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SENSORY REPLACEMENT AND SENSORY SUBSTITUTION: OVERVIEW AND PROSPECTS FOR THE FUTURE

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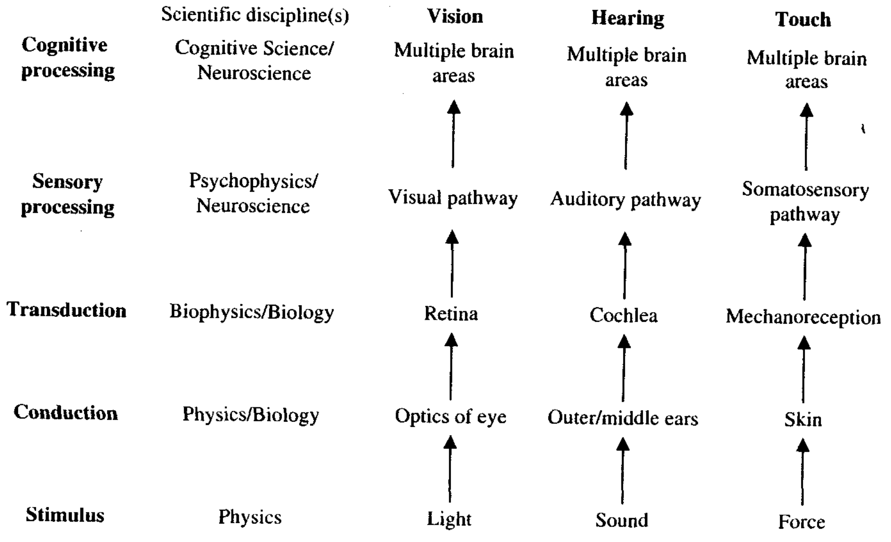
The traditional way of dealing with blindness and deafness has been some form of sensory substitution — allowing a remaining sense to take over the functions lost as the result of the sensory impairment. With visual loss, hearing and touch naturally take over as much as they can, vision and touch do the same for hearing, and in the rare cases where both vision and hearing are absent (e.g., Keller 1908), touch provides the primary contact with the external world. However, because unaided sensory substitution is only partially effective, humans have long improvised with artifices to facilitate the substitution of one sense with another. For blind people, braille has served in the place of visible print, and the long cane has supplemented spatial hearing in the sensing of obstacles and local features of the environment. For deaf people, lip reading and sign language have substituted for the loss of speech reception. Finally, for people who are both deaf and blind, fingerspelling by the sender in the palm of the receiver (Jaffe 1994; Reed et al. 1990) and the Tadoma method of speech reception (involving placement of the receiver's hand over the speaker's face) have provided a means by which they can receive messages from others (Reed et al. 1992).

Assistive Technology and Sensory Substitution

Over the last several decades, a number of new assistive technologies, many based on electronics and computers, have been adopted as more effective ways of promoting sensory substitution. This is especially true for ameliorating blindness. For example, access to print and other forms of text has been improved with these technologies: electronic braille displays, vibtrotactile display of optically sensed print (Bliss et al. 1970), and speech display of text sensed by video camera (Kurzweil 1989). For obstacle avoidance and sensing of the local environment, a number of ultrasonic sensors have been developed that use either auditory or tactile displays (Brabyn 1985; Collins 1985; Kay 1985). For help with large-scale wayfinding, assistive technologies now include electronic signage, like the system of Talking Signs (Crandall et al. 1993; Loughborough 1979; see also http://www.talkingsigns.com/), and navigation systems relying on the Global Positioning System (Loomis et al. 2001), both of which make use of auditory displays. For deaf people, improved access to spoken language has been made possible by automatic speech recognition coupled with visible display of text; in addition, research has been conducted on vibrotactile speech displays (Weisenberger et al. 1989) and synthetic visual displays of sign language (Pavel et al. 1987). Finally, for deaf-blind people, exploratory research has been conducted with electromechanical Tadoma displays (Tan et al. 1989) and finger spelling displays (Jaffe 1994).

Interdisciplinary Nature of Research on Sensory Replacement / Sensory Substitution

This paper is concerned with compensating for the loss of vision and hearing by way of sensory replacement and sensory substitution, with a primary focus on the latter. Figure C.7 shows the stages of processing from stimulus to perception for vision, hearing, and touch (which often plays a role in substitution) and indicates the associated basic sciences involved in understanding these stages of processing. (The sense of touch, or haptic sense, actually comprises two submodalities: kinesthesis and the cutaneous sense [Loomis and Lederman 1986]; here we focus on mechanical stimulation). What is clear is the extremely interdisciplinary nature of research to understand the human senses. Not surprisingly, the various attempts to use high technology to remedy visual and auditory impairments over the years have reflected the current scientific understanding of these senses at the time. Thus, there has been a general progression of technological solutions starting at the distal stages (front ends) of the two modalities, which were initially better understood, to solutions demanding an understanding of the brain and its functional characteristics, as provided by neuroscience and cognitive science.



	Scientific discipline(s)	Vision	Hearing	Touch
Cognitive processing	Cognitive Science/ Neuroscience	Multiple brain areas	Multiple brain areas	Multiple brain areas
Sensory processing	Psychophysics/ Neuroscience	Visual pathway	Auditory pathway	Somatosensory pathway
Transduction	Biophysics/Biology	Retina	Cochlea	Mechanoreception
Conduction	Physics/Biology	Optics of eye	Outer/middle ears	Skin
Stimulus	Physics	Light	Sound	Force

Figure C.7. Sensory modalities and related disciplines.

Sensory Correction and Replacement

In certain cases of sensory loss, sensory correction and replacement are alternatives to sensory substitution. Sensory correction is a way to remedy sensory loss prior to transduction, the stage at which light or sound is converted into neural activity (Figure C.7). Optical correction, such as eyeglasses and contact lenses, and surgical correction, such as radial keratotomy (RK) and laser in situ keratomileusis (LASIK), have been employed over the years to correct for refractive errors in the optical media prior to the retina. For more serious deformations of the optical media, surgery has been used to restore vision (Valvo 1971). Likewise, hearing aids have long been used to correct for conductive inefficiencies prior to the cochlea. Because our interest is in more serious forms of sensory loss that cannot be overcome with such corrective measures, the remainder of this section will focus on sensory replacement using bionic devices.

In the case of deafness, tremendous progress has already been made with the cochlear implant, which involves replacing much of the function of the cochlea with direct electrical stimulation of the auditory nerve (Niparko 2000; Waltzman and Cohen 2000). In the case of blindness, there are two primary approaches to remedying blindness due to sensorineural loss: retinal and cortical prostheses. A retinal prosthesis involves electrically stimulating retinal neurons beyond the receptor layer with signals from a video camera (e.g., Humayun and de Juan 1998); it is feasible when the visual pathway beyond the receptors is intact. A cortical prosthesis involves direct stimulation of visual cortex with input driven by a video camera (e.g., Normann 1995). Both types of prosthesis present enormous technical challenges in terms of implanting the stimulator array, power delivery, avoidance of infection, and maintaining long-term effectiveness of the stimulator array.

There are two primary advantages of retinal implants over cortical implants. The first is that in retinal implants, the sensor array will move about within the mobile eye, thus maintaining the normal relationship between visual sensing and eye movements, as regulated by the eye muscle control system. The second is that in retinal implants, connectivity with the multiple projection centers of the brain, like primary visual cortex and superior colliculus, is maintained without the need for implants at multiple sites. Cortical implants, on the other hand, are technically more feasible (like the delivery of electrical power), and are the only form of treatment for blindness due to functional losses distal to visual cortex. For a discussion of other pros and cons of retinal and cortical prostheses, visit the Web site (http://insight.med.utah.edu/research/normann/normann.htm) of Professor Richard Normann of the University of Utah.

Interplay of Science and Technology

Besides benefiting the lives of blind and deaf people, information technology in the service of sensory replacement and sensory substitution will continue to play another very important role — contributing to our understanding of sensory and perceptual function. Because sensory replacement and sensory substitution involve modified delivery of visual and auditory information to the perceptual processes in the brain, the way in which perception is affected or unaffected by such modifications in delivery is informative about the sensory and brain processes involved in perception. For example, the success or lack thereof of using visual displays to convey the information in the acoustic speech signal provides important clues about which stages of processing are most critical to effective speech reception. Of course, the benefits flow in the opposite direction as well: as scientists learn more about the sensory and brain processes involved in perception, they can then use the knowledge gained to develop more effective forms of sensory replacement and substitution.

Sensory Replacement and the Need for Understanding Sensory Function

To the layperson, sensory replacement might seem conceptually straightforward — just take an electronic sensor (e.g., microphone or video camera) and then use its amplified signal to drive an array of neurons somewhere within the appropriate sensory pathway. This simplistic conception of "sensory organ replacement" fails to recognize the complexity of processing that takes place at the many stages of processing in the sensory pathway. Take the case of hearing. Replacing an inoperative cochlea involves a lot more than taking the amplified signal from a microphone and using it to stimulate a collection of auditory nerve fibers. The cochlea is a complex transducer that plays sound out in terms of frequency along the length of the cochlea. Thus, the electronic device that replaces the inoperative cochlea must duplicate its sensory function. In particular, the device needs to perform a running spectral analysis of the incoming acoustic signal and then use the intensity and phase in the various frequency channels to drive the appropriate auditory nerve fibers. This one example shows how designing an effective sensory replacement begs detailed knowledge about the underlying sensory processes. The same goes for cortical implants for blind people. Simply driving a large collection of neurons in primary visual cortex by signals from a video camera after a simple spatial sorting to preserve retinotopy overlooks the preprocessing of the photoreceptor signals being performed by the intervening synaptic levels in the visual pathway. The most effective cortical implant will be one that stimulates the visual cortex in ways that reflect the normal preprocessing performed up to that level, such as adaptation to the prevailing illumination level.

Sensory Substitution: An Analytic Approach

If sensory replacement seems conceptually daunting, it pales in comparison with sensory substitution. With sensory substitution, the goal is to substitute one sensory modality that is impaired or nonfunctioning with another intact modality (Bach-y-Rita 1972). It offers several advantages over sensory replacement: (1) Sensory substitution is suitable even for patients suffering sensory loss because of cortical damage; and (2) because the interface with the substituting modality involves normal sensory stimulation, there are no problems associated with implanting electrodes. However, because the three spatial modalities of vision, hearing, and touch differ greatly in terms of their processing characteristics, the hope that one modality, aided by some single device, can simply assume all of the functions of another is untenable. Instead, a more reasonable expectation is that one modality can only substitute for another in performance of certain limited functions (e.g., reading of print, obstacle avoidance, speech reception). Indeed, research and development in the field of sensory substitution has largely proceeded with the idea of restoring specific functions rather than attempting to achieve wholesale substitution. A partial listing follows of the functions performed by vision and hearing, which are potential goals for sensory substitution:

- **Some functions of vision = potential goals for sensory substitution**
    - access to text (e.g., books, recipes, assembly instructions, etc.)
    - access to static graphs/pictures
    - access to dynamic graphs/pictures (e.g., animations, scientific visualization)
    - access to environmental information (e.g., business establishments and their locations)
    - obstacle avoidance
    - navigation to remote locations
    - controlling dynamic events in 3-D (e.g., driving, sports)
    - access to social signals (e.g., facial expressions, eye gaze, body gestures)
    - visual aesthetics (e.g., sunset, beauty of a face, visual art)
- **Some functions of audition = potential goals for sensory substitution**
    - access to signals and alarms (e.g., ringing phone, fire alarm)
    - access to natural sounds of the environment
    - access to denotative content of speech
    - access to expressive content of speech
    - aesthetic response to music

An analytic approach to using one sensory modality (henceforth, the "receiving modality") to take over a function normally performed by another is to (1) identify what optical, acoustic, or other information (henceforth, the "source information") is most effective in enabling that function and (2) to determine how to transform the source information into sensory signals that are effectively coupled to the receiving modality.

The first step requires research to identify the source information necessary to perform a function or range of functions. Take, for example, the function of obstacle avoidance. A person walking through a cluttered environment is able to avoid bumping into obstacles, usually by using vision under sufficient lighting. Precisely what visual information or other form of information (e.g., ultrasonic, radar) best affords obstacle avoidance? Once one has identified the best information to use, one is then in a position to address the second step.

Sensory Substitution: Coupling the Required Information to the Receiving Modality

Coupling the source information to the receiving modality actually involves two different issues: sensory bandwidth and the specificity of higher-level representation. After research has determined the information needed to perform a task, it must be determined whether the sensory bandwidth of the receiving modality is adequate to receive this information. Consider the idea of using the tactile sense to substitute for vision in the control of locomotion, such as driving. Physiological and psychophysical research reveals that the sensory bandwidth of vision is much greater than the bandwidth of the tactile sense for any circumscribed region of the skin (Loomis and Lederman 1986). Thus, regardless of how optical information is transformed for display onto the skin, it seems unlikely that the bandwidth of tactile processing is adequate to allow touch to substitute for this particular function. In contrast, other simpler functions, such as detecting the presence of a bright flashing alarm signal, can be feasibly accomplished using tactile substitution of vision.

Even if the receiving modality has adequate sensory bandwidth to accommodate the source information, this is no guarantee that sensory substitution will be successful, because the higher-level processes of vision, hearing, and touch are highly specialized for the information that typically comes through those modalities. A nice example of this is the difficulty of using vision to substitute for hearing in deaf people. Even though vision has greater sensory bandwidth than hearing, there is yet no successful way of using vision to substitute for hearing in the reception of the raw acoustic signal (in contrast to sign language, which involves the production of visual symbols by the speaker). Evidence of this is the enormous challenge in deciphering an utterance represented by a speech spectrogram. There is the celebrated case of Victor Zue, an engineering professor who is able to translate visual speech spectrograms into their linguistic descriptions. Although his skill is an impressive accomplishment, the important point here is that enormous effort is required to learn this skill, and decoding a spectrogram of a short utterance is very time-consuming. Thus, the difficulty of visually interpreting the acoustic speech signal suggests that presenting an isomorphic representation of the acoustic speech signal does not engage the visual system in a way that facilitates speech processing.

Presumably there are specialized mechanisms in the brain for extracting the invariant aspects of the acoustic signal; these invariant aspects are probably articulatory features, which bear a closer correspondence with the intended message. Evidence for this view is the relative success of the Tadoma method of speech reception (Reed et al. 1992). Some deaf-blind individuals are able to receive spoken utterances at nearly normal speech rates by placing a hand on the speaker's face. This direct contact with articulatory features is presumably what allows the sense of touch to substitute more effectively than visual reception of an isomorphic representation of the speech signal, despite the fact that touch has less sensory bandwidth than vision (Reed et al. 1992).

Although we now understand a great deal about the sensory processing of visual, auditory, and haptic perception, we still have much to learn about the perceptual/cognitive representations of the external world created by each of these senses and the cortical mechanisms that underlie these representations. Research in cognitive science and neuroscience will produce major advances in the understanding of these topics in the near future. Even now, we can identify some important research themes that are relevant to the issue of coupling information normally sensed by the impaired modality with the processing characteristics of the receiving modality.

Achieving Sensory Substitution Through Abstract Meaning

Prior to the widespread availability of digital computers, the primary approach to sensory substitution using electronic devices was to use analog hardware to map optical or acoustic information into one or isomorphic dimensions of the receiving modality (e.g., using video to sense print or other high contrast 2-D images and then displaying isomorphic tactile images onto the skin surface). The advent of the digital computer has changed all this, for it allows a great deal of signal processing of the source information prior to its display to the receiving modality. There is no longer the requirement that the displayed information be isomorphic to the information being sensed. Taken to the extreme, the computer can use artificial intelligence algorithms to extract the "meaning" of the optical, acoustic, or other information needed for performance of the desired function and then display this meaning by way of speech or abstract symbols.

One of the great success stories in sensory substitution is the development of text-to-speech devices for the visually impaired (Kurzweil 1989). Here, printed text is converted by optical character recognition into electronic text, which is then displayed to the user as synthesized speech. In a similar vein, automatic speech recognition and the visual display of text may someday provide deaf people with immediate access to the speech of any desired interactant. One can also imagine that artificial intelligence may someday provide visually impaired people with detailed verbal descriptions of objects and their layout in the surrounding environment. However, because inculcating such intelligence into machines has proven far more challenging than was imagined several decades ago, exploiting the intelligence of human users in the interpretation of sensory information will continue to be an important approach to sensory substitution. The remaining research themes deal with this more common approach.

Amodal Representations

For 3-D space perception (e.g., perception of distance) and spatial cognition (e.g., large-scale navigation), it is quite likely that vision, hearing, and touch all feed into a common area of the brain, like the parietal cortex, with the result that the perceptual representations created by these three modalities give rise to amodal representations. Thus, seeing an object, hearing it, or feeling it with a stick, may all result in the same abstract spatial representation of its location, provided that its perceived location is the same for the three senses. Once an amodal representation has been created, it then might be used to guide action or cognition in a manner that is independent of the sensory modality that gave rise to it (Loomis et al. 2002). To the extent that two sensory modalities do result in shared amodal representations, there is immediate potential for one modality substituting for the other with respect to functions that rely on the amodal representations. Indeed, as mentioned at the outset of this chapter, natural sensory substitution (using touch to find objects when vision is impaired) exploits this very fact. Clearly, however, an amodal representation of spatial layout derived from hearing may lack the detail and precision of one derived from vision because the initial perceptual representations differ in the same way as they do in natural sensory substitution.

Intermodal Equivalence: Isomorphic Perceptual Representations

Another natural basis for sensory substitution is isomorphism of the perceptual representations created by two senses. Under a range of conditions, visual and haptic perception result in nearly isomorphic perceptual representations of 2-D and 3-D shapes (Klatzky et al. 1993; Lakatos and Marks 1999; Loomis 1990; Loomis et al. 1991). The similar perceptual representations are probably the basis both for cross-modal integration, where two senses cooperate in sensing spatial features of an object (Ernst et al. 2001; Ernst and Banks 2002; Heller et al. 1999), and for the ease with which subjects can perform cross-modal matching, that is, feeling an object and then recognizing it visually (Abravanel 1971; Davidson et al. 1974). However, there are interesting differences between the visual and haptic representations of objects (e.g., Newell et al. 2001), differences that probably limit the degree of cross-modal transfer and integration. Although the literature on cross-modal integration and transfer involving vision, hearing, and touch goes back years, this is a topic that is receiving renewed attention (some key references: Ernst and Banks 2002; Driver and Spence 1999; Heller et al. 1999; Martino and Marks 2000; Massaro and Cohen 2000; Welch and Warren 1980).

Synesthesia

For a few rare individuals, synesthesia is a strong correlation between perceptual dimensions or features in one sensory modality with perceptual dimensions or features in another (Harrison and Baron-Cohen 1997; Martino and Marks 2001). For example, such an individual may imagine certain colors when hearing certain pitches, may see different letters as different colors, or may associate tactile textures with voices. Strong synesthesia in a few rare individuals cannot be the basis for sensory substitution; however, much milder forms in the larger population, indicating reliable associations between intermodal dimensions that may be the basis for cross-modal transfer (Martino and Marks 2000), might be exploited to produce more compatible mappings between the impaired and substiting modalities. For example, Meijer (1992) has developed a device that uses hearing to substitute for vision. Because the natural correspondence between pitch and elevation is space (e.g., high-pitched tones are associated with higher elevation), the device uses the pitch of a pure tone to represent the vertical dimension of a graph or picture. The horizontal dimension of a graph or picture is represented by time. Thus, a graph portraying a 45° diagonal straight line is experienced as a tone of increasing pitch as a function of time. Apparently, this device is successful for conveying simple 2-D patterns and graphs. However, it would seem that images of complex natural scenes would result in a cacophony of sound that would be difficult to interpret.

Multimodal Sensory Substitution

The discussion of sensory substitution so far has assumed that the source information needed to perform a function or functions is displayed to a single receiving modality, but clearly there may be value in using multiple receiving modalities. A nice example is the idea of using speech and audible signals together with force feedback and vibrotactile stimulation from a haptic mouse to allow visually impaired people to access information about 2-D graphs, maps, and pictures (Golledge 2002, this volume). Another aid for visually impaired people is the "Talking Signs" system of electronic signage (Crandall et al. 1993), which includes transmitters located at points of interest in the environment that transmit infrared signals carrying speech information about the points of interest. The user holds a small receiver in the hand that receives the infrared signal when pointed in the direction of the transmitter; the receiver then displays the speech utterance by means of a speaker or earphone. In order to localize the transmitter, the user rotates the receiver in the hand until receiving the maximum signal strength; thus, haptic information is used to orient toward the transmitter, and speech information conveys the identity of the point of interest.

Rote Learning Through Extensive Exposure

Even when there is neither the possibility of extracting meaning using artificial intelligence algorithms nor the possibility of mapping the source information in a natural way onto the receiving modality, effective sensory substitution is not completely ruled out. Because human beings, especially when they are young, have a large capacity for learning complex skills, there is always the possibility that they can learn mappings between two sensory modalities that differ greatly in their higher-level interpretative mechanisms (e.g., use of vision to apprehend complex auditory signals or of hearing to apprehend complex 2-D spatial images). As mentioned earlier, Meijer (1992) has developed a device (The vOICe) that converts 2-D spatial images into time-varying auditory signals. While based on the natural correspondence between pitch and height in a 2-D figure, it seems unlikely that the higher-level interpretive mechanisms of hearing are suited to handling complex 2-D spatial images usually associated with vision. Still, it is possible that if such a device were used by a blind person from very early in life, the person might develop the equivalent of rudimentary vision. On the other hand, the previously discussed example of the difficulty of visually interpreting speech spectrograms is a good reason not to base one's hope too much on this capacity for learning.

Brain Mechanisms Underlying Sensory Substitution and Cross-Modal Transfer

In connection with his seminal work with the Tactile Vision Substitution System, which used a video camera to drive an electrotactile display, Bach-y-Rita (1967, 1972) speculated that the functional substitution of vision by touch actually involved a reorganization of the brain, whereby the incoming somatosensory input came to be linked to and analyzed by visual cortical areas. Though a radical idea at the time, it has recently received confirmation by a variety of studies involving brain imaging and transcranial magnetic stimulation (TMS). For example, research has shown that (1) the visual cortex of skilled blind readers of braille is activated when they are reading braille (Sadata et al. 1996), (2) TMS delivered to the visual cortex can interfere with the perception of braille in similar subjects (Cohen et al. 1997), and (3) that the visual signals of American Sign Language activate the speech areas of deaf subjects (Neville et al. 1998).

Future Prospects for Sensory Replacement and Sensory Substitution

With the enormous increases in computing power, the miniaturization of electronic devices (nanotechnology), the improvement of techniques for interfacing electronic devices with biological tissue, and increased understanding of the sensory pathways, the prospects are great for significant advances in sensory replacement in the coming years. Similarly, there is reason for great optimism in the area of sensory substitution. As we come to understand the higher level functioning of the brain through cognitive science and neuroscience research, we will know better how to map source information into the remaining intact senses. Perhaps even more important will be breakthroughs in technology and artificial intelligence. For example, the emergence of new sensing technologies, as yet unknown, just as the Global Positioning System was unknown several decades ago, will undoubtedly provide blind and deaf people with access to new types of information about the world around them. Also, the increasing power of computers and increasing sophistication of artificial intelligence software will mean that computers will be increasingly able to use this sensed information to build representations of the environment, which in turn can be used to inform and guide visually impaired people using synthesized speech and spatial displays. Similarly, improved speech recognition and speech understanding will eventually provide deaf people better communication with others who speak the same or even different languages. Ultimately, sensory replacement and sensory substitution may permit people with sensory impairments to perform many activities that are unimaginable today and to enjoy a wide range of experiences that they are currently denied.

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VISION STATEMENT: INTERACTING BRAIN

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Brain functional studies are currently performed by several instruments, most having limitations at this time. PET and SPECT use have labeled glucose as an indicator of metabolic activity; however, they may not be used within a short time interval and also can be expensive. MRI is a versatile brain imaging technique, but is highly unlikely to be "wearable." MEG is an interesting technology to measure axon-derived currents with a high accuracy at a reasonable speed; this still requires minimal external magnetic fields, and a triply shielded micro-metal cage is required for the entire subject. While thermography has some advantages, the penetration is very small, and the presence of overlying tissues is a great problem. Many brain responses during cognitive activities may be recognized in terms of changes in blood volume and oxygen saturation at the brain part responsible. Since hemoglobin is a natural and strong optical absorber, changes in this molecule can be monitored by the near infrared (NIR) detection method very effectively without applying external contrast agents (Chance, Kang, and Sevick 1993). NIR can monitor not only the blood volume changes (the variable that most of the currently used methods are measuring) but also hemoglobin saturation (the variable that provides the actual energy usage) (Chance, Kang, and Sevick 1993;Hoshe et al. 1994; Chance et al 1998). Among the several brain imagers, the "NIR Cognoscope" (Figure C.8) is one of a few that have wearability (Chance et al. 1993; Luo, nioka, and Chance 1996; Chance et al 1998). Also, with fluorescent-labeled neuroreceptors or metabolites (such as glucose), the optical method will have a similar capability for such metabolic activities as PET and SPECT (Kang et al. 1998).

Nanotechnology and information technology (IT) can be invaluable for the development of future optical cognitive instruments. Nano-biomarkers targeted for cerebral function representing biomolecules will enable us to pinpoint the areas responsible for various cognitive activities as well as to diagnose various brain disorders. Nano-sized sources and detectors operated by very long lasting nano-sized batteries will be also very useful for unobstructed studies of brain function. It is important to acknowledge that in the process of taking cognitive function measurements, the instrument itself or the person who conducts the measurements should not (or should minimally) interfere with or distract the subject's cognitive activities. The ultimate optical system for cognitive studies, therefore, requires wireless instrumentation.

It is envisioned that once nanotech and IT are fully incorporated into the optical instrumentation, the sensing unit will be very lightweight, disposable Band-aid™ sensor/detector applicators or hats (or helmets) having no external connection. Stimuli triggering various cognitive activities can be given through a computer screen or visor with incorporating a virtual reality environment. Signal acquisition will be accomplished by telemetry and will be analyzed in real time. The needed feedback stimulus can also be created, depending on the nature of the analysis needed for further tests or treatments. Some of the important future applications of the kind of "cognoscope" described above are as follows:

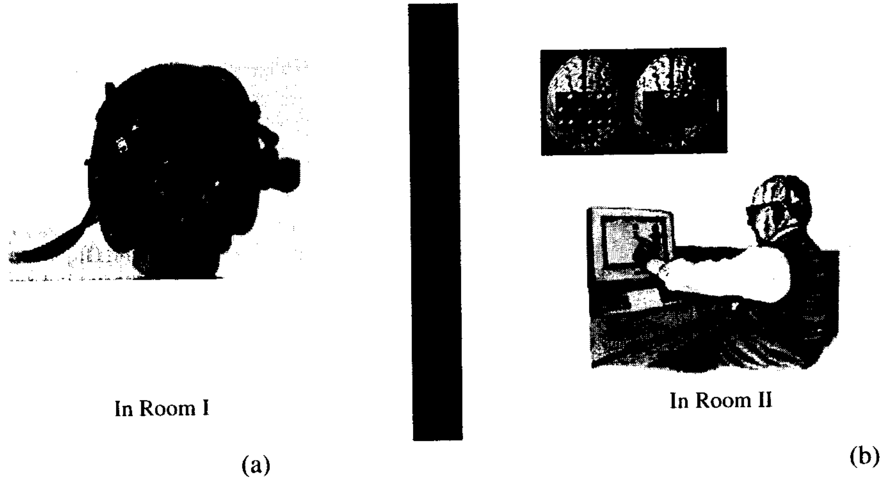

Figure C.8. A schematic diagram of the future NIR Cognosope. (a) A wireless, hat-like multiple source-detector system can be used for brain activities while the stimulus can be given though a visor-like interactive device. While a subject can be examined (or tested) in a room (room I) without any disturbance by examiners or other non-cognitive stimuli, the examiner can obtain the cognitive response through wireless transmission, can analyze the data in real-time, and also may be able to additional stimuli to the subjects for further tests, in another room (room II).