific viewing tasks, information is mapped away from the blind retinal area (A), in combination with edge enhancement in the surrounding portion of the image (B). Real-time eye position information can be used to relocate the region of interest for these operations in the wide-field frame buffer, to maintain registration of the warp with the impaired retinal area. A similar warp operation could be used to magnify a section of the image for a person with poor (central) visual acuity. Obviously, objects in the warped area will look "stretched" or "squashed", but we expect users to get used to this distortion rather quickly. If the person's contrast sensitivity is reduced locally, contrast enhancement operations such as *local edge enhancement* can be performed within the ROI only, without affecting the remainder of the image. Finally, if a person experiences distortions (see Appendix I), a *distortion compensation* algorithm could be used to make crooked lines look straight and improve object recognition. In this case the system needs to have an accurate map of the wearer's distortions, which can be obtained only with special tests—e.g., by asking the person to align dots on a screen into a regular pattern, under strict eye movement control. Distortion compensation and warping may partially cancel each other, as in the case where a small scotoma has perceptually been filled in with information from the surrounding visual field (see Appendix 1).

Bear in mind that image remapping must be identical for the two eyes, as long as both eyes have useful vision. On the positive side, if scotomas in the two eyes only partially overlap, warping is necessary only for the joint portion of the scotomas.

- *Prosthetic vision: image acquisition.* To achieve the expected shift of the image across the electrode array stimulating the retina or cortex when the wearer executes an eye movement, the eye position signal can be used to either (mechanically) "pan" the camera capturing the image, or (electronically) shift the region of interest (ROI) in an image acquired by a wide-field camera. In the latter case, the ROI becomes the only section of the image projected onto the electrode array, eliminating the need for a mechanical servo system. Either solution allows for more "natural" scene viewing in prosthetic and artificial vision than head or body movements.
- *Retinal prosthesis: stimulation.* If a retinal prosthesis is to receive power and signal input from outside the eye through a directional transmission channel such as an IR laser beam, the transmitter has to remain aligned with the intraocular receiver chip. Initially one can build in a safeguard: if the eye goes out of alignment the transmitter is switched off. To retain continuous image information, however, the eye position must be used to control the IR beam projection, for example through servo-adjustable hot mirrors that maintain the IR beam in the center of the pupil and of the intraocular chip, regardless of eye position.

Radio frequency (RF) transmission of power and image information can eliminate the need for this compensation, however: the inductive coupling between the transmitter coil in the visor and the receiver coil on/in the eye is only moderately reduced for eye movements up to 30° off center. Therefore, as long as the energy transfer of the system exceeds the power required, and the information signal does not depend on the amplitude of the carrier wave (e.g., FM or digital encoding), retinal stimulation by such a system is almost immune to eye movements.

- *High resolution, wide field image capture.* Current video cameras (typically 512×512 or 640×480 pixels) tend to cover a field of view of 30° or less, to retain acceptable quality: the resolution for a 30° diagonal image of 640×480 pixels is equivalent to 20/45 visual acuity. A high resolution camera with a wide field of view would be of great use. As an example, an 80° camera with a 6.4×4.8K chip would provide up to 3.5× magnification with better resolution, and with an ROI roaming through the image under control of eye movements or other cues. Another configuration allowed by such a system would be that of a low resolution large field image, with a high-resolution ROI as a central inset; just as in the normal visual system, this would provide enhanced and prosthetic vision with a large field of view, with modest processing power, and increased detail near the center of fixation.
- *High resolution, high contrast flat panel displays.* Most electronic displays systems for the visually impaired still use CRT screens because of their better resolution in visible lines per image, larger screen area, higher contrast, and lower cost; however, from a standpoint of size and weight, CRTs are inconvenient for both portable and stationary systems. Flat panel display technology has made rapid progress in recent years, and is likely to produce high resolution, high contrast screens for vision enhancement, from well under an inch to many feet in size over the next decade, at a

price that can compete in the consumer market. High-resolution color will be standard with most of these screens.

- *Advanced optics.* To allow light-weight head-mounted systems for portable enhanced vision, further developments in the areas of Fresnel lenses, holographic optical elements, and diffractive optics are needed. Such elements will allow presenting a wide-field projected image to the wearer.
- *Image control, e.g., freeze frame, storage, instant replay, automatic tracking, zooming, and image stabilization.* These features may be useful to normally sighted individuals and machine vision applications, and gain particular importance for a low vision patient. One example was given in the "glimpse of the future," in the form of Greg's bionic eye tracking his golf ball: using feature extraction and recognition algorithms in combination with the system's ROI functions, this capability can be provided without much effort. Image stabilization, using accelerometers mounted on the camera, would also use these functions, greatly improving the ease of use of these systems at high magnification, especially for elderly individuals with severe tremors. For another example, a person with serious reading problems who wishes to prepare a dish from a recipe may have to refer to the recipe repeatedly, and to do this would have to pick up a magnifier, relocate the place in the recipe where a particular ingredient is mentioned, read the instruction, put down recipe and magnifier, and execute the instruction. Storing the recipe in video memory will simplify this task, especially if text navigation through a virtual frame of highly enlarged text is driven by eye movements in a manner similar to using a mouse to scroll through text or images on a computer screen.
- *Image interpretation and re-coding, e.g., presenting text, extracting motion or depth, and warning for upcoming obstacles.* Freezing an image allows many other manipulations in the realm of feature extraction and interpretation. Thus, if a person has severe problems with sustained reading, continuous text can be presented serially—either as separate words presented in a single locations or as a scrolling string without line or page breaks—or in a different sensory modality, e.g., as spoken text or braille. Similarly, depth, parallax, and other motion information—steps, a curb, approaching vehicles) can be enhanced visually or announced through an auditory or tactile warning signal.
- *Symbol translation, e.g., sign and landmark interpretation.* This would take the system yet another step towards assistance of individuals with little or no vision. Systems equipped with these features would help the wearers orient themselves in unfamiliar surroundings such as airports and stations, and would thus complement other navigation systems such as the long cane.
- *Mapping one image dimension onto another, e.g., color or depth onto grayscale or flicker.* In a visual prosthesis using electro-neuronal transduction, image dimensions such as color may prove very difficult to convey meaningfully and reproducibly. Such a dimension can be mapped (temporarily) onto another one, and after some training the user should be able to interpret the information. This feature can also be of help if a person has great difficulty processing visual information of one type, but less trouble handling other modalities, for example following a stroke.
- *Display of external (synthetic) information, e.g., virtual reality, video games and communications.* While this might seem a "gadget" for normally sighted individuals, to a blind or visually impaired individual it might mean the difference between disability and employment, between isolation and integration. And as we learned from our friend Greg, it can also improve the user's privacy.

Optional specifications

- *Spectral range selection (monochrome vs. color, UV, IR).* Features such as these would have applications mostly as enhanced vision for normally-sighted users with special requirements, from physicians enhancing their view of X-rays by using false color to weather and surveillance services.
- *Remote operation of the input unit, e.g., telepresence.* This application would have no particular use for low vision patients, but its importance for machine vision and robotics is obvious. The acquisition unit(s) can be located almost anywhere, and the user controls the operation and analyzes the images, usually in real time, at a safer or more comfortable location.

15.7 Current endeavours

15.7.1 Vision enhancement

Compared to the large amount of research being conducted in visual perception and image processing, the considerable increase in low vision research and clinical work over the last decade, and the efforts to develop new equipment for the totally blind, surprisingly little work is being done to develop broadly applicable rehabilitative technology for visually impaired users. Most devices and technologies currently available are either task-specific—e.g., closed-circuit television (CCTV) readers, screen enlargement software—or at best range-specific—e.g., magnifiers with fixed working distance, telescopes and microscopes with fixed magnification. In the last decade, some research in low vision enhancement explicitly aimed at producing equipment—e.g., the POVES project in Europe [8]—, and several manufacturers in the US have introduced head-worn visors and small mouse-like video cameras to improve the flexibility and portability of opto-electronic video enhancement. The Low Vision Enhancement System (LVES; see figure 15.4) [9] was the first and most ambitious attempt at integrating video technology, image processing, and low vision research; yet it still leaves much to be desired in ease of operation, capabilities, and cosmetics. Appendix II describes the LVES in some detail, as a stepping stone towards future forms of low vision enhancement.

Advantages of the LVES and similar video-based devices over optical low vision aids are their variable magnification and working distance, autofocus operation (or large depth of field), and optional contrast enhancement and/or reversal. Advantages of the newer and smaller devices are their portability (compared to most CCTVs) and range of applications. Yet, comparing the current LVES with image processing power already available, and with the wish list presented above, it is clear that this is only a first step. In fact, the edge enhancement, warp, and distortion compensation capabilities that were planned from the start, and that do exist in laboratory software simulations of the LVES, were not implemented in the 1994 production model.

The incorporation of a DSP chip for autofocus was a first step in that direction, but the planned follow-up research and more powerful image-processing hardware and software were never implemented, primarily for financial reasons. Only as the components for such improvements become more readily available and affordable can further improvements of these devices be expected



Figure 15.4 LVES wearer performing ADL. The 1995 autofocus LVES (left), allowing a patient with severe visual impairment to perform detailed visually guided activities.

15.7.2 Prosthetic vision

At least 9 groups are currently working on visual prosthesis development: 5 through retinal, one through optic nerve, and 3 through cortical stimulation (see figure 15.5).

Three of the retinal prosthesis groups [10][11][12] are experimenting with prototypes consisting of a head-worn camera, a belt-pack image processor—called Retina Encoder by the German consortium; its purpose is to maximize the image information conveyed by the limited number of electrodes—and multiplexer, a single-channel infrared (IR) or radio-frequency (RF) energy and information transmitter on a pair of glasses, demultiplexing circuitry inside the eye, and an electrode array on the retina. The principle of these *epiretinal* systems is to replace the degenerated photoreceptors by a pattern of electrical stimulation activating secondary neurons. Intraoperative tests by two of the groups [13][14] have demonstrated that patients blind from photoreceptor degenerations will perceive small dots of light corresponding in location to the local retinal stimulation, and in brightness to the electrical stimulus strength and or repetition rate.

Two other retinal prosthesis groups are experimenting with light-sensitive devices implanted under the retina [15][16]. The principle of these *subretinal* devices is to replace the degenerated photoreceptors by converting local illumination patterns into electrical current patterns that stimulate surviving secondary retinal neurons. While this is a much simpler design than that pursued by the epiretinal prosthesis groups, the light energy incident on these devices, even in bright sunlight, may not be sufficient to generate the necessary electrical threshold currents. On-chip signal amplification, while feasible in principle, will

require significant levels of IR or RF energy to be sent into the eye, and will lead to heat dissipation and temperature rise which may well damage the retina. It is not clear whether this limitation can be overcome with current technology.

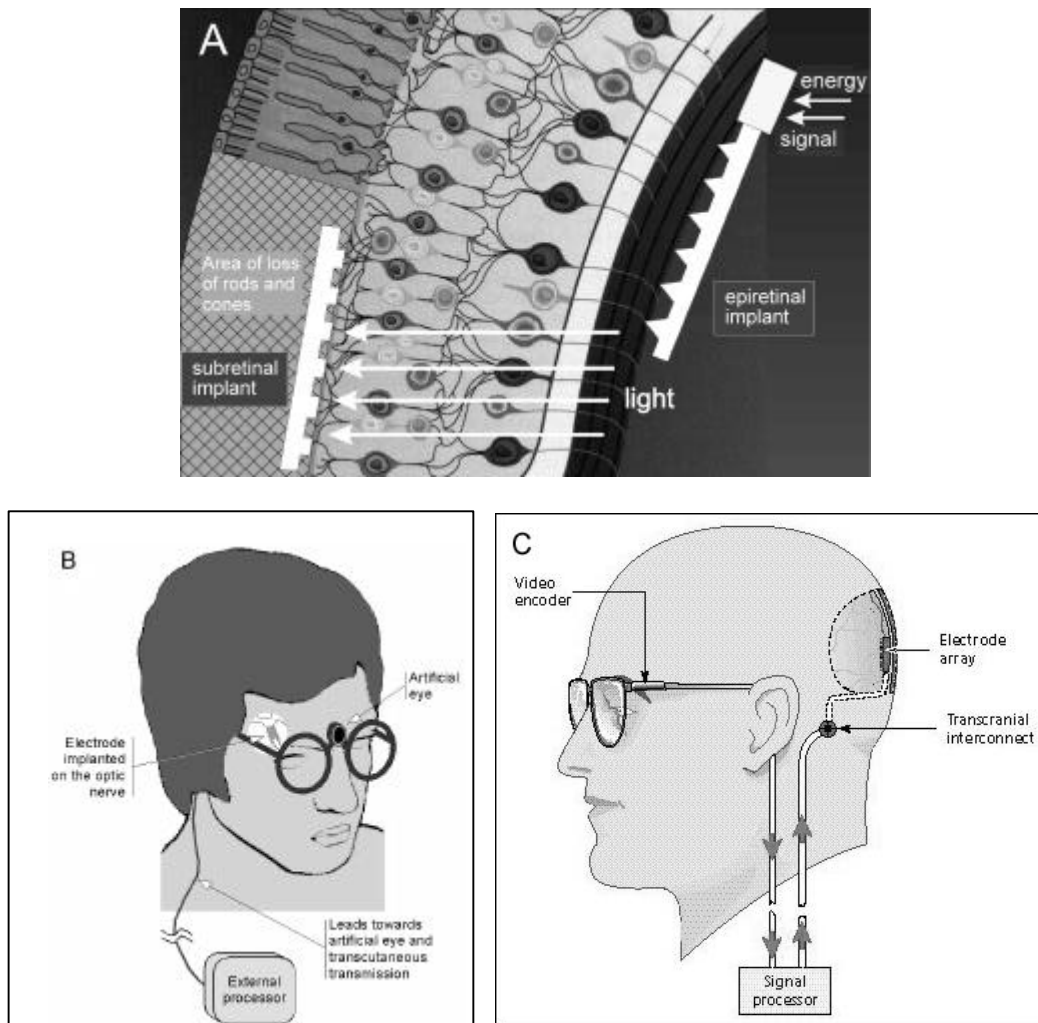


Figure 15.5 Schematic representations of the three types of visual prostheses currently under development. The intraocular prosthesis (A) replaces photoreceptor function through stimulation of secondary nerve cells, and can be placed either under or on top of the retina (image courtesy of Drs John Wyatt & Joseph Rizzo III, MIT Draper Labs and Prof Eberhart Zrenner, Univ. of Tuebingen). The optic nerve prosthesis (B) aims at replacing the function of all retinal cell layers, and consists of a cuff electrode array around the optic nerve (image courtesy of Dr Claude Veraart, Univ Catholique de Louvain). The cortical prosthesis (C) provides visual function if the eye and optic nerve no longer provide viable connections to the brain, and consists of a matrix of needle-like electrodes penetrating into the visual cortex (reprinted from R. A. Normann, E. M. Maynard, K. S. Guillory, D. J. Warren, pp. 54-59 in [1], with permission).

A research group in Belgium [17] has been exploring for several years, in a blind volunteer, the feasibility of using *optic nerve* stimulation to convey functional visual information. Due to the limited number of electrodes—4 in the prototype used—only very crude stimulus discrimination is possible.

Ever since the 1960s, when Brindley demonstrated the feasibility of vision restoration through *cortical* electrical stimulation [18], the concept of a cortical prosthesis has been pursued. Currently, 3 groups are pursuing the development of working prototypes, either in non-human primates [19][20] or in blind volunteers [21]. While the principle of such a device is very similar to that of the epiretinal prosthesis, two major hurdles need to be

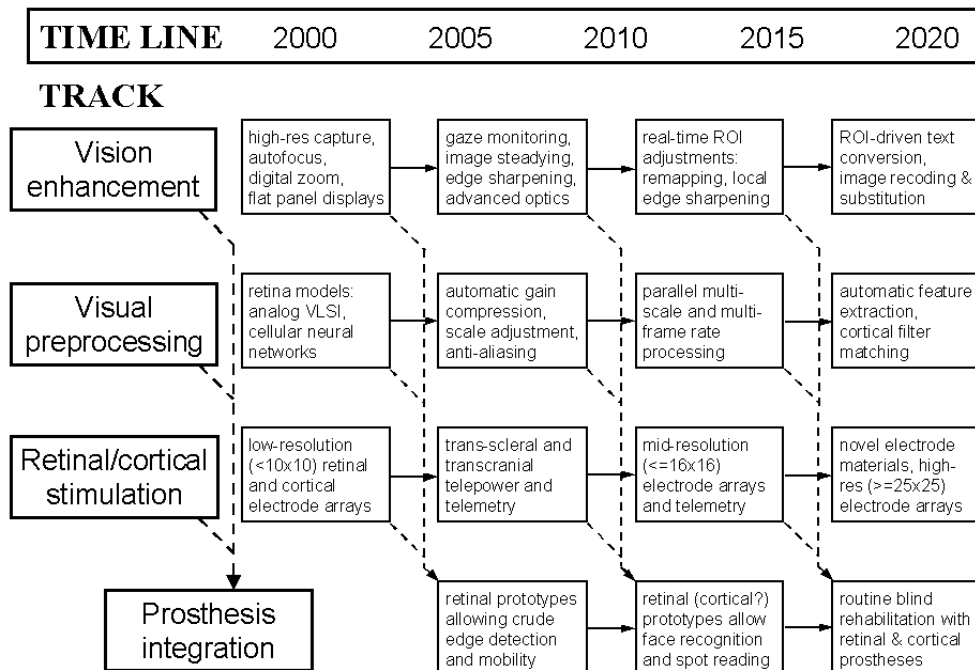
cleared: 1. Electrodes implanted over or in brain tissue tend to become encapsulated in glial tissue, significantly reducing their efficacy for neuronal stimulation or recording, although better results are being obtained with novel penetrating electrode designs [22]; and 2. The inverted mapping of the visual cortex, compounded by the inaccessibility of the primary projection of peripheral vision in the human brain, severely limits the possibility of presenting recognizable, wide-field images through a cortical prosthesis. In time, more suitable electrode materials may solve the encapsulation problem; similarly, it is feasible to construct an inverse map for each prosthesis wearer's cortical projection and to use the peripheral projection in higher cortical areas, but all this will require extensive research and development efforts.

It appears, then, that visual prostheses are feasible, but not yet practical, with the epiretinal prosthesis probably as the first contender for a working prototype in a blind individual.

15.8 Towards a functional visual prosthesis

As indicated in Table 15.1, we expect to see work towards a visual prosthesis developing along three parallel tracks over the coming decade: the *vision enhancement* track, the *retinal preprocessor* track, and the *retinal/cortical stimulation* track. Later, progress made along these tracks can be combined towards the building of visual prosthesis prototypes.

Table 15.1 Anticipated time line and development steps towards functional visual prostheses



Areas of concentrated effort can be identified for each of the three tracks:

- *Vision enhancement.* If we divide this track into capture, processing, and display of image information, a quick look at our wish list shows that progress is needed in each of these areas. Some of our needs, such as high resolution image capture over large dynamic ranges, high resolution flat panel displays with high contrast, and advanced optics are being addressed by researchers and developers worldwide, so we should concentrate our efforts on areas specific to low vision applications: eye position monitoring, ROI movement control, local contrast enhancement, image remapping,

automatic track and zoom, image stabilization, feature extraction and re-coding, frame storage, symbol translation, and substitution for a lost property of normal vision (e.g., color). Note that these areas are not unique to low vision rehabilitation: they are addressed by image processing hardware and software, especially in machine vision and robotics.

- *Research in enhanced vision serves a dual purpose.* Not only to improve the tools of vision rehabilitation, but also to provide a "front end" for electro-neural visual prostheses. The two applications share the need for improvements in eye position monitoring and ROI movement control, image acquisition, image stabilization, and some types of image processing. Other functions, especially image remapping, interpretation, and re-coding, and translation into other sensory modalities, are of importance only for individuals using their remaining vision and/or sensory substitution.
- *Retinal preprocessing.* Of the three tracks considered here, the one modeling retinal preprocessing is probably most advanced. Over the past 5 years, Werblin and co-workers have developed several generations of cellular neural network (CNN) chips [23], which can perform sophisticated operations to mimic the dynamic range, temporal processing and lateral interactions occurring in the retina. Further advancements in retinal research will be required to allow adequate modeling of the many functions performed by inner retinal cells. Moreover, what is not currently provided are the gradients in cell density, populations, and connectivity—especially in convergence from photoreceptors to ganglion cells—found in the human retina as one goes from fovea to periphery. The development of separate CNN chips to mimic the properties of central and peripheral retina, would be a highly desirable step towards a visual prosthesis preprocessor. Even more useful would be CNN versions containing on a single chip the gradients in density and connectivity from center to periphery.
- *Retinal and cortical stimulation.* Considerable progress has been made over the past years in developing stable electrode-tissue interfaces for retinal stimulation, yet it is clear that the long-term safety and efficacy of these devices remains to be established through chronic testing in both animals and humans blind from retinal degeneration. Moreover, major research and engineering efforts will be required to achieve viable long-term cortical stimulation. Topics to be addressed range from biocompatibility issues to questions concerning the effects of long-term electrical stimulation on retinal and cortical tissue, from effective stimulus waveforms and thresholds to the study of spatial and temporal resolution, and from implantation and stabilization techniques to signal transmission and power supply. Progress is being made in all these areas. Short-term feasibility of stimulation has been demonstrated in human subjects as well as animals. Yet, of the three tracks, this appears to be the one that has the longest distance to cover.
- *Integrating the components.* In the next 5-10 years, one can hardly expect that all developments along the individual tracks will be fully developed. Certainly, the vision enhancement components on the wish list has elements that will require more time—ROI movement control, tracking, recognition, translation—or depend on outside resources—high-resolution components, image stabilization, hardware zoom. Yet, even if we are conservative about the available elements, a functional prototype visual prosthesis can be put together within 5 years. Such a device will have no other purpose than to provide totally blind persons with enough light perception and rudimentary resolution to enable them to navigate; to discern doorways, stairs, obstacles, and people; and in general to perform independently a number of daily living activities. To be sure, the prosthesis will only complement a blind person's

current skills: as an example, a long cane will be better than this device at detecting a low curb or step, but the prosthesis will operate beyond the reach of the cane.

The prototype retinal prosthesis may consist of a small wide-field camera mounted on the inside of a pair of sunshades. From the end of the visor's temple arm, a cable would carry the camera signal down to a backpack, containing the battery and switches for zoom and contrast manipulation as well as a CNN-type image processor to precondition the image for optimal detectability, and to reduce the resolution to that of the electrode array. The return signal would go to an RF loop in the frame of the visor for signal and power transmission into the eye. A decoder chip inside would perform power management and control functions for the microelectrode matrix. This matrix should have the highest resolution available at the time, but it will not match the 100x100 resolution of the CNN chip. Yet, for the simple tasks sketched above, an 8x8 matrix would already be a big help.

The cortical version of the device would require much more elaborate image pre-processing—a "CNN++" chip—to match the properties expected by cortical cells. In this configuration, the return signal from the backpack would go to an RF transmitter behind the wearer's ear, and from there to a receiver and demultiplexer chip under the skin. From there, a wire bundle under the skin would lead to an entry port in the skull and to the electrode array. The properties of early CNN++ chips will be tentative at best, and vision from a cortical prosthesis will be less "natural" than that from a retinal prosthesis.

As was stated above, the details of inner retinal processing have not been completely unraveled, but it is likely that the CNN chip mimicking outer retinal processing will be adequate for a retinal prosthesis: both human and animal experiments have demonstrated that bipolar cells in the retina are the most likely targets for electrical stimulation, and further inner retinal processing may thus be performed by the retina itself. This gives the retinal approach a "leg up" over the cortical approach. Obviously, the retinal approach can only work in the presence of a healthy optic nerve.

15.9 Towards the next generation

Once the first prototype has been implanted, and the concept has been proven, the development will become much more complex. Not only will such diverse entities as the FDA, insurance companies, organizations for the blind, and venture capitalists want to get in on the act, but also the number of avenues to be explored for improvement of implant survival, electrode density, threshold stability, resolution, and many other aspects will increase tremendously. A few reasonable expectations can be stated, however:

- Vision enhancement hardware and algorithms will become more and more powerful, and by 2020 should be able to fulfill most of today's fantasies in image acquisition, preprocessing, and display. The limitation is and will be the level of remaining vision. The unknown factor is how much additional information "bandwidth" one can achieve with an impaired system, through innovative presentation and training techniques.
- Retinal preprocessing simulation in hardware and software will probably become highly sophisticated, and it is possible that by 2020 working models of the *lgn* and primary visual cortex will also be available on-chip, including their interactions. If so, it would seem that the principal beneficiaries will be the designers of human-like machine vision systems.
- With current electrode technology, it does not seem likely that very high transfer densities, either in the retina or in the cortex, will ever be attained. A highly suc-

cessful prosthesis for the peripheral retina and a low-density macular prosthesis may be possible, however, with obvious benefits for RP patients. For a higher-density "foveal" prosthesis—though still well below that required for normal visual acuity levels—, a cortical approach seems more promising: the foveal projection of the primary visual cortex is exposed, and a much larger area for stimulation is available than in the retina. Of course we have tacitly assumed that the preprocessing algorithms work, and that a form of self-organizing information transfer will develop to make electrodes carrying one representation hook up with cells that expect that information; only then will the world seen by a transplant recipient make visual sense.

- A hybrid form, a peripheral retinal prosthesis combined with a foveal cortical prosthesis is of course a possibility. There may be other alternatives, however: experiments to develop "artificial neurons" that may interface with higher order neurons in the retina, the *lgn*, or the visual cortex may open new avenues to nerve cell stimulation, and attempts to stimulate the re-growth of retinal nerve fibers damaged by glaucoma or trauma may allow true functional recovery. Also, initial experiments in retinal cell transplantation suggest that at least partial recovery of visual function may become a reality over the next decade or two. Hybrid techniques incorporating more than one of the methods in this section may optimize the outcome.

Throughout this development process, there is obviously going to be cross-pollination of ideas and techniques, not only among the three tracks we have indicated here, but also with other areas of artificial vision and imaging, and biomedicine. Efforts such as the publication of the present volume will stimulate this exchange: probably the greatest barriers to integration are the lack of a platform of information exchange, and of a common language among researchers of varied plumage.

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Appendices

Appendix I: Visual impairment

A.I.I Common causes of visual impairment

In the United States and other developed countries, almost all low vision and blindness is associated with diseases that destroy tissue in the retina, optic nerve, or visual cortex, with irreversible consequences for the patient's vision. The most common causes of vision loss in the developed world are:

- *Age-related macular degeneration (AMD)*. This disease destroys photoreceptors in the macular area (the central part of the retina, where spatial resolution is highest), but may vary greatly in severity. In the "wet" or exudative form of AMD, membranes containing new blood vessels grow under the retina. These vessels will leak and form scar tissue, which can have disastrous effects on central vision if the fovea (center of the macula, used for fixation and high resolution tasks) is destroyed. Laser treatment or surgery may be used in an attempt to stop this process, but these treatments are not always effective, and may carry too much risk for the patient's vision. In the "dry" form of AMD, a slowly expanding area of atrophy leads to a horseshoe-shaped scotoma (blind area) around the fovea. Gradually this horseshoe closes up to a ring and invades the fovea. AMD typically arises after age 70, increasing in frequency to affect as many as 25% of individuals over 85; however, most patients have only a "background" form of the disease, and these patients suffer only mild vision loss. Patients with AMD rarely go blind, since they retain their peripheral vision, but most of them go legally blind (see below).
- *Glaucoma*. In this disease, due to pressure in the eye, or weakness of the support tissue around the optic disk or "physiological blind spot" (the place where optic nerve fibers leave the eye), optic nerve fibers are damaged and eventually die, leading to a loss of visual information being sent to the brain. The disease is diagnosed most often in middle age. By the time the damage begins to show in sensitivity tests such as a visual field map, a very high proportion of optic nerve fibers may already have been destroyed.
- *Retinal dystrophies*. A collective term for a group of diseases that affect the photoreceptors and/or the retinal pigment epithelium (a layer of cells under the retina, on which the photoreceptors depend for their metabolism). Several of these diseases come in both inherited and sporadic (no family history) forms; they may affect only the rods or only the cones; and they commonly have specific distributions across the retina. One of the best-known examples is retinitis pigmentosa (RP), which commonly first manifests itself through nightblindness and through visual field loss in the mid-periphery, which then expands to form a ring scotoma that spreads outward and

inward until only a narrow island of central vision is left. This process takes several decades, so even though the disease commonly is diagnosed before the age of 20, patients may never go totally blind. Another retinal dystrophy bears similarities to AMD, but is distinguished by its onset in early adulthood; it is commonly referred to as Stargardt's disease.

- *Systemic diseases.* The most important systemic diseases affecting the eyes are diabetes and vascular occlusive disease. In diabetes, weakening of the blood vessel walls can lead to leakage of blood into the central retina (macular edema), and proliferation of abnormal new blood vessels can lead to more extensive bleeding and retinal detachment (see below). Laser treatment can contain the progression of the diabetic retinopathy and save vision. Vascular occlusive disease is the retinal equivalent of a stroke, in which an artery or vein is blocked by a small blood clot, and retinal tissue dies if the blockage cannot be reversed rapidly. Both these diseases are most common in middle age.
- *Retinopathy of prematurity (ROP).* One of the complications of highly premature births. The retinal circulation is not fully developed until after birth, and abnormal new blood vessels may exert traction on the retina, leading to retinal detachment (see below). The disease may also impair the development of the fovea, since foveal cells and their connections develop late in gestation.
- *Retinal detachment.* The retina is pulled loose from the underlying choroid layer which provides its metabolic supply. Retinal detachment may be caused either by traction exerted on the retina, as in ROP or in high myopes (whose eye is abnormally long), or by trauma. Although reattachment surgery is often successful, scars may be caused by the surgery itself or, in long-standing cases, by lack of metabolic support to the retinal tissue. Most frequent occurrence is in middle age or later.
- *Congenital disorders of the fovea.* Several other conditions can cause the fovea to develop abnormally. The most common ones are albinism (in which lack of foveal development is associated with abnormal projections from the eye to the two hemispheres of the brain) and achromatopsia (absence of cone photoreceptors, which causes photophobia, i.e. discomfort and blinding in bright lighting conditions). These disorders are often accompanied by nystagmus (involuntary oscillating eye movements), which may also occur as an isolated phenomenon. Nystagmus has been blamed for the failure of sharp foveal vision to develop, but it is possible that lack of foveal development and nystagmus are both caused by some other factor.
- *Optic nerve diseases* can damage the nerve fibers from the eye to the brain. Possible causes are a blockage in blood supply to the optic nerve (similar to a stroke; often only in one eye), pressure (e.g., by a tumor), or demyelinating disease (e.g., multiple sclerosis).
- *Damage to the visual cortex,* either by stroke (often only in one cerebral hemisphere) or by demyelinating diseases.

In developing countries, where the incidence of blindness is much higher than in the developed world, the causes of blindness are very different. The most important causes there are either reversible, such as cataract, or preventable. Cataract causes opacities in the crystalline lens through changes in its protein structure; this typically starts in middle age, but in otherwise healthy individuals it does not acutely interfere with vision until old age.

The three most common preventable eye diseases are:

- *Vitamin A deficiency.* Leads not only to abnormalities in the photoreceptors (the rod photopigment rhodopsin requires a vitamin A metabolite for its synthesis), but also to

a variety of disorders related to immune system insufficiencies, and to high child mortality.

- *Trachoma*. An inflammatory disease of the conjunctiva, caused by a micro-organism (chlamydia) transmitted by flies, and endemic in Asia and Africa. The disease process gradually encroaches on the cornea, which becomes scarred and opaque.
- *Onchocerciasis (river blindness)*. A parasitic infestation of the cornea, wall of the eye, and optic nerve that is endemic in South America and sub-Saharan Africa, and is transmitted by a water-borne insect (blackfly).

In addition, chronic systemic diseases such as tuberculosis, pneumonia, and several sexually transmitted diseases lead to numerous cases of eye disease and vision loss in the developing world.

A.1.II *Impact of visual impairment*

The principal measures used to quantify visual performance, and therefore to express the impact of visual impairment, are visual acuity, contrast sensitivity, and visual field defects. Less customary tests measure hyperacuity (e.g., the precision with which they can align two line segments), depth perception (e.g., the ability to place two test targets at the same depth), the ability to assess facial expressions, reading speed as a function of character size, color discrimination, dark adaptation, and visually guided object manipulation.

Visual acuity quantifies the best level of resolution a person can achieve, expressed as a fraction of "normal" acuity. Following Snellen's convention to measure visual acuity at 6 meters or 20 feet, the letter size a normally sighted person can just recognize at that distance is designated as 20/20 in the USA, and 6/6 in Europe. A convenient rule of thumb is, that this acuity corresponds to the ability to see the 1 arcmin gaps in a 5 arcmin high sans serif capital such as the "E". Adjacent lines on most letter charts follow a logarithmic size progression, with 3 lines per octave, i.e. 10 lines per decade. Thus a 20/200 letter, which a normally sighted person could just recognize at 200 feet, is 10 times the size of a 20/20 letter, and located 10 lines above it. Someone who cannot identify a 20/200 letter with either eye is considered legally blind in most countries.

There are many other types of acuity charts; some use symbols or non-Western characters, while others are calibrated for use at closer distances, e.g., at 40 cm.

Contrast sensitivity is the ability to distinguish light-dark gradients in an image. It, too, can be measured with a chart on which symbols must be identified. The size of the symbols remains constant throughout the chart, and patients view it from a distance at which the symbols can easily be recognized. The contrast of each group of symbols is reduced with respect to the previous one. Thus on the most frequently used chart, the Pelli-Robson chart, the first group of 3 characters has a contrast close to 100% (deep black on the light chart background), and the contrast of each subsequent group of 3 characters decreases by 0.15 log units, i.e., 0.5 octaves. Contrast sensitivity is expressed as the reverse of log contrast of the last letters that can be seen. Normally sighted young observers have contrast sensitivities around 1.9, i.e., a threshold of approximately 1.3%.

Visual field defects can be mapped in several ways. Typically, the eyes are tested separately. The patient is asked to look at a stationary fixation target and to indicate with a button press when (s)he perceives a test light presented elsewhere. The test light can be moving (kinetic perimetry: the patient indicates when the light disappears or reappears, i.e., enters or leaves a scotoma), or be presented briefly and in random order at a number of pre-selected positions (static perimetry). Steady fixation is required to obtain a reliable visual field map; in static perimetry it is commonly verified by presenting test flashes at the

physiological blind spot. Someone who has lost the peripheral field, and whose central visual field is less than 20° in diameter (tunnel vision), is also considered legally blind in most countries.

In *hyperacuity* and *depth adjustment* tests in the fovea, normal subjects can achieve thresholds corresponding to resolutions of 5 arcsec or less. If the same tests are performed in the periphery, thresholds rise rapidly, at least 3 times as fast as the increase of the smallest recognizable letter size on the acuity chart.

We can divide low vision patients into several broad classes, depending on the types of defects brought on by eye disease:

- *Lack of foveal development (ROP, albinism, achromatopsia, congenital nystagmus).* These patients have limited performance on all tasks related to (hyper)acuity, and can generally be helped to some extent with magnification. Many of them also have contrast sensitivity and illumination problems. Visual acuity may be in the 20/100 to 20/200 range.
- *Central field loss.* This is most often caused by macular degeneration, but it is also associated with some retinal dystrophies and optic nerve disorders. In addition to causing severe loss of acuity (20/70 to 20/200 in "dry" AMD, considerably worse in exudative AMD: 20/400 if treated, as bad as 20/1000 if scarring continues) this condition is particularly disabling because it forces the patient to use the peripheral visual system which, even with proper magnification, has poor text resolution: adjacent letters appear "jumbled" together. Note that an advanced form of this condition (i.e., no foveal vision left) forces the patient to develop a new fixation area in a portion of the retina not normally used for this task. Such a preferred retinal locus (PRL) is usually situated close to the edge of the central scotoma, and can be an area with either relatively good acuity or relatively little surrounding damage. Central field loss is frequently compounded by distortions and contrast sensitivity loss adjacent to the scotoma.
- *Peripheral field loss.* This may be caused by advanced glaucoma, optic nerve disorders, and diseases such as RP. A special form, hemianopia, is the loss of a large part of the left or right visual hemifield following a stroke that has affected the visual cortex. Patients with peripheral field loss often have problems with orientation and obstacle avoidance. In advanced stages (tunnel vision), field restrictions cause reading problems, and acuity and contrast sensitivity may also be reduced. Unexpected reading problems may also occur at earlier stages (see below).
- *Localized scotomas in one or more retinal locations.* These may be caused by diabetic retinopathy or occlusion of retinal blood vessels, but nowadays are often created artificially when laser burns are applied to the retina to prevent further damage from diabetic retinopathy or exudative AMD. Patients may have problems with reading, acuity, contrast sensitivity, and distortion, as well as difficulty localizing objects and avoiding obstacles.
- *Reduced contrast sensitivity.* This often arises as a secondary effect of a disease process, and frequently goes undiagnosed. Its effect on visual perception can be likened to a dense fog: differences not only in image luminance but also in color look "washed out". While patients with contrast sensitivity loss may not have much trouble seeing contours and other pronounced light-dark and color gradients, gradual brightness and hue changes across a scene become very difficult to detect. Not surprisingly, problems with face recognition are often cited by patients with reduced contrast sensitivity.
- *Illumination and adaptation problems.* These are frequently experienced by patients with diseases of the photoreceptors, such as macular degeneration and retinal dystrophies. Many AMD patients report a need for bright illumination, but this need can often be addressed by contrast enhancement.

- *Metamorphopsia (distortions)*. Ophthalmologists instruct AMD patients to test themselves for distorted vision by looking at a printed regular grid pattern at least once a day, as any distortion could be an early symptom of a membrane growing under the retina. Chronic distortions are also reported by patients with a history of retinal detachment, and they may persist in the vicinity of a longstanding scotoma, especially in AMD patients. The traditional explanation is in terms of "wrinkling" of the retina, but there are indications that the cortical projection may reorganize itself around the projection of a small scotoma such as a laser scar: some patients report perceiving an uninterrupted line if two line segments are projected onto the retina with the gap covering the blind retinal area, which suggests that the small "vacated" cortical area is now receiving information from the area around the scotoma.
- *Unexplained problems in sustained reading* occur if a patient is unable to read running text at a print size a few times her acuity limit, while "spot" reading (e.g., a single word, price tag, or number) with the same print size poses no problem. This can arise if the person has of a small island of relatively good acuity surrounded by a scotoma, as in mid-stage "dry" AMD, or a scotoma to the right of the fixation point or PRL (sometimes called a 'leading scotoma'), depriving the patient of "look-ahead" information that readers presumably use to choose the target for their next fixation.

Appendix II: The Low Vision Enhancement System (LVES)

In the mid-1980s, inspired by reports on "virtual reality helmets" and image processing technology for satellite images being developed by NASA researchers, ophthalmologists and researchers at The Johns Hopkins University's Wilmer Eye Institute first proposed the idea of a head-mounted video system for low vision patients. A one-day workshop at Wilmer in November 1985 led to a formal application for a NASA technology transfer project. After initial studies it was decided that commercially available camcorder components might be used for first-generation image acquisition and display, and that the thrust of NASA's input into the project would be in the area of image processing. Three quarter inch monochrome CRT screens were determined to be the only commercially available displays with the necessary resolution and contrast values for a wide field viewing system. Hence, until better display options become available, the LVES system will be monochrome and use CRT displays. Polaroid was contracted to develop the projection optics for this system. Alpha prototypes were manufactured early in 1991, but it took until mid-1994 before Visionics Corporation, a Minneapolis-based company founded specifically to manufacture and market the LVES, issued the first production model. In the fall of 1995 LVES was upgraded with an autofocus system for the zoom objective, controlled by a DSP chip maximizing edge sharpness in a pre-selected region of interest. Evaluation research at the Wilmer Eye Institute and a dozen VA medical centers under grants from the Department of Veterans Affairs Division of Rehabilitation Research and Development demonstrated the system's efficacy for a number of activities of daily living, but also concluded that the system in its current form was too heavy for all but the most motivated users. Simultaneously, the system was being prescribed by over 30 centers in the US and a number elsewhere (Canada, Germany, United Kingdom, Netherlands, Italy, and Spain).

The LVES consists of two main components: the headset and a control unit doubling as a battery pack, worn around the waist. The headset features three CCD cameras. Two of these, the so-called orientation cameras, with fixed focus objective, 60° field of view, and near-unit magnification, are located in front of the wearer's eyes and provide separate

images with near-natural disparity. The third camera, with 1.5-9× variable magnification and variable focus, is placed above the center axis of the unit and provides a cyclopean view to both eyes. At low magnification, the focus range is from about 1 cm (macro) to infinity; as magnification is increased, this range is progressively limited. A low power (2-4 diopters) lens is permanently attached to the zoom objective, to reduce the near point distance at maximal zoom. With a 2 diopter add, the focus range at 9× is from 25 cm to infinity. The camera house can be tilted downward to ease posture during operation at close working distances.

The camera signals are sent to the backpack, where a set of switches provides camera selection, motorized zoom selection, autofocus lock (in which case the zoom lever can double as a manual focus control), and a contrast selection group: two switches and a rotary dial allowing users to select regular or enhanced video, with normal or inverted polarity, and to set the mid-point of the brightness scale if they select enhanced contrast. The selected and conditioned video signals are returned to the headset where they are displayed on two forward-facing ¾" CRTs in the rear half of the temple arms. The aspheric optical projection system images the screen at infinity, subtending 50° horizontally by 38° vertically. Given the CRT resolution of 300 vertical line pairs, the image resolution is 5 arcmin, which can be a limiting factor for wearers with visual acuity better than 20/100.

The system is customized for the wearer by centering the 8 mm exit pupil of the projection system on the eye pupil, and by building in the wearer's spherical and cylindrical eyeglass prescription. A head support system with four straps supports the unit's 1.0 kg weight, and keeps the projection system aligned with the eyes. The backpack has RCA jacks for external video input and output, a phone jack to allow communication with the DSP chip, and a Ni-Cd battery pack providing 1.5-2 hours of operation. The unit can also be powered with 12 volt DC (wall adapter or car battery).