determine the identity and layout in three dimensions of a group of familiar objects if we had designed our system to deliver 400 maximally discriminable sensations to the skin. The perceptual systems of living organisms are the most remarkable information-reduction machines known. They are not seriously embarrassed in situations where an enormous proportion of the input must be filtered out or ignored, but they are invariably handicapped when the input is drastically curtailed or artificially encoded. Some of the controversy about the necessity of preprocessing sensory information, the author thinks, stems from disappointment in the rates at which human beings can cope with discrete sensory events. It is possible that such evidence of overload reflects more an inappropriate display than a limitation of the perceiver. Certainly, the limitations of the system we have been working with are as yet attributable more to the poverty of the display than to overtaxing the information handling capacities of the epidermis.

References

[1] J. C. Bliss and H. D. Crane, "Touch as a means of communication," *Stanford Research Inst. J.*, no. 5, p. 7, 1969.
[2] J. J. Gibson, *The Senses Considered as Perceptual Systems.* Boston, Mass.: Houghton-Mifflin, 1966, pp. 266–286.
[3] D. O. Hebb, *Organization of Behavior.* New York: Wiley, 1949.
[4] J. Holt, *How Children Learn.* New York: Pittman, 1967.
[5] K. Koffka, *Principles of Gestalt Psychology.* New York: Harcourt, Brace, and World, 1935.
[6] W. Metzger, *Gesetze des sehens.* Frankfort: Kramer, 1953.
[7] L. G. Roberts, "Machine perception of three-dimensional solids," Lincoln Laboratory, Massachusetts Institute of Technology, Cambridge, Tech. Rept. 315, 1963.
[8] W. Schiff, "Perception of impending collision: A study of visually directed avoidant behavior," *Psychol. Mono.*, vol. 79, no. 604, 1965.
[9] B. F. Skinner, *The Technology of Teaching.* New York: Appleton, 1968.
[10] J. G. Taylor, *The Behavioral Basis of Perception.* New Haven, Conn.: Yale University Press, 1962.
[11] E. B. Titchener, "Instructors' manual," pt. 2, in *Experimental Psychology*, vol. 2. New York: Macmillan, 1905.
[12] H. Wallach, M. Moore, and L. Davidson, "Modification of stereoscopic depth-perception," *Am. J. Psychol.*, vol. 76, pp. 191–204, 1963.

Optical-to-Tactile Image Conversion for the Blind

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***Abstract*—This paper describes two optical-to-tactile image-conversion systems being developed for the blind. The first is a reading aid in which an area on the printed page about the size of a letterspace is translated into a corresponding vibratory tactile image. The tactile image is produced by a 24-by-6 array of pins driven by piezoelectric bimorphs. The array of 144 pins fits on the distal and a portion of the middle phalanges of one finger. The piezoelectric bimorphs cause the pins to impact the skin in a nonlinear manner. Precise measurements on this bimorph-finger system are given. These measurements also show that shades of "grey" can be displayed by sequentially varying the threshold level.**

Three experiments conducted with the reading aid involved measurement of legibility, reading rate, and the effect of field of view. Legibility in the 92-98 percent range was obtained at the design magnification. A reading rate of 50 words per minute was achieved with one subject after roughly 160 hours of practice. Three other subjects achieved reading rates of over 10 words per minute after about 40 hours of practice. Reading rate increased markedly as the number of columns in the array was varied from one to six.

The second optical-to-tactile image-conversion system is merely an extension of the first to permit information to be acquired from the environment. In fact, ultimately only one system with two sets of optics, one appropriate for the printed page and one appropriate for environment sensing, would be used. A portable, battery-operated experimental model is described.

Two preliminary experiments with this environment sensor involved form recognition and pursuit tracking. Performance by blind subjects using the tactile display matched performance by sighted subjects using a corresponding light display. However, several problems must be overcome before this application can be satisfied in practical situations.

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I. Introduction

FOR THE PAST hundred years, tactile displays have been suggested for many purposes, including sensory aids for the blind and deaf, sensory feedback for remote manipulators and prosthetic limbs, control and navigational displays for astronauts and aviators, and "feelies." Very few of these suggestions have been developed to the point of common usage. However, advances in materials, electronics, and computer technologies now make much more complex tactile displays feasible, although many difficulties presently confront the designer of tactile displays. There are few commercially available tactile stimulators, and special designs are not always straightforward. Also, little is known about optimum stimulus parameters and about the characteristics and capabilities of the tactile channel. Thus, the engineering of tactile displays is just developing, and the neurophysiological, psychophysical, and perceptual foundations for an engineering design philosophy have yet to be assimilated.

In this paper two recent projects in the design of tactile displays are described. Both of these projects involve optical-to-tactile image-conversion devices. The objectives of both systems are to enable a blind person to read normal printed material and obtain information about his surroundings important to mobility.

II. Reading Aid for the Blind

Our basic design for a direct-translation reading aid with a tactile output has been described by Linvill and Bliss [1], and Bliss [2]. In this design an area about the size of a letter space is imaged on an array of phototransistors. The signal from each phototransistor controls a tactile stimulator in a corresponding array of tactile stimulators. Thus, a vibratory tactile image is produced of whatever is printed on the page.

A primary consideration in the design of this reading aid was the spatial resolution of the tactile image. Of course, with appropriate optics a single movable phototransistor coupled to a single tactile stimulator could in principle permit a person to eventually obtain by scanning enough information for letter identification. However, if the scan is manual, reading would be extremely slow. If it is automatic, perceptual considerations would limit the scan rate so that a slow reading rate would also result. Therefore some parallel channels are necessary for an acceptable reading rate. In this paper, we consider the case of completely parallel input for the vertical dimension and a single horizontal scan. We also consider parallel input in the horizontal dimension but, since the scan is horizontal, additional columns of channels provide no new information and the optimum number depends on a tradeoff between perceptual and economic considerations.

By considering the spatial spectral content of alphabetic shapes as they occur in normal printed material, we showed that a minimum of 24 phototransistors are needed in the vertical dimension of the array [2] in order to obtain acceptable legibility of alphabetic shapes. Experiments with various numbers of vertical columns, each with 24 phototransistors, indicate that higher reading rates can be achieved as the number of vertical columns is increased [3]. These considerations have led to the reading aid shown in Fig. 1, which is based on a 24-by-6 array of phototransistors and a corresponding stimulator array.

The optical pickup probe shown in Fig. 1 was developed in our laboratories. It contains a monolithic integrated array of 144 phototransistors on a single silicon chip 120 mils by 60 mils. This phototransistor array was especially designed and constructed in the Stanford University Solid-State Laboratories for this application, and has been described previously by Gary and Linvill [4], and Brugler *et al.*, [5]. The phototransistors are operated in the charge-storage mode [6] with a storage time of about 5 ms. Thus the image is updated every 5 ms, several times more frequently than necessary to be within the perceptual time of the user.

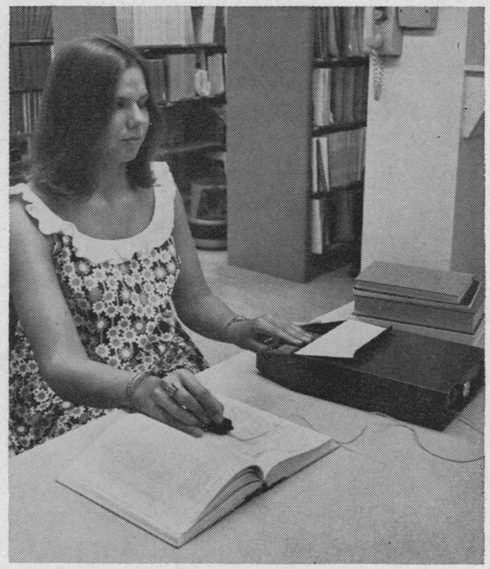

Fig. 1. Portable model of the reading aid. This model, designed for personal use by a blind person, incorporates the features of the previously described models of the reading aid plus battery operation, adjustable magnification, and reduced size.

As the probe is moved across the printed page, images of the print are sampled by the 24-by-6 phototransistor array. The phototransistor signals are multiplexed over six wires to the tactile stimulator drive transistors as shown in Fig. 2. An automatic threshold-control circuit frees the reader from all adjustments as he changes from mat to glossy paper. This threshold-control circuit adjusts the black–white decision boundary to a fraction of the peak signal from one column of the phototransistor array averaged over about 10 seconds.

Tactile Stimulator Properties

Of the various physical possibilities for tactile stimuli we chose mechanical vibration because of the convenience and simplicity of the piezoelectric bimorph as a stimulator, and because a nonpainful sensation is obtained with good two-point discrimination. In addition, these stimulators require less power than any we have found, and they can be closely packed relatively easily.

A piezoelectric reed mounted as a cantilever is illustrated in Fig. 3. Such reeds are constructed of lead zirconate and are commonly used as generators in phonograph cartridges. In the reed illustrated in Fig. 3, the upper and lower surfaces are coated with nickel and serve as the electrical terminals. The center conductor is a thin brass sheet. Under application of voltage of proper polarity, the upper lead zirconate slab contracts longitudinally, the lower one extending. The result is that the reed flexes and the end deflects upward. The opposite polarity of voltage has the opposite effect.

In our application a short 10-mil diameter wire is fastened to the free end of the bimorphs along a vertical axis as shown in Fig. 3. The array of free tips is accu-

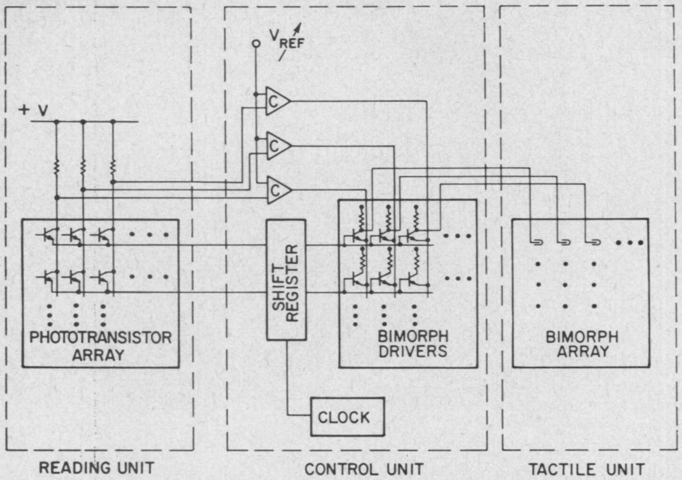

Fig. 2. Simplified block diagram of multiplex electronics. The shift register specifies which row of six bimorph drivers is to receive signals from the six phototransistors in the corresponding row. Thus, the phototransistor signals are transferred, one row at a time, to the bimorph drivers, over six wires.

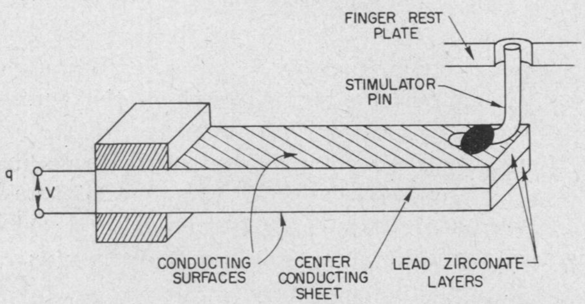

Fig. 3. Piezoelectric bimorph reed mounted for use as a tactile stimulator.

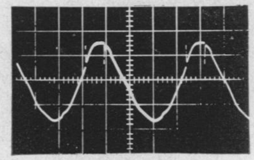

Fig. 4. Position of the bimorph with small voltage spikes superimposed to show interval during which bimorph is in contact with the finger. Horizontal scale: 1 ms/div. Vertical scale: 2.5 mils/div.

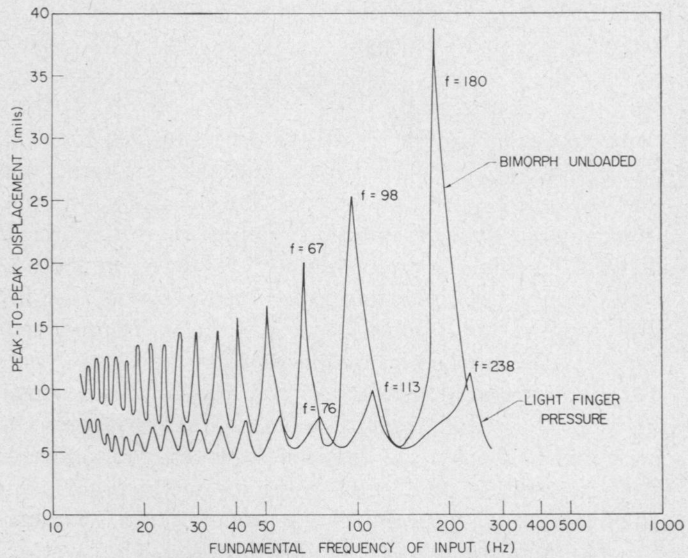

Fig. 5. Bimorph deflection as a function of the repetition rate of 2.6-ms driving pulses.

rately positioned with respect to a perforated plate that is curved to fit the finger. The pins move through a 40-mil hole to impact the skin. This mode of tactile stimulation has been studied by Rogers and some results follow.

The most intense sensation is felt when the rest position of the skin is slightly above the rest position of the bimorph pin tips. Under this condition the bimorph tip impacts the skin, and contact between the skin and the pin is broken each cycle of bimorph vibration as shown in Fig. 4. This figure shows that the peak-to-peak swing of the bimorph is 8.3 mils, but only a small portion of this occurs while the bimorph is in contact with the finger. The depth of skin indentation was about 2.6 mils or 65 microns. The duration of the skin contact under the conditions illustrated was approximately 0.8 ms out of the total period of 4.3 ms or about 67 degrees. This was roughly the maximum indentation that could be obtained on this subject's index finger.

Fig. 5 illustrates the resonant characteristics of this stimulator in both loaded and unloaded conditions. For these curves, the bimorph stimulator was driven with a 0-to-30-volt pulse, 2.6 ms in duration, and the period was varied in order to give fundamental frequencies from 12.5 to 250 Hz. As shown in Fig. 6, the bimorph invariably responded to these pulses by ringing at or near its major resonant frequency. In Fig. 5 it is the peak-to-peak amplitude of the first cycle of response after each drive pulse that is plotted for each driving frequency.

The upper curve in Fig. 5 is for the bimorph vibrating in free air. The lower curve is for the same bimorph when it was allowed to contact a finger during a portion of its upward swing. Note that loading the bimorph stimulator greatly reduces the peak-to-peak amplitude and also raises the resonant frequency. Also, notice that the peak in the response versus frequency plots do not occur at exact integral divisions of the fundamental. In particular, the peaks are closer together with the bimorph unloaded and farther apart under load than would be expected by integral divisions of the corresponding observed fundamental. (Figs. 4, 5, and 6 are for one bimorph and slightly different results would be expected from other bimorphs.)

Method for Displaying Several Intensity Levels

The existence of these peaks in response below resonance suggest a method for achieving a graded intensity of stimulation corresponding to "tactile grey." For example, in our reading aid, if the threshold level distinguishing between black and white was sequentially varied through four discrete levels, stimulators corresponding to fully black portions of the image would be pulsed every cycle and thus near their resonant frequency; stimulators corresponding to gray portions of the image would be pulsed every other cycle or every third cycle of the clock frequency, depending on which of the four

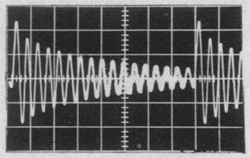

Fig. 6. Lightly loaded bimorph driven by rectangular pulses 2.6 ms in duration and 80 ms apart. Horizontal scale: 10 ms/div. Vertical scale: 2.5 mils/div.

threshold levels their phototransistor signal exceeded. This four-level grey scale should improve the image quality of the letter shapes as has been shown in facsimile systems. We are presently experimenting with this system.

Our experiments have also shown that the bimorph response to various electrical waveforms can be predicted by Fourier analyzing the drive waveform, if the bimorph response to purely sinusoidal waveforms is known. Since the bimorph essentially filters out all drive frequencies other than the fundamental, as a good approximation only this component need be considered. This means that drive pulses of very short duration will give the same deflection waveform as a purely sinusoidal drive signal, and this property is useful in multiplexing signals into an array of stimulators because each bimorph does not need a separate storage element.

Many special techniques for construction of piezoelectric bimorph stimulator arrays have been worked out by J. A. Baer and J. P. Gill. The bimorph reeds are individually tested and carefully selected on the basis of resonant frequency. The method of mounting the reeds has progressed through many stages to the present techniques based on mounting the reeds in epoxy, which permits 40-mil wide reeds to be positioned on as small as 45-mil centers.

An example of a finished array using these techniques is shown in Fig. 7. This is a 24-by-6 array with the rows on 50-mil centers and the columns on 100-mil centers.

For several months several complete reading aids have been operational. A description of some tests with these reading aids follows. Lesbarkeit

1) *Legibility:* To verify directly the design resolution requirements for the reading aid, a legibility experiment was performed. Random strings of upper-case letters and numbers and lower-case letters were printed in four sizes of Mid-Century typescript. (This printed material was identical to that used by Arps *et al.*, [7]). Each letter and number was manually scanned with the reading aid by two sighted and two blind subjects. All four subjects were instructed to take as much time as they needed to make each identification. The sighted subjects made their identifications by observing the light display and the blind subjects used the tactile array. The performance of each group is shown in Fig. 8. Legibility in the 92–98 percent range was obtained at the letter-space height for which the reading aid was designed (i.e., 160 mils or 24 samples across the height of the letter space). Since the size of the letters on the light display in no way taxed visual acuity, the sighted subjects' performance primarily

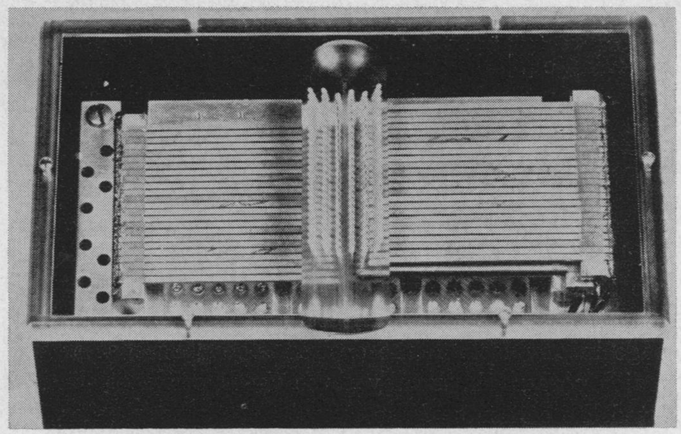

Fig. 7. Tactile stimulation array. The 24-by-6 array of tactile stimulators fits on one fingertip. The stimulator pins are spaced 50 mils apart along the finger and 90 mils apart across the finger. The perforated surface is curved to fit the finger.

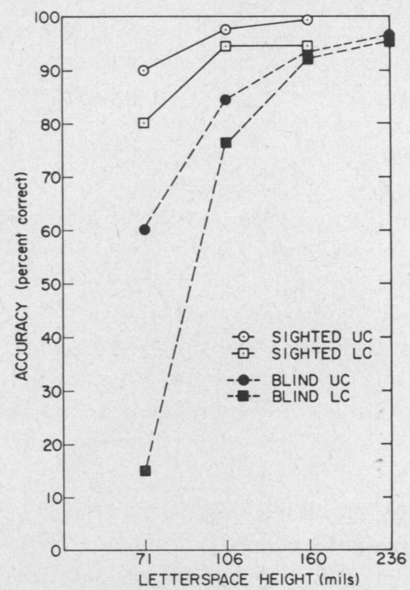

Fig. 8. Reading-aid-output legibility as a function of letter-space height. Recognition accuracy on random strings of upper-case letters and numbers UC, and on lower-case letters LC, was measured for sighted subjects observing the light display and for blind subjects using the simulator display.

indicated sampling rate influences on legibility. For sampling rates less than the design value, legibility dropped rapidly. For example, with the 71-mil letter-space height (equivalent to about 10 photosensors across the height of the letter space), a visual lower-case legibility of 81 percent was obtained. Tactile performance was significantly worse, probably because of the smaller size of the letters, as well as the poorer resolution. Although some reading is possible with 81 percent legibility, it is slower, less accurate, and generally unsatisfactory.

2) *Reading Rate:* We have made reading-rate determinations at many stages in the development of this reading aid. With an early computer simulation of the reading aid, rates of 30 correct words per minute were obtained [1]. With an early complete reading aid, four subjects read at rates greater than 10 words per minute and two of

these subjects read at rates greater than 20 correct words per minute [2].

Our most recent reading-rate determinations, taken with the reading aid in its present configuration, are shown in Fig. 9. These measurements were taken with the subject operating the reading aid in a natural way under standardized conditions. The data reported are for one subject and materials of similar difficulty level.[1] Each of the sessions lasted approximately 2 hours. The subject read silently at her own speed and scanned the printed page in any fashion she desired. She paused after each major paragraph, usually three times per page, and related the contents of the story to the experimenter. Her comprehension was always judged to be equal to or better than that of a good-sighted reader's understanding of the material.

These experiments can be viewed as exercises in which we attempted to assess the "actual" operating characteristics of the entire device. While earlier investigations have explored various design and theoretical aspects, this was the first extended usage of the complete unit under normal conditions. Thus, these data include several sources of variation not accounted for in the earlier computer-simulation experiments. An additional burden imposed was the manual tracking task. In early experiments, a tracking aid was used, which provided very free horizontal travel and an optional locking brake for vertical movement that held line registration once it has been established. However, with the probe shown in Fig. 1 and a trained subject, this tracking aid was found to be of little or no value. However, the tracking task does impose the considerable burden of keeping its scanning rate, position, and direction coordinated with the decoding process. Closely related to this condition are the less perfect images of letters produced by phototransistor sampling of the printed page as opposed to the perfectly registered letters produced by a computer-driven display.

We were greatly encouraged by the subject's apparently steady increase in reading rate from 20 to approximately 51 words per minute over the seven-month interval that comprised roughly 128 hours of reading practice and 32 hours of highly abnormal experimental manipulations.

3) *Window Width and Mapping:* Once the reading aid was in the new configuration of Fig. 1, it was possible to recheck some of our earlier data [1] relating to the number of columns of stimulators required for adequate reading. In this set of exploratory experiments with the reading aid we duplicated those earlier manipulations, but substituted hand tracking, bimorph stimulators, and lowercase letters for computer-driven bimorph stimulators and block capital letters.

Since it is possible to consider the field of view of the phototransistor array as a "window" that moves past the letters, it is reasonable to ask how large this window should be and how many points are needed within the window for adequate resolution. Using the same subject

[1] *Malcolm X.* New York: Grove Press, 1966.

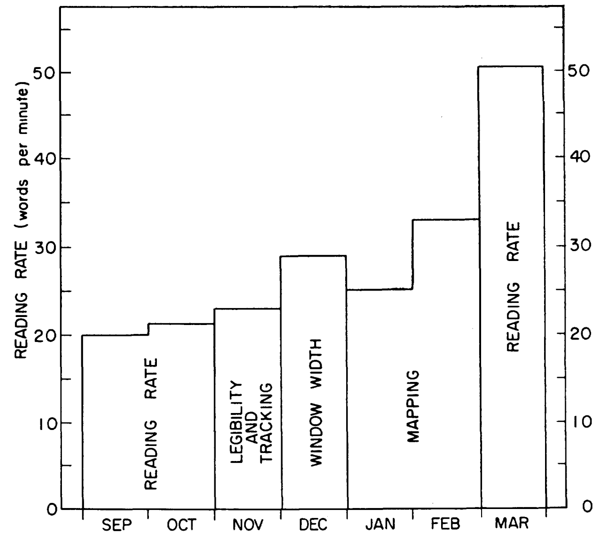

Fig. 9. Reading-rate measurements and experiments conducted on one subject from September 1968 to March 1969.

as the earlier computer experiment we varied the number of columns of data in the window from 1–6 (5 columns were not tested). The results are shown in Fig. 10.[2] As with the earlier experiment we found that reading rate increases as the field of view increases. It is important to note, however, that in both of these experiments the maximum window width did not take in any more than one character. In fact, the subject was required to perform some degree of temporal integration in all but the 6-column condition. The next logical step is to increase the field of view to take in more than one letter at a time. However, simply increasing the number of channels would impose complexity, cost, and size problems relative to the present reading aid. An obvious alternative is to reduce the density of the stimulators by distributing them over a large area. We were able to obtain some data bearing on this issue by separating the active columns in the 2- and 3-column conditions, as shown in Fig. 10. While these exploratory data are not precise enough to support a definitive determination, there is no apparent decrement within the range of separations tested.

The closely related question of the effect of various mapping configurations was also investigated during this period. The results of these configurational changes are also plotted in Fig. 10. With the exception of the 2-column condition, which did not constitute a very great distortion of the character font, none of the abnormal mappings tried seemed promising. In fact, they all seemed to produce approximately similar results. While some of

[2] The apparent decrease in reading rate between the 4- and 6-column conditions is probably due to an equipment malfunction that precluded effective stimulation by the outer columns of stimulators and probably introduced some "noise" into the image. Some strength for this interpretation is provided by the results obtained when those outer columns were driven with the same data as their immediate inboard neighbors. In this case the combined effect produces one of the best results obtained, leading to the interpretation that a completely functional 6-column array can be expected to produce greater reading efficiency than realized in this experiment. Subsequent experience has verified this expectation.

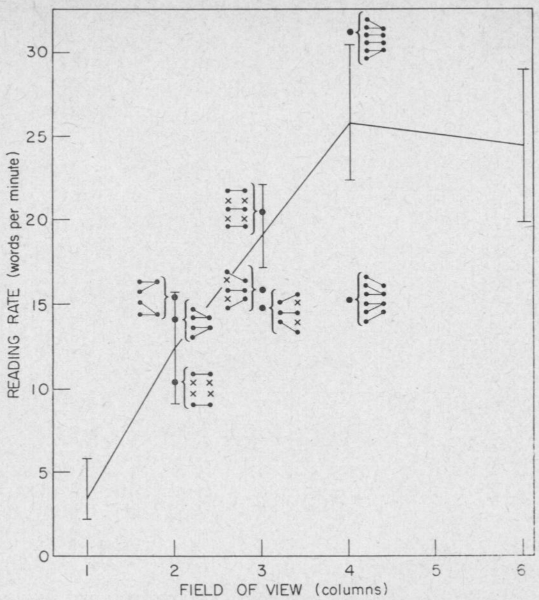

Fig. 10. Reading rate as a function of field of view and phototransistor-to-stimulator mappings. Line and vertical bars indicate results as the number of phototransistor columns is varied. Right-hand dots indicate phototransistor columns and left-hand dots indicate bimorph columns. Connecting lines indicate phototransistor-column to bimorph-column mappings.

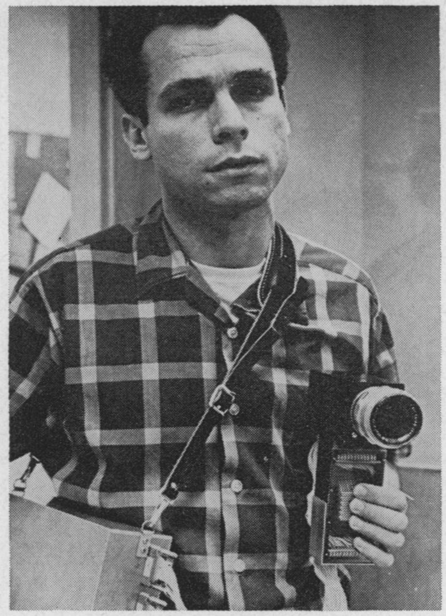

Fig. 11. Optical-to-tactile image-conversion unit for environment sensing. In the operator's left hand is the optical unit and the tactile stimulator array. Battery-operated electronics are carried under the right arm.

the variability in the data was due to the contextual problems associated with connected prose, requiring the subject to learn new character mappings in each condition also contributed to the variability.

III. An Environmental Sensor

A straightforward modification of the reading aid to extend its range of application into environment sensing can be achieved by changing the optical system. To investigate this possibility, we constructed the optical-to-tactile image-conversion system shown in Fig. 11. In this system the image formed by the lens falls on a 12-by-12 array of phototransistors. The phototransistors are functionally connected, one-to-one, to an identical array of tactile stimulators, which are in a $1\frac{1}{4}$-inch square in the handle of the device. Illumination of a phototransistor (above a threshold level) results in the vibration of the corresponding tactile stimulator. The threshold level is automatically adjusted so that reasonable operation over a 400-to-1 range of average ambient light intensity is obtained.

The field of view of the system is approximately 30°. Because the receptor array is 12 by 12, the maximum spatial frequency the device can transmit is 6 cycles/30 degrees or $\frac{1}{5}$ cycle/degree.

The normal human visual system, under optimal conditions, can resolve a grating of approximately 60 cycles/degree. By definition, this level of visual acuity corresponds to 20/20 vision. If this human terminology is applied to this device, the device may be said to have a visual acuity of about 20/6000. That is, it can at best resolve at 20 feet what the human visual system can resolve at 6000 feet. Obviously, since this is much more than legal blindness, only extremely crude images are produced.

Evaluation of the potential usefulness of such a device is a particularly difficult problem. Simple stimulus–response tasks, which are easy to interpret, do not properly measure the complex man–machine interaction that can be achieved with the device. Complex tasks are difficult to interpret by anything more than observation and anecdotal description, and these are highly subject to bias. Because of this we have attempted to develop quantitative tests and two exploratory experiments follow, one on form perception and the other involving a tracking task.

Form Detection

The purpose of this experiment was to determine how large an object had to be in order for it to be recognized on the tactile display and to compare that to the minimum size which could be recognized on the visual display. Differences between these two sizes were assumed to reflect the superiority of one modality over the other in making use of the available information, while the absolute minimum detectable sizes were assumed to reflect the limitations of the device.

The experiment consisted of presenting 44 figures (9 triangles, 7 diamonds, 3 crosses, 9 circles, 9 squares, and 7 rectangles) to the subject one at a time. The figures were white, of varying size, and taped up on a black board about 8 feet in front of the subject. He was allowed up to 1 minute to examine the figure and then asked to which of the 6 categories it belonged. He was not told whether or not he was correct and therefore, it is assumed that little or no learning occurred. The procedure was repeated three times for each of two subjects.

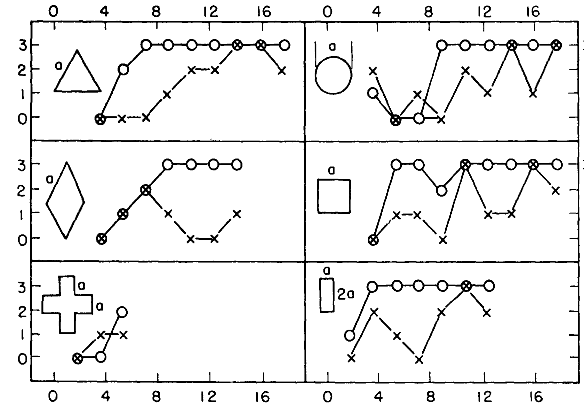

Fig. 12. Number of correct identifications (ordinate) as a function of pattern size (abscissa) for six different geometric shapes. Abscissa scale is a in degrees of field view. Tactile points are for the blind subject and visual points are for the sighted subject.

The frequency with which each figure was correctly identified is shown in Fig. 12 as a function of its size for the blind and sighted (using visual display only) subject. It will be noted that as the size of the object increases, the probability of a correct identification also increases. However, while this result is unequivocal for the sighted subject it is only marginal for the blind subject.

Although it is not surprising to find that tactile performance is inferior to visual performance, it is surprising to find that figures as large as 18° on a side (i.e., covering almost $\frac{2}{3}$ of the display) could not be reliably recognized by the blind subject. This unexpected finding, however, probably reflects no deficit at all in the tactile system but rather is due to two defects in the tactile display.

The first defect was that while the phototransistors and neon bulbs of the visual display were arranged in 12 rows in perfect register, the bimorphs in the tactile display are arranged in 12 staggered rows. Consequently, forms with straight edges were imaged with straight edges on the visual display, but with jagged edges on the tactile display. The second defect in this particular tactile display was that all bimorphs did not respond with equal intensity.

Tracking

In an attempt to measure the effectiveness of this device in a situation requiring more complex subject behavior, we devised a tracking task. In this experiment the hand-held part of the device was mounted on a tripod. The yaw rotation of the device on the tripod was coupled to a potentiometer that sent a signal to a LINC-8 computer specifying the angular direction of the field of view of the device. The computer in turn controlled the horizontal position of a light spot on a screen by means of a servo motor. Using this apparatus, tracking performances with the tactile and visual displays were compared under several conditions including the following.

a) A 12° spot of light was projected onto a white screen and randomly moved back and forth over a 90° range. The subject's task was to keep the spot centered on the display.

b) This condition differed from condition a) only in that the screen was not uniformly white but rather was a black and white striped grating with a period of 24°: the spot was completely lost when it fell on a dark bar.

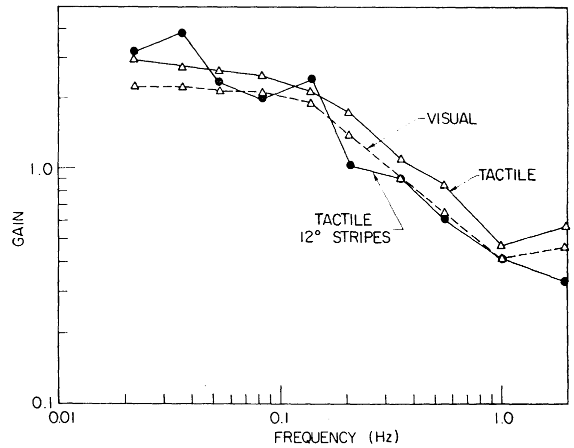

Fig. 13. Pursuit-tracking gain as a function of frequency with the environment sensor.

The data, consisting of the record of the subject's positioning of the device, were analyzed by the computer in real time to determine the subject's open-loop gain as a function of frequency. This measurement technique is common in the study of servo systems and is frequently applied to pilot behavior in aircraft. The particular technique used here is described in detail by Bliss [8]. The higher the subject's gain as a function of frequency, the better the tracking performance.

Two subjects were used, a sighted subject who tracked with the light display in some runs and with the tactile display in others, and a blind subject who tracked with the tactile display.

Characteristic results from these experiments are shown in Fig. 13. The sighted subject achieved less gain at all frequencies with the tactile display than he did with the visual display (not shown) but the blind subject performed slightly better with the tactile display than the sighted subject did visually. When the 12° stripes were added to the screen, so that the spot of light could sometimes be lost, the sighted subject's visual performance changed very little, but the blind subject's performance showed less gain and a more erratic behavior than with a blank screen.

IV. Discussion

The experiments described above indicate that with somewhat arbitrarily designed tactile displays, trained subjects can achieve information rates that are practical in certain situations. Even though psychophysical and neurological considerations had a relatively small influence in the design of these arrays, subject performance appears to be primarily limited by the devices rather than the tactile modality.

However, there were at least two instances in which tactile performance appeared to be inferior to visual in these sessions. For example, in the legibility experiment with one-half size letters, tactile legibility was considerably worse than visual. Also, in the form discrimination and tracking experiments, tactile performance appeared to be more disrupted in the more complex versions of these tasks than visual. Whether these differences between visual and tactile performance would disappear with more extended training is not clear.

Thus, we are reaching the point where psychophysical, perceptual, and neurological considerations should be taken into account to a much greater extent in the design of the displays in order to optimize performance. This brings up several questions, such as, "Does present knowledge of the tactile system suggest vastly different displays than those as yet tried?" "What additional knowledge of the tactile system is needed to develop a foundation for the design of tactile displays?" and "What experiments would help determine promising approaches for new tactile displays?"

References

[1] J. G. Linvill and J. C. Bliss, "A direct translation reading aid for the blind," *Proc. IEEE,* vol. 54, pp. 40–51, January 1966.

[2] J. C. Bliss, "A relatively high-resolution reading aid for the blind," *IEEE Trans. Man-Machine Systems,* vol. MMS-10, pp. 1–8, March 1969.

[3] J. C. Taenzer, "Visual word reading," *IEEE Trans. Man-Machine Systems,* this issue, pp. 44–53.

[4] P. A. Gary and J. G. Linvill, "A planar silicon photosensor with an optimal spectral response for detecting printed material," *IEEE Trans. Electron Devices,* vol. ED-15, pp. 30–39, January 1968.

[5] J. S. Brugler, J. D. Meindl, J. D. Plummer, P. J. Salsbury, and W. T. Young, "Integrated electronics for a reading aid for the blind," *IEEE J. Solid-State Circuits,* vol. SC-4, pp. 304–312, December 1969.

[6] R. C. Joy and J. G. Linvill, "Optoelectronic circuitry for a reading aid," *IEEE J. Solid-State Circuits* (Correspondence), vol. SC-3, pp. 451–453, December 1968.

[7] R. G. Arps, R. L. Erdmann, A. S. Neal, and C. E. Schlaepfer, "Character legibility versus resolution in image processing of printed matter," *IEEE Trans. Man-Machine Systems,* vol. MMS-10, pp. 66–71, September 1969.

[8] J. C. Bliss, "Human operator describing functions with visual and tactile displays," 3rd Annual NASA University Conference on Manual Control, *NASA SP-144,* pp. 67–80, 1967.

[9] J. C. Meindl, J. D. Plummer, P. J. Salsbury, and J. S. Brugler, "Integrated electronics for a reading aid for the blind," *IEEE Internatl. Solid-State Circuits Conf. Digest of Tech. Papers,* pp. 50–51, February 1969.

Tactile Television—Mechanical and Electrical Image Projection

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***Abstract*—The feasibility of communicating pictorial information through the skin has been demonstrated. A tactile television system has permitted blind subjects to determine the position, size, shape, and orientation of visible objects and to track moving targets. The system comprises 1) a vidicon camera utilizing a zoom lens, 2) a digital switching matrix to sequentially connect each element of the photocathode surface through a single video amplifier and signal conditioner to each of the 3) 400 tactile stimulators in a 20 × 20 matrix in contact with a 10-inch square of skin. This image-projector matrix impresses on the skin a two-dimensional vibrating facsimile of either the silhouette or the outline of a visible object. The single-channel swept system exhibits inherent economies when a great number of picture elements is to be processed.**

Since the fovea of the human eye subserving the central two degrees of detailed vision is comprised of cone cells in a matrix about 200 receptors across, the present 20-line system permits picture transmission with a linear resolution about one-tenth that of the fovea, and has proved adequate for the recognition of human faces. Calculations indicate that the input capacity of the skin of the trunk should compare favorably with that of the fovea.

We have determined the electrical-stimulus parameters for painless stimulation of the sensation of mechanical vibration with small electrodes in a closely spaced matrix. By this means it appears to be feasible to construct a light-weight, economical, and portable tactile television system to be worn by the blind as a seeing aid.

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I. Introduction

The possibility of transmitting optical information to the brain by a pathway other than the eye allows the consideration of an exciting new class of sensory aids for the blind. This technological challenge has been addressed by many groups. Since the original investigations of Noiszewski in 1897 [1], numerous experiments have been performed to determine the feasibility of using the skin as a receptor of images normally perceived by the visual system. Starkiewicz and Kulizewski have reported a 120-photocell array with transistor-energized solenoids for producing mechanical images on the fore-