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ELECTRONIC AIDS FOR THE BLIND*

by

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I. GENERAL CONSIDERATIONS

A. Introduction

As in not a few other engineering research areas, the development of technological aids for the blind began as "gadgeteering" and slowly turned towards more basic research. Most original investigations were aimed at providing instrumentation in two main areas—guidance and reading. In the early decades of this century many such devices were proposed and built, but few met with even partial acceptance. To be sure, the technological obstacles were formidable, but as one technical limitation after another was overcome, it became apparent that the more fundamental limitations were of a psychological nature. What was required was a thorough study of the informational capabilities of various sensory modalities. This type of fundamental research, coupled with more careful technological design, has produced more promising instruments in recent years. Much work nevertheless remains to be done before truly acceptable devices are developed.

In addition to the change in the outlook of researchers and designers in the field of devices, recent progress in neurophysiology begins to give some promise that artificial stimulation of the brain itself to provide a visual sensation might be achieved some day. Although this accomplishment may be still many years in the future, some work is currently being done with this objective in mind. Here, as in the case of devices, success will depend on the close cooperation of workers in psychology, engineering, and physiology. This collaboration has been increasing in recent years and interdisciplinary groups are growing rapidly.

B. Scope of the Review

The first half of the present contribution is concerned with various aspects of the problem of guidance for locomotion (Sec. II). A fundamental problem related to both guidance and reading machines, research into the relative merits of various methods of sensory stimulation, is discussed next (Sec. III). The description of research that bears on the abovementioned subject of artificial vision by direct stimulation of the brain constitutes Sec. VI and electronic diagnostic tools useful in the treatment of blindness, Sec. VII.

Methods of aiding the blind to perform industrial tasks and reading machines themselves are treated very briefly in Secs. IV and V, respectively. The latter is an enormous field in its own right on which much has been written, including some extensive surveys. A great many of the papers presented at the International Congress on Technology and Blindness held in New York City in 1963, for instance, were devoted to reading machines. The four-volume set of Proceedings of that Congress comprises many detailed research reports from all parts of the world; although the present survey was largely completed before the set was published, the present authors were fortunate to be able to avail themselves of it just before publishing their own review, which thus takes these important recent contributions into account.

II. GUIDANCE DEVICES

A. Early Work

A useful guidance device must perform certain vital functions. It must warn the user of obstacles such as walls, lampposts, mailboxes, etc., in his path, far enough in advance for him to avoid them. It must provide information about the distance and direction of the obstacle, and possibly some clues about its nature. The device must also warn of step-downs, holes in the ground, ends of platforms, and step-ups (1).

Probably the first device used for this purpose was the cane, or walking stick. Despite all the advances of modern technology, the cane remains the most used guidance aid. (Attempts made to improve the cane by giving it electronic obstacle and step-down detection are discussed further below.)

One of the earliest attempts at an electronic aid was the Exploring Optophone invented in 1912 by Fournier d'Albe (2). The device was intended to warn the user of doors, windows, and other lighted areas. It consisted of two selenium photocells connected in a bridge arrangement. The bridge supply was interrupted periodically; an unbalance produced a buzzing tone in earphones worn by the user. The device depended on ambient light for its operation. This instrument was later adapted to a reading machine, and is discussed further below.

Since that time a great many instruments have been built and tested. Much work was initiated by the National Research Council's Committee on Sensory Devices, which was in existence from 1944 to 1948. A thorough history of its work and accomplishments is summarized in the volume edited by Zahl (3).

Guidance devices may be conveniently classified according to their mode of operation, i.e., ultrasound, visible light, etc. Most of the early devices were of the "echo" type. A beam of sound or electromagnetic energy is transmitted and its echo from an obstacle is received and modified to provide information to the user. The design of echo devices thus presents two basic problems: the accurate electrical reception of obstacle information and the translation of that information into stimuli understandable by the user. As will be seen, the first problem is basically technical, the second (and more difficult) is basically psychophysical.

In a typical instrument the transmitted beam is narrow, of the order of a few degrees in width. Upon striking an obstacle enough energy of the beam must be reflected back to the instrument to be detected above the ambient noise level. As would be expected, specular reflection constitutes an important and sometimes insurmountable impasse to proper functioning. Along with error-free detection of obstacles it is equally important that the "false-alarm" rate of the instrument be kept as low as possible. Shadows, puddles of water, etc., can give such false alarms depending on the type of beam used.

The beam is usually pulse or frequency modulated. The echo is detected by a photocell, microphone, or other appropriate transducer. The resulting electrical signals are amplified and must then be fed to the user, usually through audible or tactual stimulation. Both methods have their attendant advantages and disadvantages, to be taken up more fully in conjunction with the several devices; the basic problem is discussed in Sec. III. By way of general remarks, we may say that the audible signals can be varied along two parameters, frequency and intensity, with several distinguishable levels of each parameter. In addition, some work has been done with binaural signals to provide directional information. However, the blind rely greatly upon their hearing for other uses and most would prefer not to suffer any interference with this sense. Tactual stimulation, usually by means of blunt pins vibrating or pressing on the skin, avoids this difficulty but requires more power. Here too, frequency and intensity can be varied, and pin location is another variable. A third method is direct electrical stimulation of the skin, but this method has not yet been incorporated in a practical guidance device.

In early instruments the narrow beam was aimed by the user, who thus had to scan the environment manually. This appears to be a very slow and inadequate method of obstacle detection. Later models had provision for automatic scanning of the beam. However, this scheme added another parameter (direction) to the information that had to be transmitted to the subject and it was found that even when the device was functioning correctly, the user had difficulties in learning to analyze the signals. Furthermore, many of these devices were not capable of detecting step-downs. If a separate step-down detector had to be used, it would add still another signal to be monitored by the user.

No human sense is as efficient in gathering information properties as the visual sense. The amount of information that must be carried to the user of these devices is often prohibitive for auditory and tactual senses. Improved techniques can doubtless reduce the information required to give the blind subject a clear "picture" of his environment, by eliminating much of the redundant information gathered. Furthermore, combinations of two or more modalities (such as tactual and auditory stimulation) have been suggested but have not been extensively tried (4). Perhaps a better understanding of the problems involved will come from consideration of some specific attempts at guidance devices that have been made.

B. Scanning with Electromagnetic Radiation

Several guidance aids have made use of light in the visible spectrum as a means of scanning for obstacles. The d'Albe device already mentioned (2) used ambient light. Lashly invented a somewhat similar device that collected light and gave a tone if the illumination changed. This device could be used to provide a rough outline of an obstacle (5).

Zahl describes a nonportable "pattern optical system" that made use of automatic scanning and ambient light. A cubical mirror was rotated at about 10 rpm. Each of the four mirrors scanned the environment in succession (6):

> The vertical position of an object is indicated by a frequency component of the complex tone comprising the "pattern" which is high or low in accord with high or low object position. This is accomplished by means of a lens, slit, rotating tone generator, and photocell. The lens forms an image of the object at a point on a vertical slit which corresponds with the vertical position of the object. Behind the slit is a transparent cylinder which carries a series of variable density sound tracks past the slit, thereby modulating the light which passes through to a multiplier photocell. Since the ten sound tracks (in the present model) modulate the light at different frequencies ranging from 1400 to 1700 cycles per second, light from a bright object will generate one or more frequencies which depend on the elevation of the object, and the position of its image on the slit. The apparent vertical extent of an object is determined by the size of its image, and is indicated in terms of the number of frequencies excited. Thus, the image of a given object at a given distance illuminates, say, four sound tracks, giving rise to four frequencies simultaneously. As the object moves closer to the device the image size increases so that first five and then six sound tracks are illuminated, and five or six frequencies are heard.

For closer approach, the image size is further increased until all the sound tracks are illuminated and ten frequencies are heard simultaneously. Azimuth localization is indicated by the time interval between the start of a scan and the instant the signal from an object is first heard; the time interval is short for objects on the left, longer for objects toward the right of the field of view.

Other devices used a transmitted beam of light. Under Cranberg's direction the U. S. Army Signal Corps developed such a device in 1946 (7). The principle of operation was optical triangulation, used to determine obstacle distances. A beam of light chopped by a rotating disk at 500 cps is transmitted through one lens system. The 500-cps modulation is necessary to raise the signal-to-ambient-noise ratio to a usable value. The reflection of this beam is received by a second lens system. A cone-shaped, perforated coding disk is placed between the receiving lens and a photocell. The coding disk rotates, driven by the same motor as the transmitting disk, and the perforations are shaped to give a dot-dash or frequency-variable tone. The obstacle distance determines the angle, and thus the radius, at which the reflected beam strikes the disk. Light passing through strikes a photocell whose electrical response can then be amplified and used as a stimulus to the user. The perforations are placed so that different radii produce different frequencies or different dot-dash patterns. The amplifier is tuned to the fundamental 500-cps frequency.

Twenty-five models of the Signal Corps device were constructed, for testing by the Veterans Administration, with the actual testing performed at Haverford College. The report contained several recommendations for improvements, which were summarized as follows (8):

1. Separate obstacle and curb locators which are quiescent, i.e., deliver no signal until needed, and which are not accidentally actuated by irregular movements of the instrument encountered during walking.
2. Two channel presentation through tactile stimulators; one for curb signals, the other for obstacle signals.
3. Automatic scanning for obstacle detector, about a three foot wide path at a distance of eight feet. Manual scanning retained for simplicity.
4. Maintain extreme simplicity in getting instrument into operation. The user would prefer simply to pick up the device, "flip a switch," and be ready to travel.
5. Include feature to aid user in walking a straight line. How this may be done is not known. It is listed simply to encourage thought on the subject.
6. No moving parts except tactile stimulators.
7. A dual range control for obstacle detector, near and far.
8. Distance discrimination to within one foot of instrument.
9. Attempt to reduce noise (background interference) due to bright sunlight.
10. Weight of complete instrument under four pounds. Storage battery life of four hours is sufficient.
11. Progressively complex models to accommodate users of varying degrees of ability.

In 1953 Haverford College also received a contract to develop an electronic guidance device. The laboratory investigation was subcontracted to Biophysical Electronics, Inc. It was decided that a competent guidance device must locate both obstacles and steps, and that these two functions could best be realized in two separate systems that could perhaps later be incorporated in the same unit.

Work was begun first on the obstacle detector. The principle used was the same as in the Signal Corps device, optical triangulation. The wavelengths used were in the near infrared, 7000 to 10,000 Å. Special xenon-filled lamps were built and the detecting photodiodes were carefully chosen to maximize signal-to-noise ratio. Several systems were built. Early instruments had no provision for determining the obstacle distance. Later models used two and three receiving photocells to divide the field into ranges. The distance of the object determined the angle with which the reflected beam struck the receiving lens, which in turn determined which of the closely spaced photocells was activated. Separate amplifiers and stimulators were provided for each photocell. Stimulation was tactile, using a "polarized relay" consisting of a solenoid-operated brass plunger.

The lamps were pulsed on with short (200- to 250-μsec) pulses to increase signal-to-noise ratio over ambient and transient-ambient signals. The amplifiers accordingly utilized high-pass filters and were gated with the lamp signal before driving the stimulator.

Three units of the dual-range obstacle detector were eventually produced and tested. An extensive account of the early research was published in 1960 (9). Preliminary indications were that it was superior to the Signal Corps device in all respects except sensitivity. A few obstacles were missed in trials. However, it was noted that the instrument was found to be exceptionally useful in crowded buildings where a cane is unwieldy.

The development of the curb detector, described in the report, led to the proposal that the user should receive the signal indicating a down-step, up-step, or hole at least one step in advance to enable him to alter course in time. Five basic criteria were established for evaluating the system:

1. Insensitivity to change in angle at which it is held in the hand.
2. Insensitivity to slope of the terrain.
3. Insensitivity to change in height at which it is held.
4. Power required to give adequate detection sensitivity under all conditions of operation.
5. Inherent minimum size established by optical system.

Both ambient light and echo devices were considered. The various details involved in range detection by optical triangulation, such as lens separation, image shift, and effects of tilt, slope, and height change, were very carefully analyzed. The geometry of these analyses, as well as some very useful graphical information, was described in detail. Designs of several variations of a triangulation system were developed and tested, including fixed-range detection (with both ambient light and echo techniques), variable range detection, and focus ranging.

It was later decided that since the range-measuring techniques detect a step-down or step-up by the rate of change of range detected, this rate of change should be the actual quantity measured, instead of absolute range or range differences. A step-down appears as an instantaneous rate of change of range, whereas the rate of change of range increases steadily at a step-up. ("Range" here refers to the slant distance from the device to the ground.)

An important consideration in the design of a device to perform the above function is the movement of the instrument when in use. Ideally, it should be level at all times. However, this would not be the case if carried comfortably by a subject. Photographic studies showed an average angular variation of 17° when a subject carried a mock device; a 2-in. curb produced a shift of only 2° in the received beam. Clearly, there was a need to reduce this carrying motion.

The first proposal had been to let the user maintain the level position, with means provided for signaling him if the instrument was at an incorrect angle. However, it was found that too much concentration was required of the user. A pendulum mount was then considered. Motion of the subject would cause the pendulum to swing at its natural frequency. If this frequency, and the maximum swing, of the device could be maintained at a low enough value, the rate of change of range for an up-curb could be detected. Spring mounting and hydraulic damping were also introduced to reduce the effects of motion on the performance of the device.

With regard to the scanning mechanism, two possibilities arise. The receiver (or transmitter) could scan the ground automatically, or a servomechanism could be used to cause the receiver to follow the reflected source. After much experimentation the latter system was decided upon. Preliminary results of performance tests indicate a high degree of accuracy in detection. The problems that were encountered and suggestions for their solution are all described in the report (9).

The Haskins Laboratories developed a device using a modulated light beam and triangulation, but they replaced the coding disk by a milliammeter whose pointer contained a mask to pass over an aperture in front of a photocell. The apparatus was arranged with a slit so that an equilibrium in meter deflection was reached for a given object distance. This current reading was heard as a continuous tone of variable frequency controlled by a reactance tube. One difficulty encountered with this system was saturation of the photocell by intense ambient light (10).

In 1951, Beurle described several guidance devices, two of which made use of visible light (11). One used a flashlight bulb whose beam was "chopped" by a rotating disk. In the other, several arc lamps pulsed at different frequencies and aimed at different angles were used. The reflections are detected by photocells and transformed into audible clicks, whose repetition rate gives the distance to the object. As the user approaches the object the clicks merge into a buzz of higher and higher frequency. Alternative methods of treating the output include charging a capacitor and modulating a reactance tube with it to provide frequency modulation; or using frequency-modulated ultrasound, mixing outputs, and obtaining audible beat frequencies. Results of the tests on this device were discouraging.

An important research contribution was that made by Witcher at M.I.T. over four years beginning in 1952, during which several pieces of apparatus were developed (12). One that received a great deal of attention was a step-down detector using visible-light scanning. In its final form the device utilizes a light source that vibrates in a vertical plane, scanning the ground in front of the user. The reflection is picked up by a lens system and is directed at a small photocell. The optical design is such that the reflected beam sweeps across the photocell as the vibrating source sweeps the ground. In the absence of a step-down the photocell output is a single pulse of constant magnitude for each sweep. If a step-down is encountered, a narrow dark band occurs in the reflected sweep giving a negative pip in the photocell output, which can be used to actuate an alarm, provide clicks, etc. The amplifier is tuned to the frequency of the vibratory source. Witcher also provided an analysis of the energy spectrum received (13). A basic problem encountered was again the signaling of false alarms by puddles and other areas of a reflectivity markedly different from that of the ground. It was suggested that a second photocell be used to monitor the reflectivity of the ground and adjust the amplifier gain automatically.

In addition to the visible wavelengths and near infrared, some experimenters have worked with ultraviolet light in guidance devices. The Franklin Institute attempted construction of a device using ultraviolet scanning and automatic triangulation. The instrument, first described in 1950, was in the development stage, but was later abandoned (14). Technical difficulties were encountered in using wavelengths in the range 1850-2900 Å (15).

A few instruments using visible light have been of the "passive" type as opposed to the former "active" echo devices. One such system, "Optar" (Optical Automatic Ranging), was invented by Kallmann in 1954 (16). The instrument detects the location of the image plane of an obstacle as focused by a lens system:

Optical automatic devices, using ambient light only, can locate and range objects up to about 100 feet. Shallow real images of the objects are formed by a wide-aperture lens in an image space where a moving vane with minute bars and slots periodically cuts across all light rays in one image plane after another. Whenever the bars coincide with a sharp image they modulate the light received by a photocell. Range information may be read on a meter or control directly a range-following servo mechanism.

A small hand-held guidance device for the blind ... is used for probing like a flashlight but operates on ambient light when that exceeds one foot-candle. Image space is explored several times per second by a helical vane with bars spaced the closer the nearer the objects whose image they intercept. A photo-multiplier and audio amplifier feed the resulting whistle-modulation to an earphone, 8 frequencies corresponding to 8 ranges from 20 inches to 20 feet. A motor turns the vane, also a chopper to supply via transformer and twentyfold voltage multiplier 1000 volts dc to the electron multiplier; total consumption is 50 ma from one 1.5v cell.

Kallmann's system has been recently modified in Sweden by Jacobson (17). In this device, as in the Optar, the image plane of an object in a lens system furnishes information on obstacle distance. The method of detection of the image differs from Kallmann's original device. Here, the image is swept over a slit in a plate by means of a vibrating mirror. The light that passes through the slit falls on a photomultiplier tube. If a sharp image is picked up, a series of transients appears at the photomultiplier. If the object is out of range, the image is blurred, and only slow transients appear, which can be filtered out. The output of the photomultiplier is used to drive a mechanical bistable peg providing an "on-off" tactual signal.

Another recent passive system is under development in Poland by Starkiewicz and Kuliszewski (18). This instrument, the "Elektroftalm," consists of a mosaic of photocells that control a corresponding mosaic of tactile sensors. In the models built thus far 80 and 120 elements have been used. The tactile stimulator is placed on the subject's forehead. An encouraging degree of success has been achieved in these early devices. The main limitation to further development appears to be a lack of sufficiently small and reliable components in Poland. There is also a need for a more efficient tactile transducer that can respond to several different levels of light intensity with correspondingly different pressures. Future plans include the use of television techniques and use of the chest rather than the forehead as the site of the tactile stimulators. The difficulties these researchers have encountered with the subject's interpretation of the stimuli are of similar nature to those found by the other workers mentioned above. These difficulties include adaptation, limited resolution, and frequency discrimination. As mentioned in greater detail further below, several suggestions have been made for alleviating these effects.

Still another passive system, still in the development stage, is the "edge detector" of Johnson (19). The device utilizes the optics of a stereo camera. The principle of operation stems from the fact that for near objects the image formed by one lens is not identical to that formed by the other, whereas for distant objects the two images are almost the same. A mosaic of photocells is placed in each image plane of the two lens systems. A near object produces differences in the amount of light falling on corresponding photocells in the two image planes. Each corresponding pair is connected in a bridge circuit which in the present model is driven by an audio oscillator and produces an audible signal. Various difficulties and possibilities for improvement are discussed; the device is a promising one.

C. Scanning with Ultrasound

In addition to light, sound has been used to a great extent as a means of scanning for obstacles. Devices using both ultrasound and audible sound have been constructed. Indeed, some of the earliest suggestions for an echo-type guidance device came from the study of the bat's ultrasonic "radar" (20).

Both pulse and frequency modulation have been used in ultrasonic devices. Several instruments of both types were built before 1950. Stromberg-Carlson Co. developed three pulse-modulation devices (21). One was nonportable and used two magnetostrictive transducers, one for transmission and one for reception. Transmission is in pulses, adjustable from 5 to 50 pps. Both transmitted and received pulses are transformed into audible clicks. The time between the two clicks is a measure of obstacle distance. Another model uses a frequency of about 30 kc and tactual stimulation. The stimulator consists of a modified crystal phonograph pickup cartridge, with the needle replaced by an L-shaped piece of wire.

These devices suffered from specular reflective defects. They had to be aimed directly at an object for the signal to be properly returned. Step-downs were not detected.

Hoover Co. developed a system utilizing mechanical generation of the ultrasonic waves (21). A spring-mounted core of a solenoid is made to strike a steel bar suspended at its midpoint. The received signal is mixed with a local oscillator to give an audible tone when an obstacle is within range. Distance to the object is then determined by the user by manually adjusting the angle of transmission of the sound beam. A special lever is provided for this purpose.

The development of new wideband ultrasonic transducers induced Kay to work on ultrasonic guidance devices even though in appraising previous accomplishments in the field, he concluded that the visible-light devices seemed most promising (22). He produced both a pulse- and a frequency-modulation system.

In the pulse system the variable pulse repetition rate is adjustable by the user. Sufficient time is allowed between pulses for echoes to be detected without ambiguity. The received echo is heterodyned with an oscillator at a frequency lower by 4 kc to produce audible pulses. The transmitted pulses are coupled to the headphones but are first attenuated. Kay found that converting the audible pulses from ac to dc produced a stronger component at the desired frequency, and distances were more easily judged. However, tests with the actual device showed a general inability of the subjects to judge the separation of pulses (i.e., object distance) correctly.

In a typical frequency-modulation system the frequency of the transmitted wave is made to vary above and below some value by modulation of the transmitter with a sinusoidal or sawtooth waveform. The received echo thus differs in frequency from the transmitter frequency by an amount that depends on the time of flight, i.e., obstacle distance. This difference is usually detected by mixing the two frequencies and extracting the audible beat. However, "the Doppler shift in frequency for an observer moving at three feet per second, and a transmitter frequency of 30 kilocycles, is 170 cycles per second" (23). This frequency is superimposed on the audio beat signal, making range determinations ambiguous and dependent on the subject's speed. This is an inherent limitation of ultrasonic systems of this type. Two systems were built by the Brush Development Co., one utilizing sine wave and the other, sawtooth modulation (23).

Stromberg-Carlson Co. also developed a pulse-modulation instrument in which a sawtooth wave is used to frequency-modulate the ultrasonic oscillator completely across the passbands of the transducers. Pulses of transmitted ultrasound result, the frequency varying linearly within each pulse. Again, received signals are mixed with the transmitter and the audible beat signal is extracted. The greater the obstacle distance, the higher the beat signal. Again, step-downs were not detected (23).

It has been known for many years that a bat uses ultrasonic "radar" to avoid obstacles at night. Although the exact mechanism for this phenomenon has not been determined, several hypotheses have been advanced for various species of bats. In one species, an approximately linear frequency sweep has been noted and a beat-frequency detection postulated. In another type the frequency of emitted sound was essentially constant and it was assumed that detection was by means of a Doppler shift, which gave information on velocity instead of range. Still another bat emits pulses or clicks of tones.

Kay has designed a device based on the first system, with a frequency sweep from 60 to 30 kc (22). The time required to receive an echo from an object 20 ft away is about 40 ms. If a 400-ms sweep time is used, the echo of an object 20 ft away lasts for 400 - 40 = 360 ms, producing an almost continuous beat tone. Dielectric microphones were used as transducers. The beam angle was about 10°, but wider beams were suggested for later work. A single "flashlight" type of transmitter was used in the portable devices, but Kay emphasized that the desired final form of the instrument was binaural. However, Pye has suggested that binaural operation would be too confusing and would obstruct normal hearing too much to be useful (24). It should be noted that tactual stimulation might overcome these objections.

Tests of the system showed its ability to detect smooth walls at 30 ft, if aimed directly at the wall. Posts 2 in. in diameter were detected at 10 ft and a 1-mm wire could be detected at 4 ft. Differences in types of objects were noted by differences in signal patterns when the "flashlight" was rotated. Holes were detected as the absence of an echo when the beam was swept over the ground. Multiple objects gave complex frequency patterns that Kay felt could be interpreted with practice.

In this regard it may well be that we have not gone far enough in copying the bat's radar system. The ability of the minute bat's brain to interpret and respond to the received signals so far defies even our fastest electronic computers. Bats can both search out prey and avoid dangerous obstacles with incredible speed and accuracy. It has been suggested that a more thorough knowledge of the "histological, neurophysiological, ecological, psychophysical, and behavioral" systems may well lead to a more efficient and reliable guidance device. An excellent discussion of the bat's system is given by Pye (24).

D. Scanning with Audible Sound

There has been much investigation of the "obstacle sense" or "facial sense" of the blind, the ability of many blind people to sense obstacles in their path unaided. This sense appears to consist mainly of the ability to perceive echoes of ambient sound reflected from objects (25). As a result, several investigators have attempted to augment this sense by developing a device that would produce a narrow beam of sound which the user would direct in his path. In operation, the blind subject would simply listen for echoes. In principle, the transmitted sound should not be heard at all, but in most instruments this has not been perfectly accomplished. Also, step-downs could not be determined.

Twersky has developed a "sound flashlight" that looks much like its visible light counterpart. An aluminum and papier-maché horn focuses the sound and shields the user from the beam. The audible pulses are produced by a Brush "Sound Cell" transducer. By experiment, it is found that high or low frequencies were best; 1-4 kc was worst (25,26). Twersky also worked on several mechanical "horns" and "whistles" to serve as sound generators (27).

Witcher and Washington developed an obstacle detector that was designed to be incorporated with the optical step-down detector in a single unit (28). The device added automatic scanning to the sound pulse projection. In the first system, the sound beam was generated by a crystal sound cell tuned to 10 kc by shunting with a toroidal choke. The beam was reflected from a rotating elliptical plate to provide scanning. In a later model scanning was accomplished by angular oscillation of the elliptical plate so that the sound was provided for a greater amount of time. The device worked well but would not detect smooth, small objects. It was suggested that this technique could be used in an ultrasonic scanner, with binaural reception used for location (29).

Another "clicker," as these devices are called has been built at St. Dunstan's in England, as described by Beurle (11).

An attempt has been described to design a "Pan Audio System" consisting of two hearing aids for binaural localization. No sound was transmitted; only ambient sound was used. The idea was to enhance the user's ability to detect environmental sounds and echoes and to determine their location better. Difficulties were encountered in developing the system, and the work was not completed (30).

E. Electronic Canes

The familiar white cane, long taken for granted as a standard mobility aid for the blind, has been subjected to much recent study. Sheridan at M.I.T. has conducted a study aimed at a quantitative analysis of cane performance (31). Included in the paper is a vibrational analysis of the cane including JND (Just Noticeable Difference) measurements of displacement and spring constant. An obstacle course was constructed and tests were conducted by blind and blindfolded sighted persons. Various methods of using canes and different types of canes were evaluated. A major objective of the work was establishing a more quantitative basis for the evaluation of mobility with a cane. While some correlations of the data on cane tapping and time required for traversal of the course were possible, the author suggested further experimentation in this area before a more definitive scale could be established.

In other developments the standard cane has been given added electronic sensitivity. Gibson at the Franklin Institute Laboratories for Research and Development has constructed an electronic step-down detector, incorporated in a cane (32). The capacitance of the cane tip to ground is used to modulate the frequency of an oscillator operating at about 2 Mc. Another similar oscillator of fixed frequency is mixed with the first. The audible beat frequency is amplified and can be either used as an audible signal, or to drive a small motor that causes an eccentric pin to vibrate against the hand. A step down produces a sudden change in capacity, which is felt as a sudden increase in frequency.

In operation the cane is used in the ordinary way as an obstacle detector. It is held with the tip about 2 in. from the ground and is swept from side to side. Controls are provided for setting the signal to zero when held over level ground. The cane is battery operated with provision made for charging when not in use. It has been in operation and has been quite successful.

In an even earlier development, Richardt and Shann at Bell Telephone Laboratories devised two versions of a cane incorporating an ultrasonic obstacle detector (33). In one version the crystal receiver is located near the handle and the crystal transmitter near the tip, or vice versa. The ultrasonic reflections are amplified and heterodyned to an audible frequency. The presence of an echo signal indicates an obstacle. Doppler frequency shifts are to indicate whether an obstacle is approaching or moving away, but the patent says nothing regarding the success of this feature.

In the second version, the ultrasound is transmitted by a whistle arrangement activated by pressure on the tip of the cane, which is a spring-operated plunger.

F. Straight-Line and Direction Indicators

One aspect of guidance devices not mentioned so far relates to the basic difficulty encountered by the blind in maintaining a straight path, parallel to a curb. For elderly people especially, this proves to be a very difficult and slow task. The problem is especially acute in attempting to stay on course when traversing a wide, open area. Some proposals have been recently advanced to alleviate these problems.

Jacobson has devised a magnetic compass for use by the blind (34). A special jeweled bearing compass is placed below a light source and photocell arrangement that work on the same principle as Witcher's Pointer and Line Locator, described in Sec. IV above (27). The indicator is revolved by hand over the compass and the position of the needle is indicated by a tactile output. Problems of interference by large nearby metal objects such as cars make use of the device as a general straight-course indicator problematic.

Another device has been developed by Swail that uses as its principle of operation the rather sharp directivity of the ferrite antenna of a small transistor radio (35). In order to enhance this effect and bypass several other difficulties, the radio is modified to include a multivibrator-pulsed audio output whose repetition rate depends on signal strength. This modification is incorporated into the receiver without loss of its normal function. Although several difficulties have been encountered, the device has proven feasible in many instances.

G. Conclusions

It is probably too early for general conclusions to be drawn from the research on guidance devices to date, principally because only very few devices have been produced in large enough quantities for adequate testing. In many instances, difficulties encountered in early tests have discouraged further investigation. However, some preliminary results may be stated.

Devices operating with electromagnetic radiation, either within or close to the visible range, have been most successful. One important difficulty associated with this technique is the ratio of signal to ambient noise, which can be, however, greatly enhanced by pulse modulation of the beam. Echoes from obstacles do not suffer greatly from specular reflection, although the general reflectivity of the surface affects the results to some extent. The device can be made essentially unnoticeable, especially if the light is just outside the visible spectrum. The method is adaptable to step-down detection but generally requires different scanning techniques from obstacle detection.

Ultrasonic scanning suffers greatly from specular reflection: the beam must be aimed directly at an obstacle. Furthermore, there is the Doppler limitation mentioned earlier, which makes distance judgment subject to the relative velocity of approach of the user. Step-down detection is difficult, if not impossible, with ultrasound. Another difficulty is refraction caused by thermal gradients in the air. This effect can completely obliterate signals under certain conditions (9).

Audible-sound scanning relies heavily on the concentration of the user. It also calls attention to him. Here too, specular reflection becomes a problem, and step-downs are not detected.

There is fairly general agreement that tactile stimuli would be preferable, so that interference with the reception of aural cues could be minimized.

Several important considerations not directly related to technological problems must be taken into account. A guidance device cannot be designed like a military search radar. Even the greatest technical design skill, if employed without due regard for the people who will eventually use the device, will not produce a roadworthy instrument. Before any technical investigation is undertaken, the explicit needs and abilities of the intended users must be fully understood. Most U.S. blind today are over 60 years old. Many would have a great deal of trouble in learning to interpret a complex signal emanating from a "black box." Furthermore, blind people of above-average abilities do not wish to be encumbered by such a device. They find that they are able to navigate without it and actually feel that it might slow them down. In that connection, Beurle concluded that of the several devices he discussed, including audible and ultrasonic systems, none was likely to become popular with the average blind (11); the above-average blind person could get along very well:

> With the aid of nothing more than a walking stick he can find his way to and from work or to a friend's house in the evening, or on any similar journey which he knows well. It is thought that the percentage of blind people who can do this is not as high as it might be principally because many of the blind people who do not find their way around to any extent were never encouraged to do so and in many cases were actively discouraged. Many are vaguely aware that they can "sense" a large obstacle but do not realize

they are detecting it by means of echoes of their own footfalls. Few of them know how best to put this facility to use.

> It is with this in mind that we would stress the value of the opportunity for the blind to learn route finding as children if possible, and of deliberate instruction of children and newly blinded adults with the cooperation of blind adults who are experienced in this.

Nevertheless, there are instances in which a device would be of use even to the more independent blind. Mention has already been made of the usefulness of the Benham-Benjamin obstacle detector in a crowded area such as a school hallway (8,9). Adequate step-down detection would give people more security in places such as railroad and subway stations, where dangerous platforms exist.

Progress in guidance device development in the future will probably hinge upon work in each of several areas. Technological improvements in scanning are required. A psychophysical analysis of information capabilities through various sensory modalities is also necessary. Finally, the psychological factors underlying the use of any artificial device must be investigated. Indicative of the trends in modern research in this area is the work of the M.I.T. group under Mason, who has proposed systematic evaluation of guidance-device performance by means of computer simulation. A subject would traverse an obstacle course equipped with a dummy sensor and a computer operated stimulator. Information on the obstacles and the orientation and hypothetical performance of the sensor would be fed into the computer, which would then provide an output to the stimulator. Performance of a subject with various types of sensors and auxilliary equipment could thus be readily studied and provide a quantitative basis for comparison.

III. METHODS OF SENSORY STIMULATION

A. Introduction

A recurring problem of guidance devices and reading machines is the transmission of data to the user with sufficient accuracy and speed. A great deal of investigation has been carried out in the field of sensory communication by physiologists, psychologists, engineers, and others (37). It was recognized quite early that careful study in this field was prerequisite to further works, especially in the development of reading machines, where the concepts of sensory information transfer are of primary importance.

As the search for adequate stimulation techniques continued, the problem became not so much a technological one, but a psychophysical one. Psychophysics has produced a large amount of information related to this problem, most of which has not yet been incorporated into a sensory aid device. Here lies perhaps the most fruitful area for investigation. That is not to say that the engineering aspects must "sit back" and wait for psychology to develop more quantitative results. The problems of measuring and applying stimuli and of measuring responses in both testing and practical situations are prerequisite to a psychophysical study of sensory responses and do indeed lie within the domain of the engineer.

A study of the psychophysical phenomena currently under investigation discloses many that are analogous to functions of the visual system. For example, effects of motion and location can be stimulated tactually and aurally by means of stationary tactile stimuli or earphones. The possibilities of perceiving a "picture" of the environment (or the printed word) come immediately to mind. However, much work must be done in this field before such possibilities may be realized. Several of the relevant phenomena are discussed below.

B. Cutaneous Stimulation

Some devices have been developed specifically as tactile stimulators for sensory-aid devices. Witcher designed a handle to be used on a guidance device that contained several plunger pins, to indicate the various parameters describing the obstacle and its location (28). Ballard and Hessinger developed a "Tactual Sensory Control System" that was designed for aircraft control when conditions were unfavorable for audible communication with the pilot, and that would be readily adaptable for guidance device purposes (38). The system consists essentially of a device that fits over the thumb, with four transducers touching four different parts of the thumb. The transducers were vibrating plungers, 0.04 in. in diameter, with flattened ends. Their vibration produced an uncomfortable but painless stimulus. Experiments showed that continuous variations in pressure were not sufficient to give an indication of direction. A continuously variable frequency was better, but it proved to be difficult to detect small changes. A group of four discrete frequencies was chosen as optimum.

Witcher and others have also worked on a "pegboard" arrangement to be used in conjunction with an obstacle detector (39). Protruding pins would give the user a "map" of his environment. The board itself was built, but was not incorporated into a unit with a detector. This idea might be promising when used in conjunction with an automatically scanning guidance device. The scanning mechanism could be coded or gated to operate the pins in various locations on the board corresponding to obstacles in the environment. The entire pegboard could probably be made small enough to fit in the palm of the hand.

To develop a system capable of transmitting the requisitely large amounts of information through sensory channels other than vision, a lengthy analytical and experimental program will be required, with emphasis on the psychophysical aspects of the problem. The conviction is growing among workers in guidance devices that stimulation should be tactile in order to leave hearing unimpeded for aural cues. In a reading machine either or both tactile and aural signals could be used. A good deal of work has been done along these lines, much of it by psychologists not directly concerned with the problem of sensory aids.

In connection with an informational study of the various sensory modalities, Twersky has described a possible instrument with several sensory inputs to analyze information changes due to loss of sight or another sense (25).

Beginning about 1958, Mason has carried on several experiments to determine the pattern-recognition abilities of blind people through the tactile-kinesthetic sense (40). He then initiated a mathematical analysis of the information-transfer capacity of the various sensory communication channels and established their upper and lower bounds (41). Much of the work was done in connection with character recognition for reading machines. Several devices were constructed, including a system for tactual perception of visible patterns. A television system was used to magnify print to a height of 3-5 in. A sensor was placed so that when the blind subject passed his hand over the screen, he could detect the shape of the letter (42).

In more recent work Mason developed a tactile communication system using a stenotype coding machine in reverse. A prepunched paper tape was fed into the device and the keys were automatically activated and were "read" by the operator. The results were very encouraging and suggested possible attainment of high reading speeds with future work (43).

Another investigation into the many phenomena associated with the presentation of tactile information is underway at Stanford Research Institute, under the direction of Bliss and Kotovsky. In an interim report, they note that very little research has been done using displays with more than ten stimulators (44). They feel that "the key to a high information transmission rate is the development of a complex tactile display in which many stimulators and many sensation dimensions are used." They cite two previous investigations in this area. One was made by Guelke and Huyssen, who developed a tactile-display system for the deaf comprising 160 vibratory stimulators on the hands (45). Preliminary psychological results were very encouraging. The other investigation, by Starkiewicz, aims toward developing an 80-channel tactile display for visual patterns (18,46). The information is derived from 80 photocells.

A phenomenon of extreme importance in the presentation of visual information through the tactile sense is "apparent location." When the stimulation of two nearby areas of the skin differ in certain parameters, such as intensity or phase, the "apparent location" of the stimulus can appear to be between the two stimulated areas. The actual stimuli may or may not be felt. This phenomenon has been discussed in connection with sensory aids by Gibson (47), as well as by Békésy (48), as cited by Bliss and Kotovsky (44):

Békésy reported using two vibrators on the forearm to obtain apparent stimulation of any point between them. This was done by producing a sharp impulse in each vibrator with a short delay between them. As the delay time increased, the apparent location of the stimulus moved towards the vibrator activated first. For long delay times the pulses were felt as separate. For short delays they were felt as a single pulse somewhere between the stimulators. Békésy also reports obtaining continuous apparent motion back and forth between two vibrators by vibrating one at 50 cycles per second, and the other at 5.03 cycles per second.

In other such experiments described by Bliss and Kotovsky, stimulation was achieved by the use of two small air jets controlled by electrical valves capable of rapid on-off times. Nozzles are made of metal tubing with 0.032-in. ID. Parameters such as frequency, delay time, and intensity are adjustable. Experiments have been performed on apparent location, spatial acuity, temporal acuity, apparent motion, frequency effects, phase effects, and pain. Future experiments would use many air jets, perhaps as many as 100, and explore various areas of the skin, such as arms, legs, and chest.

An excellent presentation of the methods and basic constructs of psychophysical experimentation can be found in the compendium edited by W. A. Rosenblith (49). Some of the articles therein describe classic studies of many phenomena directly applicable to the design of sensory aids. There are several articles on cutaneous communication.

In one such article, F. A. Geldard emphasizes the necessity for psychophysical research by pointing to the failure of experiments to enable people to "hear" by cutaneous stimulation via mechanical vibrations that reproduced speech. The methods used involved exhausting training, but performance remained highly inadequate.

The variable "dimensions" with respect to the stimulation of the skin are few. The first-order dimensions are "locus, intensity, duration, and frequency, if one begins with repetitive mechanical impacts, that is, vibration. This is not the only possibility--the skin responds to thermal, electrical, and chemical stimuli as well--but mechanical vibration is the most promising one if continuous signalling is contemplated." In addition, there are some "derived" dimensions, such as apparent location and apparent motion.

The limitations and characteristics of each of these dimensions are discussed by Geldard. Important considerations included adaptation, in which sensitivity decreases with a continuous stimulus, pain, influence of one stimulus on another of the same or different type, etc. With regard to locus Geldard points to the need for special new transducers that would enable stimulation of several points. This is precisely the problem mentioned by Bliss and solved to some extent by the use of air jets (44).

An interesting result concerns the "dimension" of frequency. Geldard discusses the invalidity of previous measurements arising from the failure to control differences in subjective intensity. In measurements made in Geldard's laboratory, it was found that judgment of frequency is good only at low frequencies, and that at frequencies approaching those of speech, discriminatory ability drops rapidly. This result accounts for the failure of the "hearing by vibration" experiment.

Geldard also developed a system of vibratory signals that were coded into English letters. Only the dimensions of locus, intensity, and duration were used. Indications were that this type of system could produce information transfer rates of a feasible level.

In most comments on information transfer with respect to sensory aids one finds elimination of redundancy listed as an important requisite. Geldard pointed out, however, that some redundancy in the information presented may even be desirable, to increase the "cues." He suggested several ways of introducing this redundancy. One such method consists of using apparent motion or location. However, it would seem that these parameters might indeed be extremely useful as primary dimensions in themselves. Vibratory "tracking," which is based on these latter parameters, is discussed by Geldard, who found that the ability of a subject to "follow" the motion of a car by tactual means was quite comparable to his visual abilities.

"Psychophysics" can be thought of as a determination of terminal relationships. Input stimuli are applied and output responses are recorded and interpreted. Nothing is said about what happens inside the organism. It is through physiological studies that such information is gained. Rosner and others have conducted physiological investigations of the psychophysical cutaneous phenomena, and have shown several parallels existing in the two disciplines (50). In addition Rosner has shown that the central nervous system may be a large limiting factor in certain discriminatory abilities, rather than just the peripheral nerves.

The method of direct electrical stimulation of the skin has been investigated for many years, as reported by E. A. Jerome and H. Proshansky (51). A series of tests were made to compare the responses of subjects to vibratory tactual stimuli and to direct electrical stimuli. Various types of stimulators were tried, the most successful being a combination of a diffuse electrode and a point electrode. The diffuse electrode covered the palm of the hand, and the point contacts were applied to the cushions of the fingers. Both sinusoidal signals and differentiated pulses were used as waveforms, and it was decided to adopt the pulse system. Tests showed little difference in error rate between the vibratory and electrical stimuli.

Geldard and his colleagues have conducted a good deal of research on the problem. In his article on cutaneous communication channels he wrote (49):

> Another whole domain of possibilities opens up when we consider that only one form of energy, the mechanical has thus far entered our calculations. Not much is to be hoped for from the chemical and thermal forms of stimulation. They are both too ponderous in their operation to be of much use in communication; at best they could provide only the analogues of smoke signals. But there is the whole important realm of electrical stimulation. The skin responds with lively patterns to both direct and alternating current. Indeed the heart of the problem is that the patterns are, in general, somewhat too lively for comfort. We have devoted several years of intensive effort to finding the conditions of electrical stimulation that will yield codable vibratory patterns, bereft of pain, and that can be reproduced on demand. The problem has turned out to be a slippery one. Electricity is the great "nonadequate" stimulus; it triggers everything, as physiologists well know. However, the important stimulus

> parameters are few in number, and my colleague, Dr. John F. Hahn, has been able to isolate the really significant one in skin stimulation [52]...Where square waves are employed and are systematically varied in frequency and duration, thus obviating any influence of the change in rate of current increase such as occurs with alternating current of variable frequency, it turns out that absolute threshold is related to duration only. This fundamental discovery permits us to narrow our search for the basic medium of reception in electrical sensitivity of the skin. The great stumbling block, thus far, is the omnipresent pain. Although under some reproducible conditions pain tends to adapt out in continuous signalling, leaving behind a not too unpleasant tingle, it is doubtless asking too much, in practical communication situations, to expect that even transient discomfort from a transducer will be tolerated.

A large project has been undertaken by B. Von Haller Gilmer and Gibson at the Carnegie Institute of Technology to determine the necessary parameters for pain-free stimulation of the skin (53). The work is aimed at devising a method for an easily learnable coding system. It was found that for the highest pain to touch threshold current ratio, pulses of 0.5 ms were best. Various threshold data were accumulated for both hairy and hairless parts of the skin. Using repetition rates of 100 pps, peak currents in the skin were varied from about 1 to 4 ma. It was found that few pulses applied to hairless skin gave best results.

In a second experiment it was found that pain thresholds were more sensitive than touch thresholds as repetition rate was varied.

Important in eliminating pain is avoiding integration of the current pulses by the skin to exceed the threshold. The time constant for such integration was reported as about 30 ms for touch and somewhat higher for pain.

Suggestions for electrode size and pulse widths, amplitudes, and repetition rates to be used in a practical cutaneous communication system were included in the paper. The phenomena of apparent location and apparent motion were investigated. The former was induced using electrodes about 5 in. apart on the forearm and wrist. Pulses of different intensity applied to the electrodes produced an apparent pulse between the electrodes. Investigation is continuing on methods of sharpening the effect. With regard to apparent motion, several important phenomena were noted, and differences were observed between responses to electrical and vibratory stimulation. Gibson expressed his belief that a system for communicating spatial patterns through electrical stimulation of the skin is entirely possible, although a good deal of research is still required.

C. Aural Stimulation

Although audible stimulation is undesirable for a guidance device, it may be very profitably employed in a reading machine. A great deal of work has been done on the psychophysics of audition. Many of the phenomena encountered parallel those of cutaneous stimulation. Here too, there is an opportunity for vast improvements in applications to sensory aids.

Collin Cherry and others have studied binaural interaction of stimuli and have established limitations and capacities of this sensory system. For example, Cherry has investigated the "fusion mechanism" of the brain in binaural hearing (54). This is the ability of the brain to receive the separate responses of each ear, responses that vary minutely with respect to timing, intensity, and microstructure —"and by processes of inductive inference, break down the complex of soulds into separate coherent images, 'Gestalten,' which become projected to form the subjective 'spatial world of sound'."

If a signal is applied to each ear via earphones and if the time difference or amplitude ratio is varied, the audible image seems to move laterally between the ears. For different timing the image will "appear" in a different position. This phenomenon is analogous to apparent location and apparent motion in cutaneous stimulation.

Much research in auditory perception has been carried out at M.I.T.'s Communication Biophysics Laboratory under W. A. Rosenblith, and at the Bell Telephone Laboratories. Such parameters as pitch perception, pulse separation, intensity, and various interrelationships among them have been studied in detail (55). The physiology underlying the psychophysical results has been explored by Hollowell Davis, who investigated peripheral coding of auditory information both with regard to neural interaction in the ear and in the cortex of the brain (56).

Mills has given an account of some recent work on auditory perception of spatial relations (57). The same reference also contains articles on monaural and binaural hearing as applied to spatial orientation and auditory training for travel.

IV. INDUSTRIAL AIDS FOR THE BLIND

Several electronic devices have been designed and built to aid the blind in various industrial tasks. An acoustic "lamp reader" was developed in England to enable blind telephone switchboard operators to determine the state of flashing indicator lights on the board. The detection is by means of photocell modulation of a transistor oscillator (58).

Witcher developed a very successful "pointer and line locator" that enabled the blind to read electrical and other types of meters and printed lines, with a high degree of accuracy (59). The first design utilized a small light source and receiving photocell. The photocell modulates the frequency of one of two neon lamps used as relaxation oscillators. Earphones are used to detect the null in the beat frequency. The probe was later redesigned mechanically and transistorized (60). The receiving photocell is used as one timing resistor in an astable multivibrator. The multivibrator gives an audible signal whose frequency is proportional to the intensity of received light. The instrument is manually passed over the face of the meter and the position of the needle can be detected. The reading is taken by means of raised numbers on the meter.

Many other aids, mainly nonelectronic, have been developed for various tasks. Many new employment opportunities would doubtless become available to the blind if an extensive industrial survey could be made with a view to developing the proper instruments. Certainly many testing procedures that currently require visual measurements could be converted to tactile and auditory measurements.

A great many devices for use by the blind in industry and education are described in Volume 3 of the Proceedings of the International Congress on Technology and Blindness (61).

V. READING MACHINES

The development of reading machines for the blind is summarized very briefly here since it has been quite thoroughly treated elsewhere (62,63). An article by Freiberger and Murphy contains 66 references pertaining to past and present work (64).

With regard to future research, a few comments are pertinent to the present contribution. A reading machine must perform essentially three main functions. It must first "recognize" the printed message and convert it into electrical signals. Second, the information content must be altered to eliminate redundancy where possible. Finally, the message must be coded and transmitted to the user through some sensory modality or combination of modalities.

The first function, recognition, is essentially in the domain of character and pattern recognition, a field that has grown independently of work on reading machines. Interest in computers has spurred much research in this area and it is likely that the results will be applicable in the input stage of a reading device.

The second function is also being studied independently. Work in the areas of machine translation and information theory is concerned with very similar problems, and is crucial if adequate reading speeds are to be obtained.

The output stage of a reading machine presents much the same problem as the output of a guidance device. Here too, psychophysical studies are essential to the design of a tactile of audible stimulator. Audible systems have received most attention in the past. Both complex coded sounds and synthesized speech have been tried, and work continues in both areas. Tactile outputs are a necessity in the case of the deaf-blind. There is also an immediate need for a machine to convert print to Braille, or to a Braille signal, since many of the blind are already trained in Braille.

The previous statements should not be construed to mean that there is no need for a formal program aimed specifically at reading machines because each part of the problem is being investigated separately. Many of the problems involved in developing a reading machine are, as in the case of guidance devices, peculiar to the blind. Engineers concerned with pattern recognition and information processing as applied to bank checks or scientific data are not likely to worry about whether or not the information output rate of the machine is adequate or excessive for tactual coding. The adaption of the various techniques perfected under these several disciplines into a form useful for a reading machine permitting adequate reading speeds is a major problem in itself.

Furthermore, as was emphasized with regard to guidance devices, the researcher must always keep in mind the capabilities of the person for whom the instrument is intended. This is by no means a simple task; Freiberger and Murphy conclude (64):

> Probably no device or system now contemplated will aid all blind persons, so prescription teams must eventually be formed and educated to help a specific patient to select the best system for his particular needs.

Finally, cost is a major consideration with regard to reading machine design. Recently proposed methods often involve extensive computer instrumentation and would put the device financially out of reach of the blind for private use. They might be incorporated in a public library, but a "home" device is much to be preferred.

Some of the most fundamental and promising work in this area is being done under the direction of S. J. Mason at M.I.T. Several projects on pattern recognition, language redundancy, and tactile and multimodality displays are currently in progress and are described in current issues of the Quarterly Reports of the M.I.T. Research Laboratory of Electronics.

VI. ARTIFICIAL VISION BY DIRECT STIMULATION OF THE BRAIN

It should be stated at the outset that artificially stimulating "vision" in a blind person is not likely to become a reality in the immediate future. The neurophysiology of vision is an exceedingly complex subject and it is only recently, with the advent of special techniques and equipment, that many major phenomena are being understood. Furthermore, as will be seen in the discussion to follow, even a thorough knowledge of the physiology involved will not suffice to stimulate vision in the blind.

This review cannot attempt to summarize the physiology of vision as it is currently understood, which is the subject of major books (65,66). But it should be clearly understood that no one is working specifically on a device to stimulate vision artificially at present. The groundwork for such future research is being carried on in many areas, including physiology, psychology, histology, anatomy, engineering, etc. The final project will doubtless require collaboration among these disciplines. Such collaboration is even now a major factor in neurophysiological research. Psychological results are often required to guide experiments and interpret results of physiological investigations. As R. Jung has pointed out (67), Psychophysiology of the sense organs has preceded neurophysiological analysis of sensory mechanisms for more than 100 years, and it still provides the searchlights on this route of research.

The coordination of psychophysiological and neurophysiological experiments will lead us further than either of these approaches alone. The combination of the two may indicate a via regia to the exploration of human sensory information. The unilateral pursuit of only one method without regard for the other risks either blind neurophysiological recording or fanciful psychological hypothesis, and either of them may lead to minor side-tracks and end in a jungle of barren facts or luxuriantly growing speculations. With the help of the highly developed engineering techniques that facilitate our neurophysiological and psychophysiological research, a further advance on this path should not be too difficult and may elucidate some of the many unknown mechanisms of sensory communication.

Recent evidence has shown that a good deal of the discriminatory functions of the visual system, let alone the pattern recognition aspects, are accomplished in the brain itself, in the occipital cortex and higher centers (68). Although the complexity of anatomical and physiological detail is large in the eye, it is enormous in the brain, expecially in the human brain. Experiments were first attempted to localize such functions as pattern recognition. However, the situation has been shown to be much too complicated for such a simple description. Jung says, "The simplified conception that a primary receiving area for a given sense modality contains mosaic representation of the receptors cannot be maintained" (67).

Furthermore, the visual process is interfused with the receiving areas of other sensory modalities, such as hearing. The prospects of artificially stimulating even a simple, stationary pattern thus become more and more remote. Most of the investigations thus far have concerned the visual system from the retina to the visual cortex of the brain. However, Adler has also reported as follows (66):

> All physiologists are agreed that vision, as man experiences it, is a function of still higher parts of the brain, or perhaps of the brain as a whole. It has naturally been impossible to experiment with man by removing various portions of the cortex or tracts in order to determine their relative importance, but the experiments performed by disease show clearly that only the crudest visual sensations result from stimulation of any part of the visual paths or occipital cortex. Thus, stimulation of the retina by trauma gives rise to a sensation of bright points of light—the subject says he "sees stars." Mechanical stimulation of the optic nerve, or of the tracts up to and including the occipital cortex, as a result of trauma, by the growth of tumors, or from vascular spasm, may also cause the subject to have flashes of light, colored or uncolored. The various forms of scintillating scotoma which frequently occur in migraine are thought to be due to spasm of blood vessels in the occipital cortex. No recognizable shapes or forms are ever complained of... Visual hallucinations, taking some recognizable shape, are described by patients with tumors of the temporal lobe. This has led to the belief that the association pathways connected with the

> percepts of form must be in this region.
>
> Psychological processes, such as visual percepts, as contrasted with visual sensations, are so complex that they defy immediate physiological analysis, but continued study of the elementary physiological processes may eventually lead to a better understanding of the more complex phenomena.

Adler went on to describe various hypotheses that have been advanced to explain perception and memory of patterns in the brain, and the impossibility of adequately localizing these phenomena.

There is still another problem, however, and one that may prove to be the most difficult to overcome. Most nerve fibers are surrounded by a thin neurillemmal sheath. When a nerve is damaged, or degenerates, the sheath may remain, and the nerve can regenerate through it. The optic nerve, however, is actually a part of the brain, and as such has no neurillemmal sheath. As a result, regeneration is "theoretically impossible" (66).

The optic nerve fibers receive their nutrition from the ganglion cells in the retina. In most forms of blindness the retina degenerates. As a result, the optic nerve degenerates irreversibly. To make matters worse, says Adler (66),

> occasionally cells within the central nervous system, when deprived of their connections with other parts of the nervous system exhibit chromatolysis, and their fibers degenerate. This has been designated "transneuronal degeneration." It occurs in the lateral geniculate body when lesions are made in the retina. Hence, the degeneration does not stop here, but may proceed up to the cells in the calcarine cortex.

Nevertheless, work is being done to investigate regenerative processes in the optic nerve of animals; for example, in goldfish (69, 70). Regeneration can take place in these animals and further study may some day lead to methods of regeneration in humans.

The above discussions make the problem seen hopelessly complex. However, work to date has shown enormous progress in unraveling this complexity. The cooperation among the various disciplines promises continued elucidation of the many phenomena as yet not understood. There is much in this problem that lends itself to engineering analysis and research. To begin with, there is the vastly important problem of neurophysiological instrumentation. The extraction of neurological signals from the large amount of noise present in the system is an extremely difficult task. Large-scale computers must often be employed.

Information theory provides an important method of representing the functional differences among different types of neurons. It is also used to describe events on a system-wide basis. Several phenomena (and at least one important hypothesis concerning the mechanism of memory) depend upon feedback loops in the neuron chains (71). Here too, engineering theory is important in describing the system. "Scanning" mechanisms and neuronal "networks" are other neurophysiological phenomena that are currently being analyzed with the aid of engineering concepts. A good deal of work on neural nets is being done at M.I.T. Engineering mathematics is often a powerful tool in reducing the complexity of a sensory system to workable levels.

Several very interesting hypotheses have been recently advanced by Tanner (72), who has discussed the possibilities of using one sensory system to substitute for another with appropriate artificial inputs.

Proceeding from an informational analysis of a sensory channel, he suggests several areas of possible research, mainly on a long-range basis. The discussions are, as the author admits, of a highly speculative nature.

There are several areas in which research in engineering could be of immediate value. As a parallel to the many electronic models of the nerves that have been developed (73,74,75), models simulating visual neurons could be built and combined in a model electronic "retina" or "eye." This might divulge a good deal of information with regard to interneuron phenomena. The model would be based on current electrophysiologic findings that do indeed lend themselves well to such an endeavor. The electrical characteristics of the various types of neurons in the retina, optic nerve, lateral geniculate body, etc., are known in many cases. It is possible that from these models further hypotheses may be drawn concerning other, as yet unknown and unmeasurable neuron interactions, as for example, the function of the horizontal and amacrine cells in the retina which serve to interconnect the rods, cones, and their associated neurons. As Jung has pointed out, these models do have limitations and care must be exercised to guarantee that the models do not violate physiologic principles (67):

> It would be very helpful for the neurophysiologist if information engineers would pay more attention to special neuronal mechanisms of the cortex which can be so beautifully demonstrated in the visual system. As neurophysiologists we have to accept and to investigate the nervous system as it is. We cannot change its mechanisms except by lesions. On the other hand, communication

> engineers can build and alter their models at will to approximate biological realities. In other words, we should be glad if our colleagues in the fields of technical communication would not only construct their fine computing machines to facilitate physiological analysis, but would also build neuronal models that resembled brain mechanisms. Then perhaps instead of telling us how the neurons of the nervous system should work according to their theories, they would be able to base their models and theories on neurophysiological findings in actual neuronal networks, such as the visual system. Then we might expect useful results from the cooperation of neurophysiologists, psychologists, and engineers.

An example of a direct application of physical and engineering theory to the physiological problem of vision is provided by the work of Ollendorff (76). He develops a mathematical model of the ionic diffusion processes in the retina and the generation of an optical signal in the neurons of the visual system. Like Tanner, he speculates on the possibility of substituting one sensory system for another. He also suggests the feasibility of constructing an electronic model of the visual system.

Another fruitful area for research is the radio stimulation and recording of the electrical activity of the brain. At present most of this work is done through wires and implanted electrodes, which inhibit the behavior of the animal to some extent. Furthermore, if and when an artificial visual sensation is stimulated within the brain, it would be extremely difficult to maintain electrodes and wires leading out of the scalp surgically. Implantable receivers and externally transmitted signals would probably have to be employed.

This work would then be a prerequisite for such a future project. This radio stimulation could work side by side with brain-mapping experiments to provide more information on brain response. Fischler and Frei have designed and built a subminiature apparatus for radio-telemetering of EEG data for laboratory animals and humans (77). The telemetered data show excellent correspondence with conventionally recorded responses.

An important physiological problem concerns the determination, insofar as is possible, of the locations of various functions in the brain. Although, as has been mentioned, many important processes cannot be localized, there are several general functions that do take place in specific areas. Much of this "mapping" lends itself to engineering instrumentation and analysis. For example, a group directed by Killam at Stanford University is investigating psychophysiological responses of cats to visual stimuli and conditioning (78). Pulse modulation is employed in determining the location within the brain of the various conditioning responses of the cats.

The standard methods for such mapping involve inserting the electrodes into the brain and recording data from them. The insertion is controlled from the known anatomy of the brain to within a fraction of a millimeter of the desired area. After the recording has been completed, the animal is sacrificed and the brain is fixed and sectioned. Under microscopic inspection the exact location of the electrode and the histology of the tissues can be determined.

The enormous complexities involved in "understanding" sensory responses and their interpretation by the brain have been discussed by Shipley (79). It appears to be extremely difficult to localize the areas of visual response since a great many areas have been found to respond to various types of visual stimuli. An important lesson may be driven home by this sobering discussion. In the present state of the art advances must necessarily be of a small and limited nature. Attempts to encompass a large part of a sensory system in some new theory will doubtless render that theory highly speculative and will require enormous assumptions. The more limited an experiment is in scope, the greater is its chance of success in applicability.

VII. ENGINEERING CONTRIBUTIONS TO DIAGNOSIS OF VISUAL DISEASE

Another important area (not directly connected with the "artificial eye") in which engineering techniques are applicable, and in which much remains to be done, is the diagnosis of visual defects. In many diseases of the visual system accurate and early diagnosis of a defect can save the patient's sight. Only a few of the various types of diagnostic instruments that have been developed will be mentioned.

In patients with corneal opacities it is often very important to know what previous treatment the patient has received. Other complications such as cataract, neoplasm, etc., may have developed, and this detection is an important presurgical step. Ordinary opthalmoscopy using visible light is often inadequate to examine the interior of an eye with a corneal opacity. Friedman has developed a method of using infrared light in an opthalmoscope to provide greater penetration (<u>80</u>). A near-infrared receiver is placed between the objective and eyepiece-lens assemblies of an ophthalmoscope. The ordinary light source is used; the infrared viewer responds to the reflection of those wavelengths from the eye. If desired, an infrared filter can be placed after the light source so that the light is invisible to the patient, thus permitting dilation of the pupil. It is found that many subcorneal conditions could be clearly diagnosed with the aid of the infrared viewer.

The constancy of the interocular pressure of the eye is important in maintaining the fixed distances of the lens and cornea from the retina, as discussed for instance by F. W. Weymouth (81). If the interocular pressure becomes too great, probably owing to oversecretion of electrolytes, the optic nerve fibers may be damaged at the point at which they pass out of the eyeball. This condition is called glaucoma, and the instrument used to measure interocular pressure is a tonometer.

Many currently used tonometers are limited in accuracy by various effects such as corneal stiffness, asymmetric curvature of the cornea, and surface tension of tears. Mackay and Marg have developed a tonometer that eliminates these difficulties through a special probe (82). The area of the probe touching the eye consists of a small (2-mm-diam.), pressure-sensitive plunger, surrounded by an insensitive, 3-mm-diam. ring. The ring flattens the eyeball surface momentarily and the plunger responds to the interocular pressure. Measurements are made by allowing the plunger to move a ferrite core and alter the inductance of a coil. Feedback and FM detection are employed and the reading is made essentially linear by allowing only small movements of the plunger. The instrument allows the operator to distinguish between actual interocular pressure and an artifact arising from the extra pressure of the probe.

Also important in assessing the various factors in the eye associated with glaucoma is blood circulation in the fundus oculi. Broadfoot has developed a photoelectric device for examining this circulation (83). A modified ophthalmoscope is used. The light source is chopped by a disk with three holes, each covered by a filter of different color. After reflection from the eye the light is detected by a photomultiplier cell. Electronic switching is employed to distinguish between the three channels, red, green, and cyan. By interpreting the relative absorption of red light by the choroid of the eye, the condition of the circulation can be determined.

Electroencephalography (EEG) has also been used to provide clues to possible lesions in the brain connected with blindness, or severely impaired visual ability. A good deal of work has been done in this area and much remains. Abnormal EEG patterns have been linked to various visual defects but difficulties in interpretation of EEG patterns have limited the success of these projects. A great deal of engineering research has been devoted to devising better methods for this interpretation.

Finally, significant technological contributions have been made in electromyography, electroretinography (84), and electro-oculography (85). The list of diagnostic aids continues to grow; there is room for much technical research in instrumentation for both diagnosis and treatment of visual defects.

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