PROCEEDINGS

1972 CARNAHAN CONFERENCE ON ELECTRONIC PROSTHETICS

UKY TR60-72-EE4

DECEMBER 1972

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JOHN S. JACKSON, EDITOR
R. WILLIAM DE VORE, ASSOCIATE EDITOR

CARNAHAN HOUSE
UNIVERSITY OF KENTUCKY
LEXINGTON, KENTUCKY

DEDICATION

This record of the Proceedings of the 1972 Carnahan Conference on Electronic Prosthetics is dedicated to four men whose professional accomplishments have so greatly benefitted the handicapped throughout Kentucky.

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THERAPY FOR CEREBRAL PALSY EMPLOYING ARTIFICIAL SENSE ORGANS FOR ALTERNATIVES TO PROPRIOCEPTIVE FEEDBACK

by

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Introduction

Federal assistance for the education of handicapped children, provided through Title VI-B funding,* has made it possible to bring concepts from neurophysiology and hardware from bioengineering to bear on the stability and mobility problems of athetoid cerebral palsied (CP) children. A team comprised of a neurophysiologist, an electrical engineer and an electronics specialist have devised artificial sense organs and feedback devices which are utilized by physical and occupational therapists in treatment of CP children in the Orthopedic Wing of the Lowell School in Seattle, Washington. The project represents a major facet of the Program for the Physically Handicapped in the Special Education Department of the Seattle Public Schools.

Rationale

While clinical neurologists traditionally view athetoid movements (described as wormlike, random, purposeless, writhing movements of the head and extremities)(1) made by CP individuals as a direct expression of pathological neuronal discharge patterns intrinsic to damaged subcortical motor centers, modern engineering concepts provide an alternate explanation for "involuntary movements" in terms of defective control system function. What have been viewed as primary motor disturbances may actually be sensory disturbances, in that alterations in muscle stretch receptor sensitivity might distort proprioceptive feedback to the point that postural stability and the execution of smooth voluntary movements are impossible (2). An obvious possibility for the production of changes in stretch receptor sensitivity (either in the direction of derangement or towards compensatory readjustment) exists by virtue of the control of stretch receptors through the gamma efferent system (3). An indication of the actual occurrence of such derangement is that some children reporting on the subjective experience of passive manipulation or active movement of their extremities give the impression that they receive no information about limb position via proprioceptive channels (except for joint pain felt at the extremes of the range of motion).

The postulate that athetoid movements of the head and limbs result from impaired proprioceptive feedback is being tested by devising artificial sense organs which provide feedback over auditory and visual pathways to inform CP children of the positions of their heads and extremities. The substitute feedback systems for head and limb position control use sensors patterned after receptors in the vestibular system and joint-angle receptors,

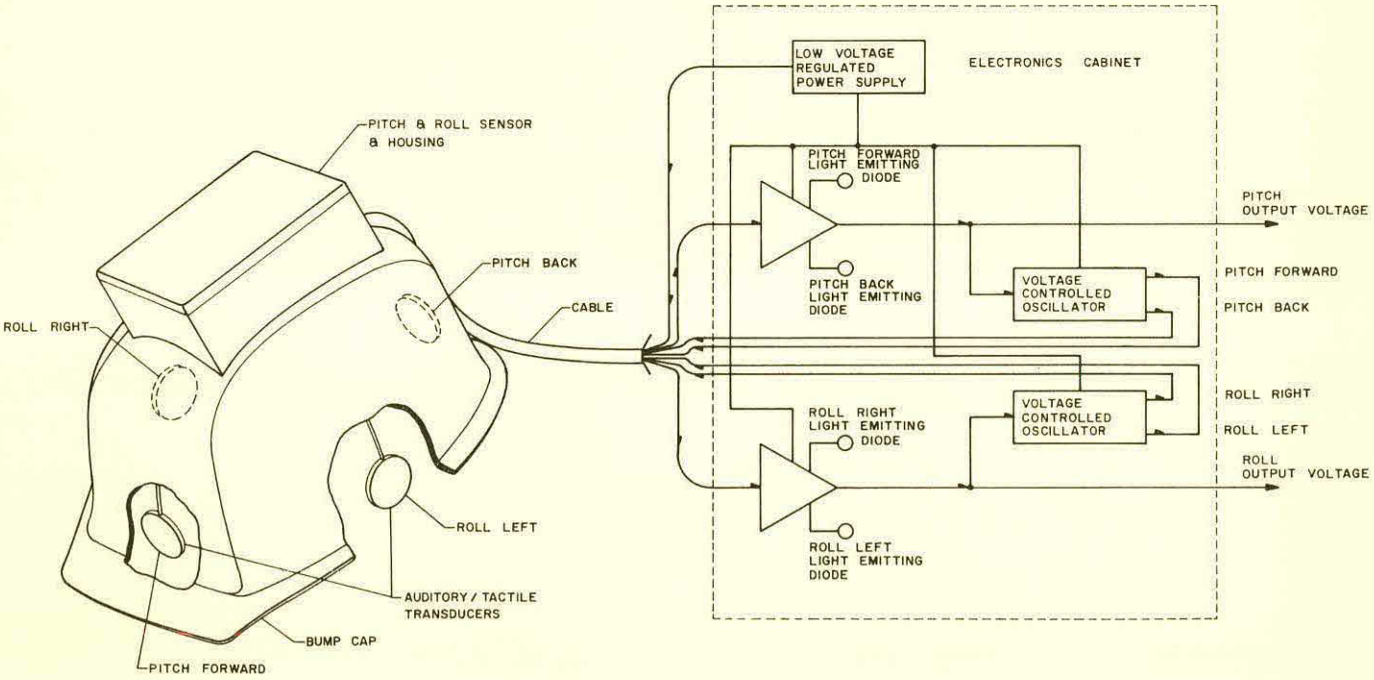

FIGURE 1. Block diagram of a balance control device.

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* Title VI-B, ESEA, under P.L. 89-313, HEW Office of Education.

respectively. Provision is made in each system for automatically reinforcing the children for their efforts at position control using information obtained via the alternate feedback channels. Comparisons of postural stability and quality of voluntary movement, sampled with and without the use of the assistive devices, are made for each child through the use of filmed examples of particular postures and movement activities.

Balance Control Device (BCD)

The BCD employs mechano-electrical transducers (rotational potentiometers with pendulums attached to their shafts) to measure fore-and-aft and side-to-side tilt of the head. The two transducers are mounted on, and the stimulators for auditory feedback mounted within, a helmet worn by the subject (Fig. 1). Tilt is converted to rotation of the potentiometer shafts via the pendulums; the potentiometer outputs are then converted to a pulse frequency code by voltage-controlled oscillator circuits. The oscillators drive piezoelectric "unimorphs" which produce a click sound for each pulse. As the head deviates from the neutral position, the subject hears clicks emanating from the unimorph positioned on the side of the helmet toward which the head is tilting. Click frequency increases linearly with tilt (accurate to 2 per cent within the range of plus or minus 20 degrees). Thus the subject "hears" his head position in terms of the pattern of sound within the helmet, and "steers" towards a neutral head position indicated by near or total absence of sound in both fore-and-aft and side-to-side channels. In daily prescribed activities, the child uses proportional feedback from his auditory system to systematically exercise the neck muscles which stabilize his head. (He practices with each channel separately before attempting simultaneous control of both axes of tilt.) The sensitivity of each channel can be increased gradually to progressively "shape" better and better head control.

Secondary visual feedback is provided via four-light emitting diodes, each one representing the direction of tilt to which its illumination corresponds by its position on the control panel. The visual feedback, while not proportional, helps the child discover the direction of deviation of the head quickly. Those children who can use both auditory and visual cues simultaneously generally perform very well. An automatic positive reinforcement mechanism incorporated into the system is especially valuable for working with children who have difficulty understanding verbal instructions or who otherwise lack motivation for utilizing alternate channels for monitoring head position. If the head is held within pre-set limits of tilt (adjustable to suit the stage of training), a control unit actuates a movie projector which displays a cartoon for the child to watch. The film drive is stopped each time the head tilts too far, and re-activated when the head is brought back within the desired limits.

Both line voltage-powered and battery-powered versions of the head control system have been developed and tested. The latter unit provides only auditory feedback, but allows the child complete freedom of movement. When the counter with which it is equipped is connected to a readout unit, the counter displays the total number of pulses accumulated while the head was tilted too far along either axis. Using the couter in the classroom will enable us to measure the carry-over of head position control learned in therapy sessions.

Limb Position Monitor

The limb position monitor (LPM) uses potentiometer-based transducers to measure the angle of ro-

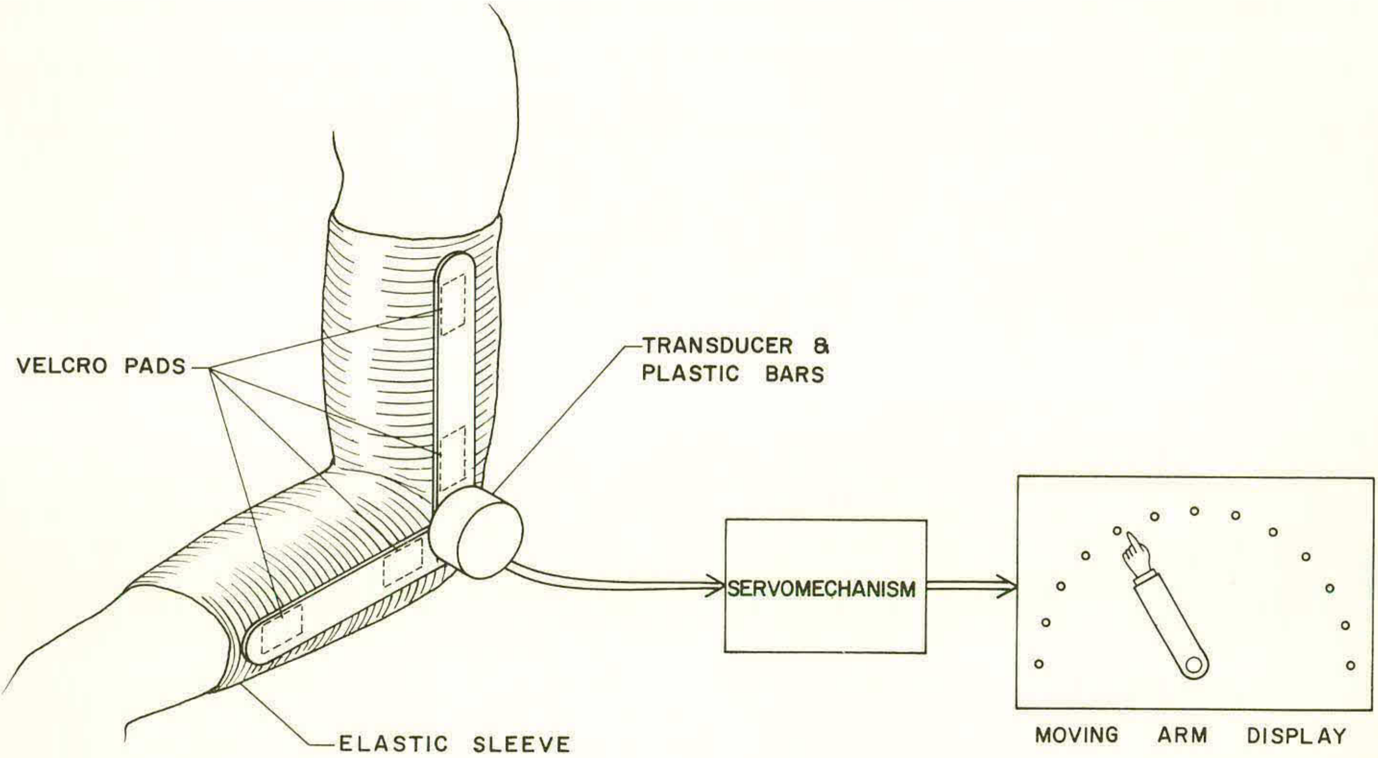

FIGURE 2. Limb position sensor.

tation about the elbow or wrist joint. The potentiometers are mounted on goniometers positioned at the elbow or wrist joint so that their shaft rotation corresponds to the angle between the goniometer arms. The proportional voltage corresponding to the amount of rotation activates a servo motor which moves a small dummy arm through the same angle (Fig. 2). The child monitors the position of his own arm by watching the corresponding movements of the dummy arm. A display panel behind the dummy arm, in the form of a protractor with the pivot point of the joint in question at the middle of the baseline, indicates 180 degrees of possible rotation.

Initially, the child is asked to move his elbow or wrist joint over whatever range of motion is permitted by his innate muscle tone and motor control. Smoothness of the movement is encouraged, along with stopping the movement at the same upper and lower limits each time. Then the child is instructed to move his arm or hand in such a fashion that the dummy arm swings smoothly back and forth between the extremes of a range of motion which the therapist indicates by positioning marker lights in any two of the sockets which demarcate 10 degree intervals throughout the 180 degree arc. An auditory signal (a slightly unpleasant sound, so that the child tends to avoid rather than promote its production) informs the child if he exceeds the upper or lower limits of the desired motion . As control is gained, the range of allowable motion is gradually diminished by moving the marker lights closer together. Finally, only one light is left on and the child is instructed to keep the finger of the dummy arm pointed at that light as long as he can. Here the child gains experience moving his arm, and in holding the arm still at various positions, with accurate visual feedback as to the results of his efforts.

Data Collection

To date, seven children have served as subjects in the study. Six of these are cerebral palsied, of the athetoid type, and one has a brachial plexus injury due to birth trauma. Of the CP children, three are using the LPM; one uses the BCD; and two are using both devices. The child with the brachial plexus injury is using only the LPM; the intent is to encourage her use of the affected arm by giving her visual feedback about the success of her efforts. (The fascination of action-at-a-distance seems to make seeing the dummy arm move far more rewarding than seeing her own arm move.) All of the children have been given 30 minutes of daily therapy utilizing the devices during the school week, in addition to regularly scheduled conventional therapy, over periods varying from two to five months.

At present, changes in the amplitude of any tremor or oscillation present, in the duration over which the child can hold the head or arm stationary, and in smoothness of deliberate movements of various amplitudes are assessed on the basis of cinematographic records. The therapists filmed initial control sessions and re-film the children's activities at regular intervals. The therapists also keep daily progress notes including objective data (sensitivity settings, deviational thresholds, duration of holding postures) and subjective comments (smoothness of movement, muscle tone, presence of associated movements and/or drooling). Provision has been made for recording analog transducer outputs on a strip chart recorder in the near future.

Results

The films and numerical data show that athetoid CP children can be assisted via mechanoelectric "artificial sense organs" to gain better control over postural stability and voluntary movement. Duration of holding a fixed posture can be increased (in some cases by a factor of two or three fold), oscillation decreased or eliminated, muscle tone normalized, and smoothness and accuracy of movements improved. One child using the wrist sensor achieved full joint range of motion with normalized tone by the end of last school year.

Also, an observation which holds for all the children is that while the child concentrates on controlling an individual limb or his head, there seems to be a generalized lessening of extraneous associated movements of the rest of the body. (This may reflect an increase in sensitivity of stretch receptors, permitting better control, due to elevated gamma efferent outflow.) In particular, movements of the mouth are lessened and there is less drooling. This effect often persists after the end of the therapy session.

Instances of functional carry-over into the classroom of the beneficial effects of treatment utilizing these devices have been documented. One child, when requested while in speech therapy to reproduce the stability of head position which she had achieved while using the BCD in physical therapy, could find and hold the neutral position without the use of a mirror. Another child made fewer errors than usual in depressing typewriter keys with the use of a head wand during the half-hour period immediately following a session of treatment using the head control device.

Future Projections

Additional artificial sense organs will be devised to enable children to monitor, and therapists to record and modify, the positions of other body parts critical for standing balance and ambulation. Devices also will be developed which will reinforce the child for bringing several body parts into the correct relative positions simultaneously, to teach self-feeding and other skills needed for independence.

Depending on the severity of their handicap, some children may only require the use of the assistive devices described here for a period of time, and will be weaned from them gradually as they learn to "tune up" their proprioceptive channels or to monitor limb position via natural alternate channels. This may not be possible for others, who will require the use of similar devices on a continuing basis or even as permanent prostheses.

The devices discussed will be refined in use and means of production will be sought to make them available to more children in more therapy centers, wherever success so warrants.

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EXCESSIVE NEUROMUSCULAR TIME DELAY AS A POSSIBLE CAUSE OF POOR HAND-EYE COORDINATION AND HYPERACTIVITY

by

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Introduction

It is this writer's opinion that some children with learning disabilities (LD children) are suffering from abnormally long neuromuscular signal transport delays. Smith describes the results of tests in which an artificial time delay was introduced in the hand-eye coordination feedback loop of "normal" people (1). Effects of the artificial delay on the participants in Smith's tests are the symptoms of some LD children.

R. P. Rich of the Applied Physics Laboratory suggested informally that an abnormally long neuromuscular time delay would show up in the individual's simple reaction time and further suggested that such measurements be made of LD children. The reaction times of some LD children and some normal children were subsequently measured. This paper describes the results and compares the two sets of data. Some interesting and pertinent inferences may be derived from the results; however, the need for further testing is clear.

Reaction time frequency charts are fitted to gamma distribution curves and an accompanying supposition is put forth. An important idea regarding the use of behavior-modification drugs is stated.

Suggestions for further testing and remediation are made.

Background

The LD child is one of normal or above-normal intelligence who has a handicap that is not of the usual or obvious physiological nature and that interferes significantly with his ability to learn in a normal manner. Common disabilities are dyslexia (reading disability), hyperkinesis (abnormal amount of muscular action), dysgraphia (handwriting disability), dyscalculia (arithmetic disability), as well as several others.

Often, learning disabilities are attributed to brain injury, prenatal or postnatal. The LD child has been given many names of which "brain injured" is just one. Although hard signs of brain injury are not always present, he may still be referred to as brain injured. Hence, the following description of a brain-injured child applies as well to the LD child since he is the one and the same.

Description of a Brain-Injury Syndrome

Clements lists ten descriptors for the brain-injury (BI) syndrome (2); usually, only a few are present in one child. The first, however, applies to every LD child (by definition): it states, in effect, that the child is of near-normal, normal, or above-normal general intelligence and is not generally mentally retarded.

The following symptoms given by Clements appear to be caused by retarded neuromuscular response:

> He experiences difficulty in mastering tasks which are dependent upon intact visual-motor-perceptual integration.
>
> He experiences difficulty in printing, writing, and drawing; he exhibits poor and erratic performance copying figures and often attempts to adjust to his disability by perseverance and/or meticulous pencil strokes, etc.
>
> He is often generally awkward or clumsy in either fine muscle performance or in overall coordination, or both. He may be a victim of hyperkinesis or merely restless and fidgety.
>
> He may be highstrung, irritable, or have quick changes of emotional behavior from high temper to easy manageability and remorse; he may be panicked by what would appear to others as a minimally stressful situation.

Time Delay Effects on Performance and Behavior

Reference 1 is a compilation of reports dealing with the effects of added time delay on human performance in a closed-loop control system. The subject performs such tasks as hand tracing through a printed maze, drawing geometric figures, writing or printing, or speaking. In each case, a transport-time lag is artificially added between time of execution and the time when the subject perceives the result. The delays are achieved by diverse means, the most notable being through the use of magnetic tape recorders.

For hand-eye tasks, the subject writes on a surface hidden from his view. The writing is viewed by a television camera and recorded on magnetic tape by a recorder that is capable of playing back the signals while in the process of recording. The distance between the record and the playback heads, and tape speed, produces the time delay. The delayed playback signals are viewed by the subject on a television screen.

When a visual delay as small as 0.04 second was introduced, the general "effect on performance was disastrous" (1). The motion pattern became inaccurate and disorganized, and the subject often showed emotional disturbances and loss of motivation. Small time delays seriously affected the neatness and accuracy of handwriting. As the delay was increased, the performance worsened. Errors of additions and omissions in writing words were comparable to errors in speech that were caused by delayed auditory feedback.

The subjects experienced no significant improvement in performance through practice, although some showed improvement by shifting to short, discrete, jerky, "wait-and-see" movements. Beyond that, no improvement was derived from additional practice.

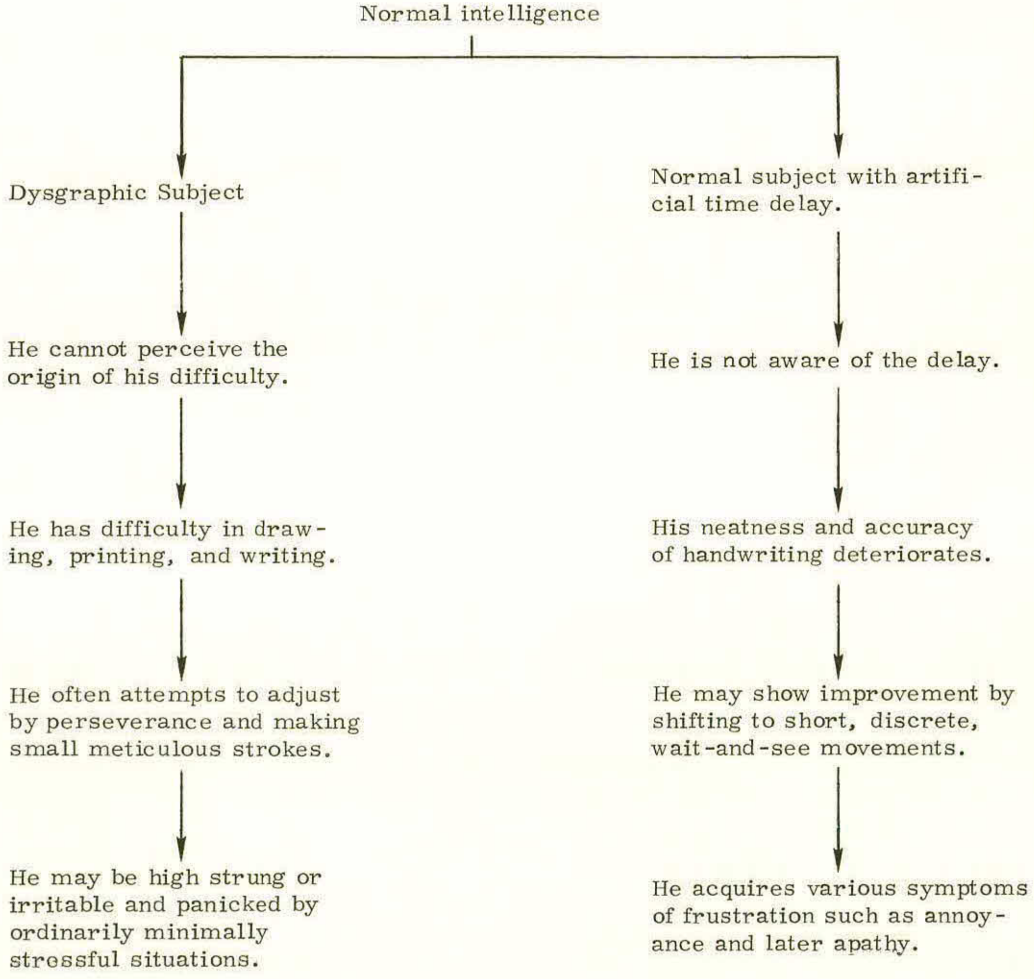
Interestingly, the subject being tested was not aware of the delay, except that the sensory effects were in some way not aligned with his performance, and continued performance produced a deterioration in perceptual discrimination.

Comparison of BI Syndrome and Effects of Artificial Time Delay

The behavior and performance symptoms of children exhibiting the BI syndrome given earlier, and those of normal people when subjected to an artificial time delay show a high positive correlation and suggest very strongly the presence of common causal factors. The characteristics of the syndrome and effects of added time delay are summarized in Table 1.

Table 1

Comparison of BI Syndrome and Effects of Artificial Time Delay



Effects of Drugs on LD Children

Medication has proven to be effective in reducing hyperactivity and irritability and in increasing the attention span of some LD children (3). The drugs one naively expects to be effective are tranquilizers, sedatives, and relaxants; but they usually do not work. For many LD children, these drugs have actually worsened their behavior problems, while stimulant drugs produce some alleviation, an effect opposite to that expected. It is noteworthy that stimulants can reduce hyperactivity and irritability and increase attention span. I would suggest that the stimulants reduce the excessive neuromuscular time delay present in many LD children.

Reaction Time Measurements

Reaction Time Meter

A simple device was designed and built to accurately measure simple reaction time. A block diagram is shown in Figure 1.

The functioning of the meter is as follows: The operator actuates the reset switch, resetting the display, extinguishing the stimulus lamp (if it was turned on initially), and starting a sequence that produces a randomly delayed pulse. After the delay, which is less than 1 second, the stimulus lamp comes on. Upon recognizing the lamp-on condition, the subject actuates a button that is mechanically coupled to a crystal phono-pickup. A pulse from the pickup stops the clock and extinguishes the stimulus lamp. The subject's reaction time is read from the display.

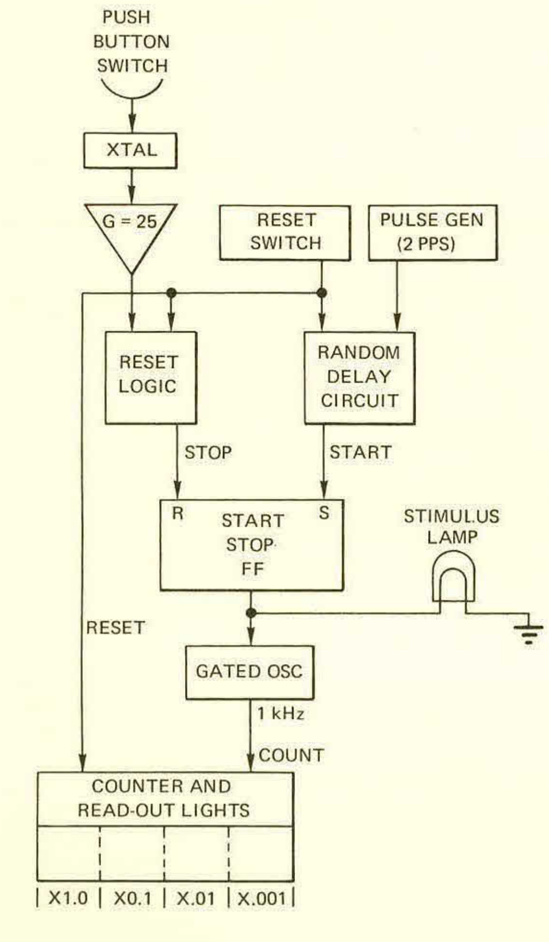


Fig. 1 REACTION TIME METER, SIMPLIFIED BLOCK DIAGRAM

Testing

The subjects were instructed simply to watch the light and press the button as fast as possible, when the light came on. They were encouraged to be poised with a finger lightly in contact with the button. Each subject was observed to see whether his attention was on the task. Results were ruled out when the subject was clearly inattentive. No warning was given; however, the wait time was never longer than a few seconds.

Processing and Plotting the Data

Data have been gathered from 14 subjects thus far. Some of the data have been processed to derive their means and variances. Frequency plots have been made and curve fitting has been done, the results of which are discussed under <u>Conclusions</u>. Means and variances of the reaction times (R_T) of the subjects are shown in Table 2. Age, sex, and an indication of whether the subject is an LD child, a suspected (possible or likely) LD child, or a nor-

Table 2

Listing of Average Reaction Time (R_T) and Standard Deviation (S. D.) of Various Normal and LD Children

Subject	Age	Sex	R_T	S. D.
Not LD:				
JDM	15	M	0.221	0.028
PK	12	M	0.210	0.033
AH	10	M	0.258	0.070
Possible LD:				
EP	14	F	0.261	0.054
GF	14	M	0.243	0.068
Likely LD:				
MD	10	M	0.317	0.139
SLM	10	M	0.323	0.065
LP	9	F	0.319	0.064
DL	9	M	0.341	0.100
PD	9	M	0.349	0.112
SP	8	M	0.392	0.101
LD:				
KDM	12	M	0.324	0.100
PT	8	M	0.379	0.065
RG	6	F	0.412	0.128

mal child are indicated. Also, the reciprocals of the mean values are plotted in Figure 2, which shows that the mean R_T values of LD children fall into a class separate from the others.

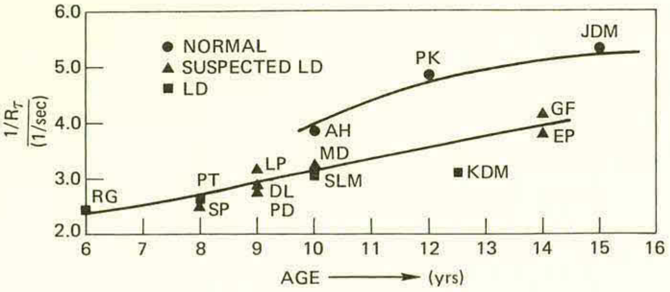


Fig. 2 RECIPROCAL OF AVERAGED REACTION TIMES OF VARIOUS NORMAL, LD, AND SUSPECTED LD CHILDREN

Characteristics of the Subjects

Figures 3 through 8 are frequency plots of reaction times from five subjects. (Figures 7 and 8 are plots of data obtained from subject PT under two different conditions, as described in the section, Use of Stimulant Drugs.)

Subjects JDM and AH are both well coordinated and high achievers; they are not LD children.

Subjects KDM and PT are of average or above-average intelligence, but have poor hand-eye coordination. Both were diagnosed as LD children, and placed in special education classes. Subject KDM is now in regular class where he is a marginally average achiever; he has a low frustration tolerance. Subject PT is hyperactive.

Subject SLM has always been in regular class and has above-average intelligence. He has poor hand-eye coordination and a low frustration tolerance; he is suspected of being an LD child.

As shown in Table 2, subjects KDM, PT, and SLM have much longer mean reaction times than do subjects JDM and AH, the well-coordinated high achievers. This fact supports the idea that some LD children have poor hand-eye coordination due to excessive neuromuscular time delays.

A comparison of Figures 3 and 5 shows that KDM's response is not only slow, but also occurs with great variation in the delay. Note that his delay varies over a span of 233 ms, a value greater than the mean for JDM (a normal youth).

Implications

The frequency plots show that there is a large constant value (greater than 130 ms) in each reaction time measurement and that it is different for each subject, which would be expected. Since each subject tested is intelligent and the children with poor hand-eye coordination have long reaction times, it is reasonable to speculate that their difficulty is related to the longer delays.

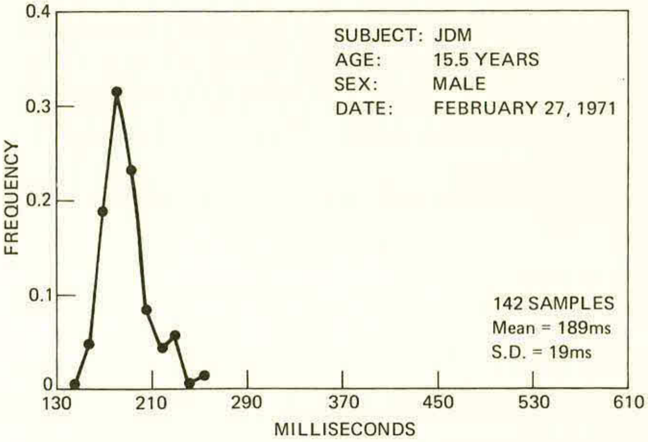


Fig. 3 REACTION TIME FREQUENCY PLOT, JDM

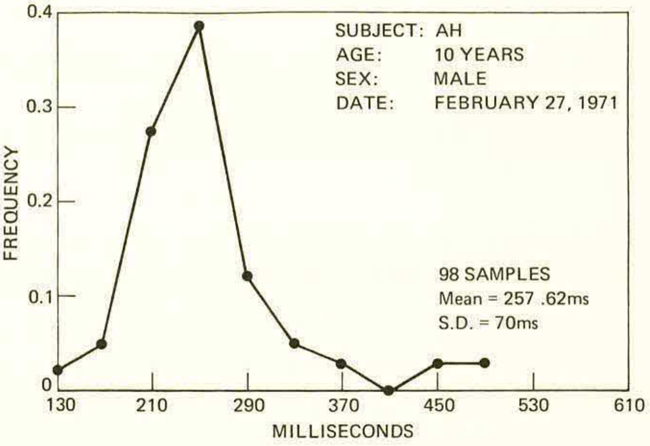


Fig. 4 REACTION TIME FREQUENCY PLOT, AH

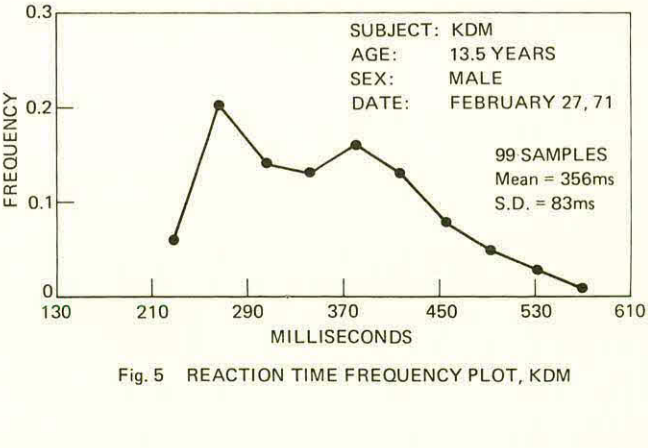


Fig. 5 REACTION TIME FREQUENCY PLOT, KDM

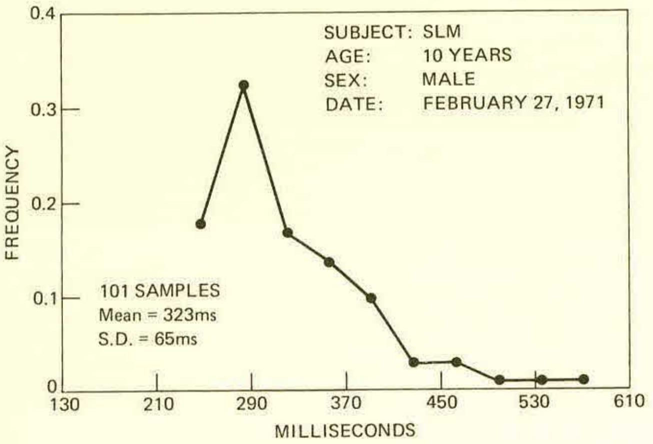


Fig. 6 REACTION TIME FREQUENCY PLOT, SLM

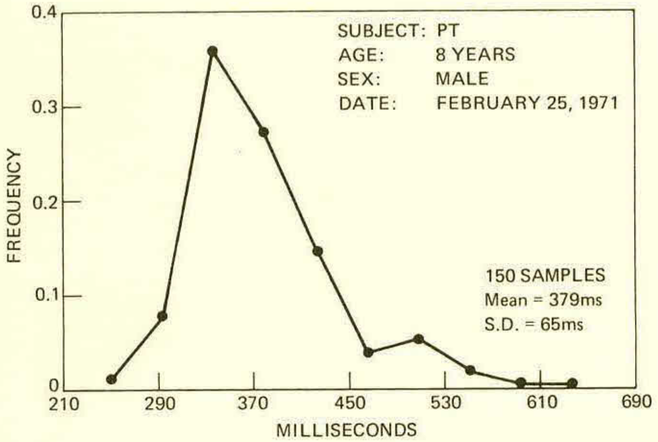


Fig. 7 REACTION TIME FREQUENCY PLOT, PT

Mathematical Analysis of Results

The shape of the frequency plots fits very well the gamma (Γ) probability density curve, as shown in Figures 9 and 10 for the subjects JDM and KDM. The distribution is described as follows (4):

$$g(t) = \frac{\alpha^r t^{r-1} e^{-\alpha t}}{\Gamma(r)}, \qquad (1)$$

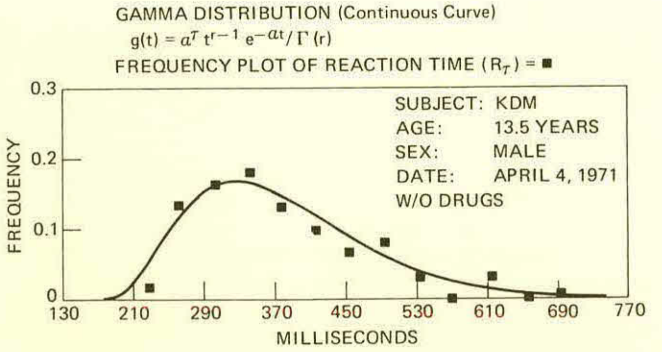


Fig. 9 FREQUENCY PLOT AND GAMMA DISTRIBUTION CURVE, KDM

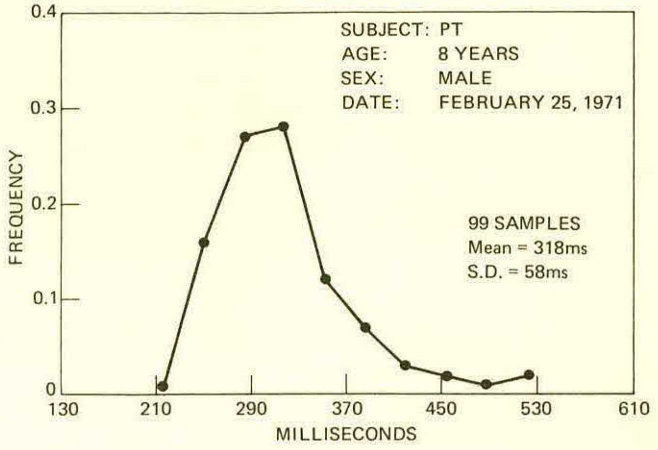


Fig. 8 REACTION TIME FREQUENCY PLOT, PT, WITH RITALIN

where the expected value (mean) is

$$E(t) = r/\alpha, \qquad (2)$$

and the variance is

$$V(t) = r/\alpha^2 = \frac{E(t)}{\alpha}. \qquad (3)$$

The parameters α and r were determined from the means and variances, which were calculated from the collected data.

The value of r varied from approximately 3 to 5 for different subjects. However, the value $r = 5$ was used to synthesize the distribution curves, because the set of data that produced that value (obtained from subject JDM) appeared to be the most reliable.

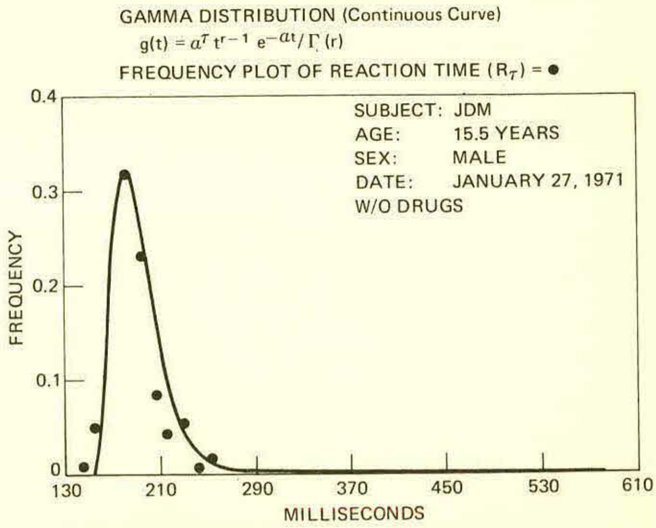


Fig. 10 FREQUENCY PLOT AND GAMMA DISTRIBUTION CURVE, JDM

The gamma distribution, Eq. (1), obtains from a cascade of exponential distributions (Eq. (4)):

$$f(t) = \alpha e^{-\alpha t} \tag{4}$$

The gamma distribution, Eq. (1) with $r = 5$, is derived from a cascade of five stages, each stage having an exponential distribution. Each stage has a variable time delay that is passed on to the next stage where a new time delay begins. Equation (1) results from convolving the exponential distributions using the equation for the distribution of the sum of a finite number of random variables. Equation (5) is the convolution equation and is discussed in Reference 3.

$$f(t) = \int_{-\infty}^{+\infty} g(\tau)h(t-\tau)dt \tag{5}$$

The smooth curves of Figures 9 and 10 were generated on an analog computer by simulating five exponential functions (Eq. (4)) and using each to drive the next. The first function was driven by an approximated impulse function (a short pulse) to obtain the impulse response of the complete chain.

The time constant of the individual exponential functions is equal to α, which was calculated for each subject. The shape of the simulated curves fits the measured data with unusual accuracy. Therefore, it appears that the neuromuscular signal from a visual input to a simple hand response may pass through five successive stages, each with an exponential probability time delay as described in Eq. (4).

Use of Stimulant Drugs

The subject PT receives the stimulant Ritalin to help him cope with his difficulties. The medicine reduces his hyperactivity, improves his hand-eye coordination, and increases his attention span.

It is generally reported that the stimulants reduce hyperkinesis by slowing the child down or "drugging" him. Two sets of reaction time data were acquired from PT, one 3.5 hours after receiving 5 mg of Ritalin and the other 0.5 hour after the next dose. The results, as shown in Table 2 and Figures 7 and 8, indicate a definite decrease (approximately 20 percent) in reaction time 0.5 hour after taking 5 mg of Ritalin. Possibly a greater differential would show up if he were to be off the medication for a longer period. Also, the standard deviation improved with the medication, providing benefits both in improved mean R_T (reaction time) and predictability.

Subject PT prefers, especially on weekends, not to receive the Ritalin. He seems to be happier without it. However, his behavior is then unacceptable by his parents' standards, and he is less inhibited. Possibly this child suffers ordinarily from a "high" such as normal people experience from an overdose of barbiturates and requires a stimulant to bring him toward normal. The symptoms of many LD children, uninfluenced by stimulants such as Ritalin, are remarkably similar to those exhibited by normal people after they have received an overdose of barbiturates. These symptoms are described in Reference 5, a portion of which is quoted in the Appendix.

Further Work to be Done

Need for More Data

Obviously, data from additional LD and normal children need to be taken before drawing defnite conclusions in relating hand-eye coordination and hyperkinesis to large time delays.

More data are needed also to determine how reaction times vary with the age of normal children and LD children. Follow-up data over a long term are needed to determine how an individual's reaction time varies with his age.

Other tests should be administered to determine the children's output sample rates. A person's motorcontrol system does not respond in a continuous manner, even when tracking a moving target. Rather, movement occurs at intervals of about 0.20 second for normal adults, a time value which is very nearly the same as the normal adult reaction time. If an LD child displayed sample times shorter than his reaction time, his would indeed be an uncertain control system.

Treatment of Data

Additional data should be subjected to further analysis to determine means and standard deviations, and to plot frequency graphs. These data could be used to help support or disaffirm the supposition that some LD children have excessive neuromuscular delay, and that this is the root of their problem.

Remediation

If the difficulty of poor hand-eye coordination is shown to derive from abnormally long time delays, there are a number of courses that can be pursued in helping LD children to learn such skills as handwriting and art.

Any assistance provided to the child that helps him to learn proper handwriting skills will have an everlasting effect since handwriting is an overlearned skill and, once learned, can be performed equally well whether the eyes are open or closed (except for gross spatial placements).

If a stimulant drug were administered to improve the ability to learn handwriting, it could be safely withdrawn when using that overlearned skill. The stimulant drug may, however, still be needed to reduce frustration and help the child control his social behavior and perform physical tasks. Since LD children generally, and possibly always, outgrow the need for stimulant drugs, their use should not be a long-term problem.

Computer aids could be used to help overcome the time lag while learning handwriting. Some study on this matter has been done by the writer and is discussed in the next section.

Reaction time measurements could conceivably be used to help determine the amount of dosage required to reduce each child's delay sufficiently to enable him to learn properly.

If, indeed, the problem is caused by excess delay, such children could be taught alternate methods and skills. For example, a school of painting called pointilism could possibly be taught some of the children. Pointilism utilizes colored dots to construct a picture, avoiding the need for the full hand-eye control required when making continuous strokes.

Further Investigations Using Mechanical Aids

Two methods, both using analog computer techniques, that speed up writing have been explored. One method uses electrical signals derived from a mechanized stylus, while the other uses muscle action potentials (MAP). These methods are described in Reference 6. Time gains of 30-50 milliseconds were made.

Figures 11 and 12 show, in simplified form, how the speeded-up displays are obtained. In the method shown in Figure 11, the stylus is coupled to electromechanical pickup devices that produce orthogonal voltages. The voltages are sent to a fast-time analog simulation where the predictive orthogonal voltages X(P) and Y(P) are computed. The signals X(P) and Y(P) are used to drive the X and Y axes of a storage cathode ray tube (CRT).

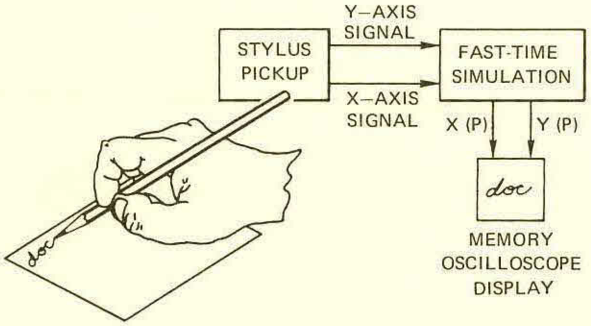


Fig. 11 SPEEDED UP DISPLAY OF HANDWRITING SIGNALS USING STYLUS POSITION SIGNALS

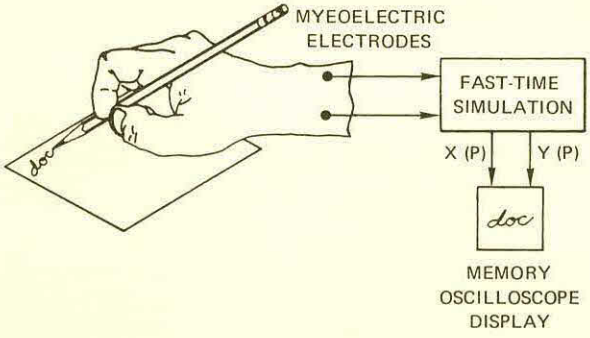


Fig. 12 SPEEDED UP DISPLAY OF HANDWRITING SIGNALS USING MAP SIGNALS

In Figure 12, the input signals to the fast-time simulation are derived from MAP signals obtained from electrodes on the subject's forearm.

The method in Figure 11 was fully instrumented to produce complete writing. Simultaneous strip chart recording of the simulation input and output signals indicated a time gain of 30 milliseconds.

The method in Figure 12 was tested using only one MAP pickup; therefore the test was not conclusive. However, tests using only the one-channel MAP signal indicated a time gain of 50 milliseconds.

Nerve Conduction Velocity

Direct measurement of nerve impulse conduction velocity is possible. This measurement could conceivably be used to indicate abnormally long neuromuscular time delay when compared with time delay measurements of "normal" children. This measurement could possibly be used as a diagnostic aid as well as a research tool. The writer proposes that this measurement be made on some normal and LD subjects to see if it is worthwhile pursuing.

Conclusions

It was proposed that some children of normal or near-normal intelligence who suffer learning disabilities, specifically poor hand-eye coordination, possess abnormally long time delays in perception, cognition, nerve conduction, and/or neuromuscular reaction. Such abnormal delays would degrade hand-eye coordination.

A small number of normal and LD children were tested to determine their reaction times. The mean times and standard deviations correlated with whether the child was normal or had certain learning disability symptoms including poor hand-eye coordination. Although the number tested was small, the evidence obtained indicates that indeed some LD children suffer time delays greater than those of normal children.

The writer feels that sufficient evidence has been produced to justify making further measurements to support the argument or to disaffirm it.

Also, one hyperactive LD child was tested to determine the effect of Ritalin on his neuromuscular reaction time. The drug reduced the reaction time, which seems to refute the supposition that stimulant drugs slow hyperactive children, thereby calming them.

APPENDIX

Effects of Barbiturates and of Another Tranquilizer*

"The authors have been working on moods, emotions, and motivations as affected by drug action since 1950 and wish to comment (without documentation) on the effects of other substances. These experiments were done on normal humans, aged 21 and over, and the treatment evaluated while the Ss were socially active.

"Three common barbiturates--secobarbital, amobarbital, and pentobarbital--have in common their ability to cause a feeling of relaxation. In many other respects they differ radically. As in the case of alcohol, there is often little similarity of effect between day-time use and the normal bedtime use of sedatives. The effect of Seconal on emotions and motivations of the active subject is most prominent on self-confidence. A 30-50 mg dose enhances self-confidence; doses of 100-200 mg cause recklessness and aggressiveness. Amytal's most significant action is on depression of anxiety. At low doses the social effects may be desirable; at high doses the suppression of anxiety may release hostile acts toward others. Nembutal at low doses produces a social nonchalance; at high doses it produces silliness.

"The effects of Dramamine (dimenhydrinate) on the active subject are superficially very like those here described for meprobamate, except that they are emotionally probably less pleasant. The effects of this drug are more dose-dependent than seems to be true of meprobamate.

"Although the ACL (and other means of evaluation of drugs in active subjects) shows similarities between meprobamate, dimenhydrinate, and secobarbital, they behave differently when they are combined with amphetamines. Meprobamate plus amphetamine yields an effect quantitatively and qualitatively like amphetamine alone, except that it is substantially more relaxed and socially more desirable, Secobarbital plus amphetamine tends to emphasize the socially least desirable features of each component (self-confidence or recklessness, impulse to get socially involved with people while being cheerfully aggressive, and talkativeness). Dimenhydrinate plus amphetamine appears to result in cancellation of the mood effects of each."

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*Quoted from Reference 5, Cameron, S. J., et al., "Effects of Meprobamate on Moods, Emotions, and Motivations," J. of Psych., Vol. 65, 1967, pp. 209-221.

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THE ELECTRIC PENCIL - A DEVICE FOR TRAINING IN FINE MOTOR SKILLS

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Introduction

The Electric Pencil provides enhanced auditory/visual sensory feedback to support training in fine motor skills in preparation for learning writing skills. The Pencil is battery-powered and self-contained and is only slightly larger than a primary pencil. The user is presented with a work sheet with dark forms or letters on a light-colored background, and is asked to follow the forms or letters with the tip of the Pencil. If the Pencil moves outside of the prescribed target area, an auditory feedback tone is actuated and remains actuated until the Pencil returns to the target area. The additional auditory feedback enhances the normal visual feedback in alerting the user to the fact that the task is not being performed properly.

It is envisioned that the Pencil may be used to train a wide class of individuals. The Pencil was originally conceived for use with children with poor visual-motor coordination such as children with cerebral palsy. However, with little or no modification to the sensory feedback mechanism, the Pencil might be used to train sight-disabled, blind, deaf, neuro-muscularly impaired, and other handicapped individuals without regard to age.

Description and Use

Electrical and Electronic Design

Basically, the Pencil detects the amount of light which is reflected from the work sheet directly below the tip of the Pencil. When the amount of light reflected is large (i. e., when the Pencil is directly over a light-colored portion of the work sheet), the auditory feedback is actuated; when the amount of light reflected is small (i.e., when the Pencil is directly over the dark target area) the auditory feedback is not actuated. Consequently in the training in fine motor skills, the normal visual feedback is augmented by the addition of the auditory feedback tone.

Figure 1 is a photograph of the Pencil. The light source, light detector, and the associated electronic circuits are housed in the lower portion of the Pencil (the portion of the Pencil held by the user during training). A ball-point pen is included to make a permanent record of the movements of the Pencil; the work sheet record is used by the instructor in measuring progress. A single 2.7 volt mercury cell provides power for the Pencil and is housed in the upper portion of the Pencil. A hearing-aid earphone or transducer mounted at the top of the Pencil converts the electrical signals to the auditory feedback tone. The Pencil housing is nylon.

Figure 2 is a block diagram of the Pencil. The light source is a light-emitting diode (LED) which operates in the red portion of the visible spectrum. Signals from the free-running multivibrator oscillator are used to flash the LED. This is done for two reasons:

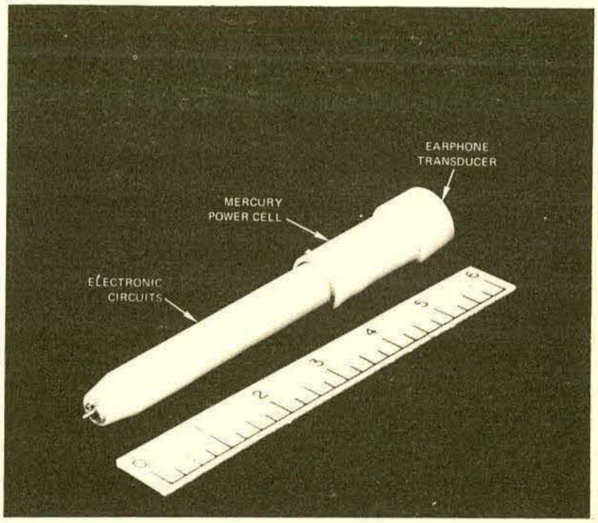

FIGURE 1. Electric pencil.

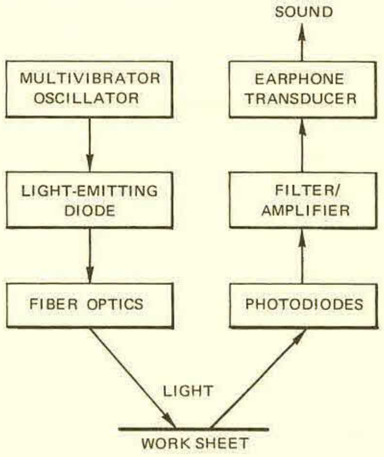

FIGURE 2. Block diagram of an electric pencil.

1. It is possible to filter the detected reflected light to discriminate against ambient light from such sources as overhead fluorescent lights or the sun. The LED is flashed at a frequency which is not a harmonic of 60 Hz.
2. Power is conserved by using small duty cycle (the fraction of the operating time during which the LED is on). This is important since the LED is the largest single power drain in the Pencil.

Light from the LED is coupled through a small bundle of glass optical fibers to the tip of the Pencil for projection onto the work sheet. The fibers are distributed uniformly around the annular opening at the tip of the Pencil to provide even illumination of the portion of the work sheet which is being used. In addition, the uniform distribution of fibers results in a rotational symmetry for the Pencil which means that the operation of the Pencil is independent of how the user rotates the Pencil about the longitudinal axis. The user may see the light emerging from the tip if he looks directly at the tip; future models of the Pencil will utilize infrared light sources to eliminate this possible source of distraction to the user.

The light from the Pencil is directed to the surface of the work sheet and is then reflected. The amount of reflected light is determined by whether the Pencil is directly above a light or a dark portion of the work sheet. Four matched photodiode light detectors are positioned symmetrically in the annular opening at the tip and electrically connected in parallel (again providing rotational symmetry). The electrical signal from the detectors is filtered to reject unwanted signals and amplified to drive a hearing-aid earphone. An auditory feedback tone of the same frequency used for flashing the LED is generated whenever the Pencil is over a light-colored portion of the work sheet. The amplifier and the earphone operate in a quasi-linear mode. This means that as the tip of the Pencil moves across the boundary from a dark area to a light area and the amount of light which is detected gradually increases, the intensity of the auditory feedback signal gradually increases to the maximum level obtained over a completely light-colored area. This maximum sound intensity is sufficiently high to alert the user but not sufficiently high to distract another individual using another Pencil at an adjacent work area.

General Information

The following are general items describing the Pencil:

1. The Pencil is 15.8 cm (approximately 6.25 inches) long.
2. The outside diameter of the lower end of the Pencil in the area held by the user is 16 mm (approximately 0.6 inch); the outside diameter of the battery housing is 20 mm (approximately 0.8 inch); the outside diameter of the earphone housing is 24 mm (approximately 0.92 inch).
3. The Pencil weighs 61 grams (approximately 2.2 ounces).
4. Proper operation of the Pencil is achieved with the longitudinal axis of the Pencil at an angle as large as 45 degrees from a perpendicular to the plane of the work sheet.
5. The resolution of the prototype Pencil (i.e., the narrowest target area that can be detected) is approximately 6 mm (approximately 0.25 inch). This is not an ultimate limit for future models of the Pencil.
6. Minature chip resistors, chip capacitors and "lid" transistors have been used in the prototype model of the Pencil to facilitate repairs; future models could use integrated circuits.
7. The mercury cell is rated at 1 Ah. Since the Pencil draws approximately 20 mA, the cell should provide 50 hours operation with continuous use and probably more with intermittent use. The cell may be replaced quickly and easily by disconnecting the upper portion of the Pencil.

Instructional Materials and Their Use

Instructional materials may be made with any type of light-colored paper stock. The dark target areas may be made with a paint brush, felt-tip marker pens, and with offset printing (except hectograph). Any dark color except red may be used since in the prototype a red light source is used. Because of the wide choice of materials and the ease with which work sheets may be prepared, the instructor has complete freedom to prepare his own instructional materials if pre-printed materials do not suit his requirements.

An individual whose eye-hand coordination skills are at a very low level could begin with tracing wide target areas such as broad straight lines (see Figure 3). As the individual's proficiency at making lines which remain within the target area passes a pre-established criterion, the width of the area could be decreased. This process could be repeated until the narrowest possible target area had been reached. A single change in direction in the target area could be introduced (similar to the letter "L") while reverting to the widest target area. Again as the individual's proficiency increased the width of the target area could be decreased. At this point a continuously changing direction (as in an arc) could be introduced using the same general procedures. The individual should now be ready to try to make simple letters.

Test Results

The Pencil has been tested with one child who has cerebral palsy. There were approximately 50 sessions each of 10 to 15 minutes duration in which the child also acted as the control subject. The child was presented with 6, 12, and 18 mm wide tar-

FIGURE 3. Sample work sheet.

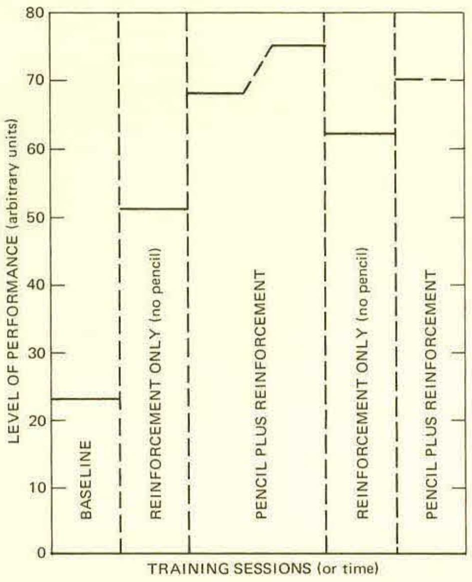

FIGURE 4. Test data for an electric pencil.

get areas. The 12 and 18 mm target areas presented no challenge to the child after the first few sessions and are therefore not included in the test results. As indicated in Figure 4 (with averages of data points) the child's progress followed a typical learning curve except for one statistically significant difference. Specifically, when the auditory feedback was eliminated, the child's performance level (as measured by the fraction of the time the child kept the Pencil within the target area) dropped by approximately 20%. The performance level then increased by nearly the same amount when the auditory feedback was reintroduced. It must be emphasized that these test results are very limited in scope, but they do show definite indications that the Pencil enhanced the coordination training for this child. No comparison was made with this child receiving any other type of training with or without other training aids.

Target Populations

The Pencil was originally conceived for use with children with poor visual-motor coordination. Without modification, the Pencil could be used with sight-disabled or blind children and adults. By substituting and/or adding other types of enhanced sensory feedback mechanisms (such as tactile or visual), it is reasonable to expect that the use of the Pencil may be extended to the training of deaf, neuro-muscularly impaired, and other handicapped individuals without regard to age.

Future Work

It should be possible to improve the performance of future models of the Pencil. Resolution may be improved by moving the light sensor(s) up into the body of the Pencil and using additional optical fibers to direct the reflected light back up to the sensors. In this way the diameter of the annular opening surrounding the ball-point pen may be decreased by at least a factor of two. This could result in a smaller diameter for the Pencil housing. A smaller mercury or other type of power cell moved closer to the lower end of the Pencil held by the user would decrease the weight and improve the weight distribution. While the Pencil is now slightly top heavy neither the weight nor the weight distribution appears to interfere with its use. It may be possible to eliminate the light source and use the ambient light in the room; this would result in a significant reduction in the complexity of the electronic circuits and increase the battery life. It should also be possible to design a sound transducer which is an integral part of the top of the Pencil, thereby permitting a reduction in the size of this part of the Pencil. It should be possible to reduce the cost of the basic Pencil to the range of $10 to $25 with volume production and appropriate production engineering (keeping in mind the rough treatment which the Pencil may receive). This would be low enough to permit the parents of handicapped children to have one of the Pencils in the home to continue any training received at school during the day. While the Pencil in its present form is most useful for training in tracing skills, it is recognized that other skills such as copying and drawing letters from memory would be important. The use of specially prepared instructional materials might facilitate this training. Fading cues as a transition between tracing and copying letters appears suitable also for the Pencil. A simple modification would permit the Pencil to operate with the auditory feedback tone completely off or on at full intensity (a type of binary mode). With the addition of a switch it would then be possible to generate the auditory feedback when the Pencil is over either a light or a dark area. In this way it would be possible to conduct a study to determine whether positive or negative reinforcement with auditory feedback is more beneficial.

Acknowledgement

The authors would like to acknowledge the help of John C. Mould and Gregg Bailey of the Applied Physics Laboratory in the design and construction of the Pencil, and Daniel Dinsmore of the School for Contemporary Education for conducting the test with the Pencil. We should also like to acknowledge the contributions and support of Dr. A. G. Schulz, Assistant to the Director, the Applied Physics Laboratory.

THE TUFTS INTERACTIVE COMMUNICATOR

by

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Summary. This paper describes an electronic assistive device which will allow the non-verbal severely handicapped to better communicate.

INTRODUCTION

Everyone has at sometime in his life experienced the frustration that results from the lack of expressive ability. That frustration stems from having a mental representation of a thought and not possessing the verbal or literal ability to express it. This problem is of only minor concern to the normal person. It is, however, a serious problem to the non-expressive handicapped. There are a large number of people in our society who are physically prevented from communicating any original thought because of some ailment (either from birth, or as the result of an accident). This has severely affected their speech, and muscular control. The unfortunate result of this is that the mind of such a person (which is often unimpaired) is "trapped" inside the body, with no possible means of contact with the world.

THE COMMUNICATOR

Patient Population

The patient population which has need for such a device consists of any person who is severely enough disabled so as to limit his physical abilities to a small number or grossly controlable functions, while his mental abilities remain intact. Ailments such as cerebral palsy and multiple sclerosis can commonly result in such conditions. In contrast, quadriplegia due to accident allows the patient to retain fine control of the hand. Speech may also be present in this case. The quadriplegic can therefore communicate using his speech, or written language by means of a writing aid.

The severely involved victim of cerebral palsy or multiple sclerosis can not avail himself of either of these. He has neither speech, nor the fine control necessary for currently available writing aids.

The research was conducted by the author under the supervision of William S. Crochetiere, Ph.D., Assistant Professor of Engineering Design, Tufts University College of Engineering. Clinical work was performed at the United Cerebral Palsy of Merrimack Valley Training Center in Lawrence, Massachusetts.

Chosen as the principle subject in this investigation was R.H. a child who is enrolled at the Training School in Lawrence. The prerequisite for any form of communication is that the patient possess an "intact inner language." This means that he must be able to mentally organize his thoughts in a fashion which when presented will be understood by those around him. R.H. has this without question. Although formal intelligence testing is impossible, R.H. has been psychologically evaluated and is reported to have a mental age equivalent to his chronological age. Mrs. Irene Johnson, teacher at the Clinic in Lawrence, predicts that under the present conditions R.H. should reach a fifth or sixth grade reading level by the time he reaches age fifteen. Presently at age 10, he is at a second grade reading level. A fifth grade level is roughly equivalent to the level at which most common newspapers and magazines are written. With this ability, R.H. should, given the proper assistive device, be able to produce original communication.

R.H. Age 10

R.H. is a severely involved spastic-athetoid, male child with basically spastic lower extremities, and an athetoid component in the upper extremities. He has some head control, but no meaningful speech. Physically, he has developed to a 6-month level. Intellectually, he has been tested by psychologist at Children's Hospital, Boston, and in language development by our Speech Therapist; and has been found to have intellectual development comparable to his chronological age - 9 years. He is enrolled at the Special Education Classroom at our Clinic and attends Classes five days a week, five hours a day.

Disability Profile of Principal Subject in this Investigation.
Table 1.

History

The Tufts Interactive Communicator was developed in the Spring of 1971 by five graduate students in a course in the Department of Engineering Design at Tufts University. This investigator was among those students, and Dr. William Crochetiere was the instructor. The class was assigned the project of designing and constructing a communicative assist for the severely handicapped. The resultant device, known as the T.I.C., allows the user to choose and print a character using two signals of the same switch. This necessitates only one physical movement.

Input devices that were designed, include head, handwave, and wrist-turn switches. Also, an eye movement detector, developed by N.A.S.A., was duplicated. This, however, has yet to prove operational.

The T.I.C. received national recognition when it was awarded the First Prize in the Graduate Division of the Annual Creative Design Competition sponsored by the American Society for Engineering Education. The Competition was held at the Society's Conference at Annapolis, Maryland in June of 1971.

Within the last year development has continued as the Master's Thesis topic of this investigator. The result is a second generation T.I.C. The new apparatus corrects the deficiencies of the previous model, as well as adds certain desirable features to the system.

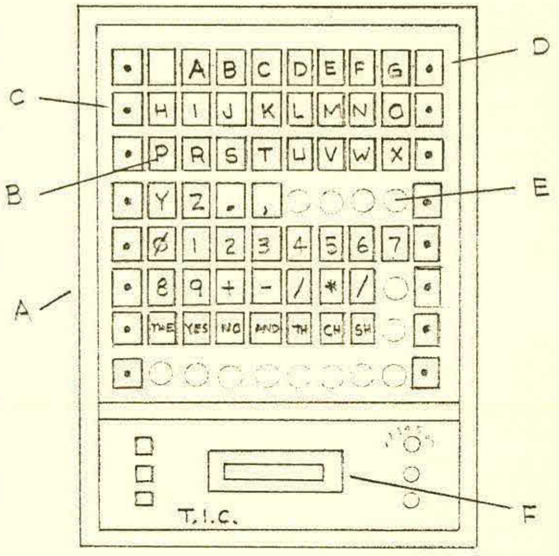
Physical Description and Operation

The Tufts Interactive Communicator is shown in Fig. 1. This unit contains the equipment necessary for communication by the handicapped user. Shown is the basic T.I.C. with its visual keyboard and instrument panel. Parts of the system not shown in this photograph are the assortment of input devices developed for operator use, and the Mite 123T Data Terminal which will record on paper all of the characters chosen by the operator.

Visual Keyboard - On the visual keyboard are mounted two vertical columns of indicators. These are designated as the cursor and error columns. Spanning the distance between these two columns are 64 sockets arranged in an 8 X 8 matrix. The information units (characters and common combinations of letters) are each contained in a plug-in character cube, Fig. 2. These "cubes" are 1" X 1" X 2½" relay cases which have been adapted for use in the T.I.C. These "cubes" marked with a boldfaced character designation, can be plugged into any of the 64 sockets, to provide every possible arrangement of characters on the keyboard.

Instrument Panel - The lower panel of the T.I.C. contains the primary output device and the external controls. The output device is the Burrough's Self-Scan display. This is an electronic display which will print up to 16 characters on its screen. These characters are 0.396 in. high by 0.276 in. wide (maximum). This will provide immediate feedback to the operator and also will present information for conversation or temporarily store short messages.

The three pushbutton controls on the panel are power-on-off, system, set, and dispaly clear. On the opposite end of the panel are three rotary switches. The clock control gives continuous variation of the sequencing speed from one second to ten seconds per step. The Row and Column switches control the number of active rows and columns on the keyboard. The upper left socket of the keyboard is designated as Position 1,1. When the T.I.C. is operated with fewer than 64 character cubes, the efficiency of operation may be improved by setting the Column and Row switches to include only those columns and rows which contain characters.



A. Visual Keyboard
B. Character Cube
C. Cursor Indicator
D. Error Indicator
E. Empty Socket
F. Electronic Display

Tufts Interactive Communicator

Fig. 1

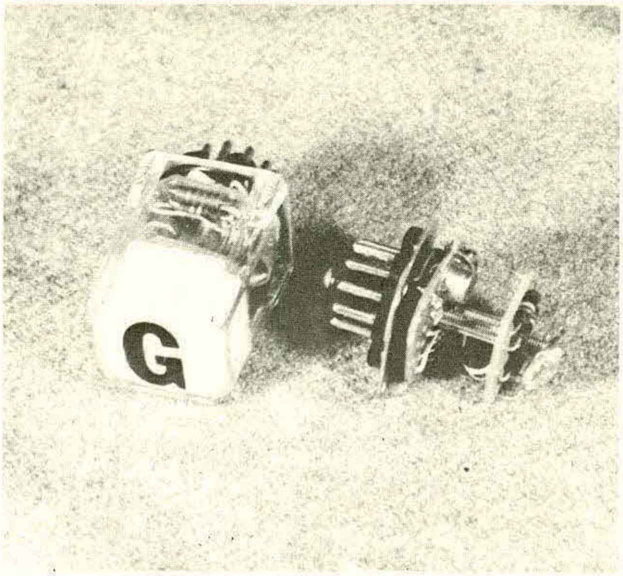
Character Cubes - With each character or set of characters contained on its own cube, any desirable arrangement on the keyboard is possible. The circuitry in the cubes is designed so that up to three characters may be presented on one cube. This provides for the output of common combinations of characters from only one operator choice. The list of characters contained in the T.I.C. is shown in Table 2. Included are the alphabet, numbers, necessary punctuation and arithmetic symbols, two and three letter combinations that are used in the teaching of reading, common letter combinations used in communication, and short words that are most common in the English language.

Hardcopy Output - The Mite 123T Data Terminal has been chosen to perform the hardcopy output function of the T.I.C. The Mite 123T is not included in the T.I.C. packaging. The 123T is contained in its own case and is attached to the T.I.C. by means of a cable. This will allow the 123T to be placed anywhere in a room. It does not necessarily have to be close to the operator. The 123T prints in uppercase letters on 8½" wide continuous roll, or fan folded paper. Interconnection is made at the rear of both the 123T and the T.I.C.

Input Devices - The T.I.C. is designed to accept any input device which will close the contacts of a switch or relay when the operator activates that device. All input connections are made through a connector in the rear of the T.I.C. The input devices which were designed as part of the original T.I.C. are still applicable to the new T.I.C. Designed as new input devices, are switches which utilize motions of the chin and the knee. The chin switch is mounted on a pair of eye glass frames. The activating bar hangs from the switch past the user's face and is taped under his chin. Normal movements of the mouth will not disturb the switch. Only the exaggerated opening of the mouth will cause the bar to be pulled low enough to trip the switch. The knee switch is designed to be mounted under a table or wheelchair tray. Lifting the knee from a rest position against the switch bar will force that bar against a switch that is mounted in the unit. The switch bar is padded to prevent injury, and spans the width of the table or tray so that precise positioning of the leg is not necessary. Pressure anywhere on its length will cause switch closure.

The input device is possibly the most important part of the system as far as the operator is concerned. Without a satisfactory means of operating the system, the T.I.C. is practically useless. Due to the variety of disabilities of the population of T.I.C. users, each operator must be specially fitted with his own input device. As was mentioned above, the T.I.C. input requirements are relatively simple. This allows for use of input devices not designed specifically for the T.I.C.

Operator Usage - Each of the cursor, and error indicators, and the character cubes contains a neon lamp. When the set button is pushed, the top cursor indicator is illuminated. This remains on until the end of a period of time which has been set on the clock switch. At the end of the time period, this light is extinguished and the next indicator (the indicator immediately beneath the first) is illuminated. This sequencing continues down the cursor column until the last row (according to the row switch) is reached. When its cursor light goes out, the first cursor indicator is illuminated. The process begins again.



Character Cubes

Fig.2

Unless the operator intervenes, the T.I.C. will idle in the cursor column. The operator must choose his desired letter, or character combination and wait for the cursor light of that row to be lighted. He then sends a command to the T.I.C. via the input switch. The T.I.C. will then stop sequencing in the cursor column, and begin to step along the chosen row, illuminating each character cube as it moves. Once the desired character cube is lighted, the operator sends a second command (identical to the first) and that character is stored in the T.I.C.'s memory register.

The T.I.C. thus passes over the remaining cubes in that row, and illuminates the error indicator. If the user knows he chose the correct character, he ignores the error light. When this light is extinguished, the chosen character is simultaneously printed on both the Burrough's Display and the Mite 123T. The cursor indicator of that row again comes on, thus enabling the user a scond pass at that row should he desire to print another of its characters. The T.I.C. resumes sequencing down the cursor column until the next command.

If the user realizes that the character he chose was incorrect, he then does not ignore the error indicator, but sends a third input signal. This negates the choice, and causes the characters in that row to be sequenced again.

If the row was accidentally chosen, and the user does not wish to print any of its characters, he simply ignores the entire sequence. The row will be sequenced and the T.I.C. will return to idling in the cursor column.

ALPHABETIC AND NUMERICAL CHARACTERS

A throuth Z exclusive of Q
QU
0-9
(space)

PUNCTUATION AND ARITHMETIC SYMBOLS

+ Plus
- Minus
* Multiply
/ Divide
= Equals
. Period
, Comma
? Question Mark
! Exclamation

COMMON TWO AND THREE LETTER COMBINATIONS

AND	FOR	OF	THE	TO	IS
IN	IF	CH	GH	SH	TH
WH	ED	OW	QU		

LETTER COMBINATIONS FOR CLASSROOM ONLY

AN	AD	AG	AT	AP	AM
AL	IT	IN	IG	ID	IP
ET	OT	UT	EG	OG	UG
EN	UN				
ELL	ASS	111	ESS	UFF	ACK
AND	ECK	ICK	ENT	END	ICK
OCK	UCK	AST	EST	ILK	USK
AMP	EMP	UMP			

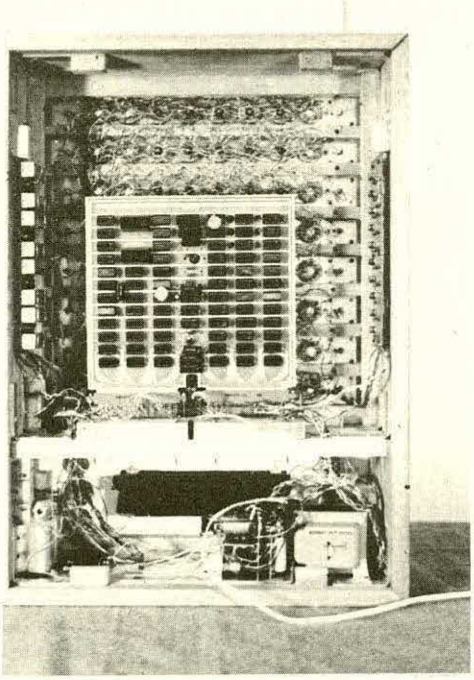
Available Character Cubes for T.I.C.

TABLE 2

The letter combinations for the classroom are supplied by Mrs. Irene Johnson, teacher at the Lawrence Public School Classroom located in the Lawrence C.P. Clinic. These are used in developing a switten vocabulary by forming words by adding letters to the combinations. An example of this is - an. Adding letters, this becomes; pan, tan, ran, etc. The availability of these cubes adds to the use the T.I.C. will find in the classroom.

Circuit Description

The circuity of the T.I.C. is contained on three circuit boards inside the T.I.C. case and in the cubes on the visual keyboard. The circuits consist of "state of the art" components. The logic circuits, which are contained on the master circuit board, are responsible for the sequencing and memory register functions of the T.I.C. Commercially available TTL Logic circuits with complimentary resistors and capacitors constitute the circuit components. The encoding function in the cubes is performed by a transistor circuit for each character. Buffering to allow the sequencers to drive the lamps in the cubes is accomplished by the use of reed relays and a transistor driver.



Rear View of the T.I.C.

Fig.3

T.I.C.

Input Voltage - 115 vac (3 pronged socket, or acceptable gound)
Power - 250 watts
Weight - 30 pounds
Size - 25 3/4" high X 18 1/4 " wide X 7 3/8" deep

Mite 123T (with separate carrying case)

Input Voltage - 115 vac
Power - 130 watts
Weight - 30 pounds
Size - 7" high X 13" wide X 18 1/4" deep

Physical Characteristics

TABLE 3

Interactive Nature of the T.I.C.

Possibly the most important aspect of the operation of the T.I.C. is its interactive nature. The T.I.C. can be classified as a semi-automatic system. The operator is in complete command of the thoughts he wishes to convey, and the equipment assists him in producing those thoughts in a fashion that is understandable to the people around him. The user does not have to provide the driving power to the equipment. He is not responsible for inputting the codes for each letter, nor is he required to generate on his own the options on the visual keyboard. On the other hand, the patient is not an idle observer who waits until the machine presents him with a choice which he can then accept, or reject. What the T.I.C. does, is allow the operator to direct the machine to perform a work task for him. This is a direct interaction with the equipment.

Meaningful written communication dictates as much originator control as possible, while the physical handicaps of that originator call for increased external assistance. The interaction between the user and the T.I.C. provides for operator control of the assisting device, and thus serves as the link between these two constraints.

TESTING AND TRAINING

Input Device

The success of the T.I.C. is determined in a large part by the compatability of an operator with his input device. If the input device suits the operator, the output of the T.I.C. is solely dependent upon the user's ability to express his thoughts by arranging characters. If the input device, on the other hand, is not suitable for the operator, the T.I.C. output will be affected both in time and accuracy.

R.H. was first exposed to electro-mechanical communication at the clinic in Lawrence where he learned to operate the Elcode, a device developed by Western Electric Company. When the original T.I.C. prototype was completed, R.H. was its first operator. The headswitch appeared to be the most convenient of the three operating input devices for R.H. This is logical since he had been trained on the Elcode to use its headswitch.

The immediate results were encouraging. R.H. was able to operate the T.I.C. to the extent of selecting letters that were requested by an observer. Eventually, the evaluation led to allowing him to spell without prompting. The words worked on were his name, and the names of his two brothers. Continued work with the prototype was plagued by equipment breakdowns. This led to the decision to discontinue training on the T.I.C.

Before the tests were discontinued, certain important information was obtained. R.H.'s response time, which included making a mental selection and a physical input, averaged 3 to 4 seconds. This necessitated running the equipment at a clock rate of 5 seconds per stop. Much of this time it was suspected was due to the inadequacy of the headswitch.

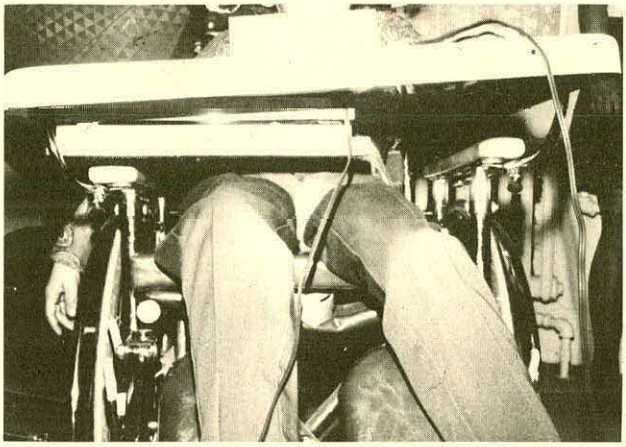
Work on a more appropriate input device for R.H. led to the development of the chin switch. R.H. had been trained by the therapists at the clinic to control the opening and closing of his mouth. This switch utilizes this control. The means of testing this device was to attach the switch to a battery and light circuit. Closure of the switch turned on the light. A game was devised which would keep R.H.'s interest, provide necessary training, and allow for record keeping to monitor his progress. The game consisted of an opponent verbally generating a list of random numbers. On number was initially determined to be a key number. Whenever R.H. heard the key, he was to signal. At all other times he was not to turn on the light.

A signal in response to the key number was one point for R.H. A signal at any other time, or a failure to signal at the key, resulted in a point for the opponent. Mrs. H., R.H.'s mother kept most of the records. The game was played over a three-month period. At the beginning, R.H. won approximately 50% of the games. As time progressed, R.H.'s ability to use the chin switch improved. By the end of the test period, there was hardly any contest. R.H. was winning nearly all the games. During this period, Mrs. H. began using a cardboard replica of the visual keyboard. Mrs. H. simulated the T.I.C. by pointing, and R.H. indicated his choices by turning the light on and off.

While working with R.H. this investigator found that the subject had excellent control of his right knee. This is to say, that he could lift his knee, from the hip, and bang it on the underside of the table. His response time for the physical motion was in the range of 1 second. From this discovery, the knee switch was developed.

A prototype knee switch was built and brought to the clinic. Fay Kimball began to train R.H. on this device during his therapy sessions. A second switch was built and installed in R.H.'s home. A code was developed for basic communication. Two switch closures, or two light blinks indicated yes, and one indicated no.

The therapy sessions consisted of one hour each week with Mrs. Kimball simulating the keyboard on a blackboard, and R.H. indicating his choices by closing the switch. The game was discarded since R.H. lost interest after only a few attempts with the knee switch. He rarely missed and did not feel the sense of competition. For three months Mrs. Kimball kept records of the response time for the selection of letters which were used in forming words which were then being simultaneously taught in the classroom. The data compiled by Mrs. Kimball is shown in Table 4.



Knee Switch Location

Fig.4

Date	Average time Per Response	Number of Responses
1/12/72	2.3 seconds	13
1/26/72	2.3 seconds	22
2/2/72	2.4 seconds	48
2/9/72	2.0 seconds	27
2/15/72	2.1 seconds	19
2/16/72	1.3 seconds	24
2/22/72	1.4 seconds	25
3/1/72	1.5 seconds	31
3/29/72	1.1 seconds	14

Summary of Results of Knee Switch Evaluation

TABLE 4

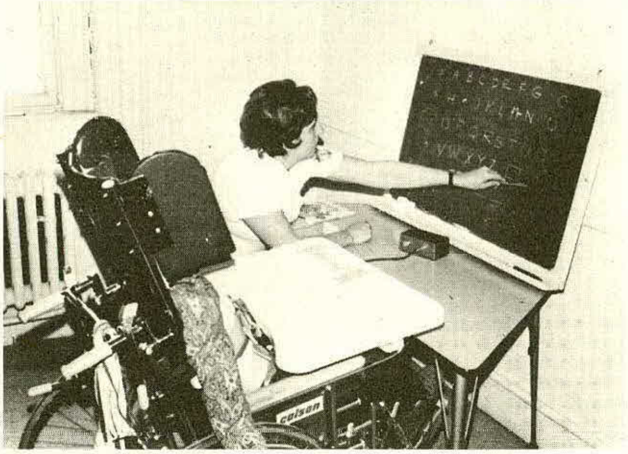
The results in the table above are not to be taken as a quantitative measure of R.H.'s improvement. There are too few trials for the data to be taken exactly. The results do show an improving trend. What can be gained from this, is evidence to support the theory that practice will improve time response to some extent. This extent is not, however, measurable at this time.

Toys

In order to provide increased practice with the knee switch, a line of toys was developed. Each toy, is operated by an input from the knee. These toys were designed and built by the students enrolled in E.S. 001, Section B, Design Graphics, a freshman course in the Tufts College of that section. Eleven toys were constructed. Two of these were given to R.H. immediately, while the remaining are awaiting minor modifications before they can be used.

Keyboard Optimization

Another area in which evaluation is being performed, is that of visual keyboard layout. Mr. Jon Mead, graduate student in the Department of Engineering Design at Tufts University, has written a computer program which will simulate the operation of the T.I.C. With this, he can evaluate different character arrangements. His evaluation criterion is the number of steps between character choices.



Training Session At the Clinic

Fig.5

CONCLUSION

The work on the T.I.C. has not come to an end. There is still a great deal left to do. Depending upon the outcome of the evaluation of the visual keyboard, the T.I.C. logic circuitry may be modified to accomodate the new method of operation. The addition of a small electronic calculator would eliminate the drudgery of long mental arithmetic calculations. Smaller additions which would add to the convenience of the handicapped user are non-printing character cubes such as, linefeed carriage return for the Mite 123T, display clear for the Burrough's display, and a bell signal to call someone to read a written message.

Each user will have his own special needs. Once these needs have been determined, special purpose cubes can be built to provide for common two and three letter combinations that are useful in his life.

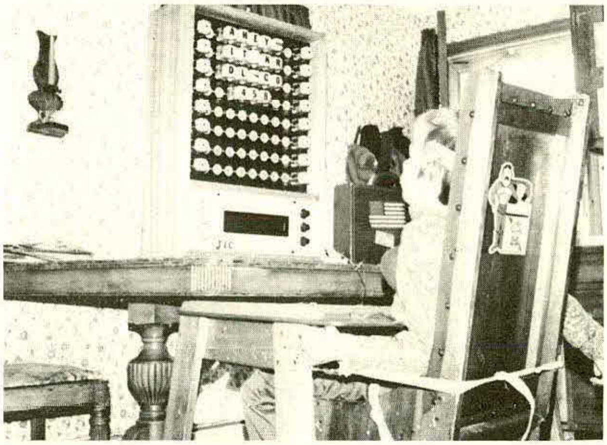
The T.I.C. that is now being evaluated will become the property of R.H. Only in this way, with the T.I.C. becoming an integral part of the user's life, can a proper evaluation be completed. R.H. is predicted to reach an eventual fifth or sixth grade reading level. This is sufficient to satisfactorily communicate using the T.I.C. It is hoped that through use of the T.I.C. this level will be reached at an earlier time in his life. The T.I.C. may even allow R.H. to progress to a higher reading level. This is all entirely possible.

The continuing design must lead on to a larger realm. Communication is essential to all persons, even the severely handicapped. Once the T.I.C. has been fully evaluated, effort should be made to correct its deficiencies and find a means of making it available to the handicapped population.

This work has changed the life of one child. It has given him the potential to unlock his mind and become a creative part of society. This in itself is reward enough for this investigator. But, if one child can be helped, so can many more. There is indeed a great deal left to do.

Patient Evaluation

Fig.6



Patient Evaluation

Fig.7

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PRACTICAL AIDS FOR NON-VERBAL HANDICAPPED

by

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Summary. An electronically simple communication system, which was developed for use by non-verbal handicapped, was evaluated to determine its effect on speed and reliability of communication in three different environments: (1) a formal testing situation where the French Pictorial Test of Intelligence was being administered; (2) a typical classroom situation; (3) a social or non classroom condition. When compared with their usual mode of communication, the use of Myocom measurably increased the speed and accuracy of response for each of the six subjects evaluated.

Introduction

In 1968, the Department of Electrical Engineering at the University of Missouri-Columbia and the Woodhaven Learning Center (then called the Woodhaven Christian Home for Exceptional Children) began a cooperative bioengineering program whose object was to solve many of the unique problems associated with education and training of physically handicapped, mentally retarded individuals. The first problem attacked was finding a convenient, reliable mode of communication for those who could not speak or utilize the conventional modes of writing or typing. A system was conceived, designed and developed which used surface myopotentials for actuation by electronically converting these signals into a controllable dc voltage. This basic system was dubbed Myocom(1).

Continued technical development and on the job qualitative evaluation of the system convinced the project team that Myocom was more than an interesting toy. We decided to put our intuitive convictions to the test of a controlled, quantitative evaluation.

Areas of Evaluation

Intellectual Abilities

No meaningful educational program for an individual can be planned and implemented unless some measure of intellectual abilities is known. Several generally accepted "standardized" tests are available for achieving this determination on normal individuals. As the degree of abnormality increases, however, the availability of valid test vehicles drastically decreases. Since the non-verbal, physically handicapped, mentally retarded individual is near the extreme in abnormality, the most usual measure of intellectual ability is an intuitive, educated guess as to the probable score on some standard test. Difficulty of communication is more than likely the underlying problem.

The French Pictorial Test of Intelligence is used as an evaluation vehicle at Woodhaven. This particular test gives information on picture vocabulary, form discrimination, information and comprehension, similarities, size and number, immediate recall. Total number of responses and number of correct responses within a fixed time period is the basis for score on this test so rapid, reliable communication is essential for any meaningful evaluation.

Performance in Classroom

Part of the educational process at Woodhaven is participation in a typical classroom environment. Although the student to teacher ratio is normally 10 to 1 or less, the diverse degrees of handicap put a premium on rapid, reliable communication if the teacher is to give each individual the necessary personal attention. Also, the teacher must have an effective way of assessing whether each individual has achieved a particular instructional objective.

The Social Situation

Several types of social intercourse were used. For example, use of basic forms of courtesy and choice of proper clothing were two of the areas involved.

Gathering the Data

How

In all cases, the raw data was obtained from direct observation by a third party. Response time, for both usual communication method and Myocom communication, was the time elapsed until the teacher decided that the response was satisfactory. Twenty-five observations were made for each condition and an arithmetic average determined as the measure for response time.

On Who

Dennis - age 12, right side bilateral hemoplegia with seizure disorder. Normal mode of communication is limited verbalization.

Randee - age 17, mixed type cerebral palsy. Normal mode of communication is limited verbalization.

Sydney - age 13, cerebral palsy with auditory difficulty. Normal mode of communication is gestures.

Joey - age 14, paraplegic, spastic cerebral palsy. Normal mode of communication is limited verbalization.

Carol - age 24, severe spastic quadraplegia. Normal mode of communication is by movement of eyes.

Larry - age 24, condition never really diagnosed. Normal mode of communication is labored verbalization plus his own special gesture system.

Results

French Pictorial Test

Dennis. Previous estimates of Dennis' I.Q. had been made; for example at age 8, a guess of 25 was based on observation; at age 9, partial testing gave an estimate of 28; and at age 10, further testing refined this to 37. At age 12, using the full scale test and Myocom, an I.Q. of 47 was obtained which is at the upper end of trainable.

Randee. At age 7, an approximation based on observation gave an I.Q. of 57. By age 10, this approximation had dwindled to 40; however, two years later an estimate made from a partial test was 41. The full scale test using Myocom gave a measurement of about 30, which placed Randee midway in the trainable mentally retarded range. He made 180 responses to test items within the hour with 3 seconds being quickest and 15 seconds being longest.

Sydney. It was estimated that Sydney lacked the ability to score at all when he was 9, indicating that he was in the custodial range. At 11, the same estimate was made. The full scale test with Myocom gave a measured I.Q. of 35. 180 responses were made within the hour limit with 3 seconds the minimum time and 12 seconds the maximum.

Joey. Joey was believed to be unable to score at age 8. Closer subsequent observation estimated a score of 30 and a partial test at age 10 raised this to 42. A definite 44 was obtained from the full scale test using Myocom which puts Joey at the upper end of trainable mentally retarded. 160 responses in 45 minutes is the base of this measure.

Carol. No estimate of I.Q. was made on Carol until age 17 when an approximate 33 was given. At 18, further observation guessed that a 45 was possible. A few test items were used at 19 and this refined estimate gave at least 39 which seemed to be confirmed at age 21 when some other test items gave a 40. The full scale test, with Myocom, was administered at age 24 and resulted in an I.Q. of 67, which ranks Carol in the educable mentally retarded range. This measure came from 180 responses within the hour limit with 3 seconds and 20 seconds being minimum and maximum response time respectively.

Larry. The previous history on Larry's I.Q. score is a guess of 32 at age 17, no measurement possible at age 19, and at age 22, a partial test showed an I.Q. of about 45. By responding 145 times in 30 minutes (3 seconds min., 9 seconds max.) the full scale test showed an I.Q. of 40, the upper end of TMR. Table 1 concisely summarizes these results.

Name	Previous Estimates of I.Q.	Full Scale Measure of I.Q.
Dennis	25, 28, 37	47
Randee	57, 40, 41	30
Sydney	0, 0	35
Joey	0, 30, 42	44
Carol	33, 45, 39	67
Larry	32, 0, 45	40

Table 1.

Response Time in Classroom

Dennis. An average of 10 seconds (25 responses) was required to respond doing numerical work when Dennis used his normal method of communication. Use of Myocom reduced the average to 6 seconds.

Randee. For Randee doing numerical work using his gesture system to communicate, an average of 12 seconds response time was required. With Myocom the average was 10 seconds. In a reading situation, "normal" response was 10 seconds while Myocom response was 6 seconds.

Sydney. Responding to numerical work was very difficult for Sydney with as much as 3 minutes required for a satisfactory response using his usual mode of communication. The most rapid was 12 seconds. Ten seconds was the 25 response average using Myocom.

Joey. Myocom reduced the average response time in a general classroom situation from 10 seconds to 4 seconds. For numerical work the reduction was from 11 to 6 seconds.

Carol. It took Carol an average of 10 seconds to satisfy the teacher with her eye movement system when responding in a reading situation. Myocom reduced this to a 3.6 seconds average. For numerical work 12 seconds were required with eye movement and 3.5 seconds for Myocom.

Larry. No measurements made.

The Social Situation

Table 2 summarizes the results of measuring response time in a social situation.

Name	"Normal" Response Time	Myocom Response Time
Dennis	9 sec.	4.5 sec.
Randee	10 sec.	4.0 sec.
Sydney	10 sec.	6.0 sec.
Joey	8 sec.	3.0 sec.
Carol	8 sec.	3.0 sec.
Larry	no measure	

Conclusions

The quantitative results of this study pretty much speak for themselves. A measured value of I.Q. was obtained for the first time on each of the participating individuals. It was shown for all but Larry that a more rapid means of communication was available for use in the classroom and out. The feeling of the professional staff involved was that reliability was much improved also. Other observable effects were lessening of frustration and spasticity when communication was improved and increased involvement in classroom activities concommitant with better communication.

Several intangible benefits were "obvious" to those participants from the professional staff. For example, the handicapped individuals seemed to get a psychological uplift from knowing they could communicate more rapidly and accurately. The instructional staff felt that a more realistic and useful course of study or training could now be prescribed for the student. We don't believe that all of this can be attributed to the halo effect.

Acknowledgements

Mrs. Barbara McEvoy, a graduate student in special education at UMC, gathered and tabulated the response time data. Mr. Robert Meirick and Mr. Ronald Riedel, Electrical Engineering graduate students at UMC, designed, built, and repaired much of the electronic equipment used for Myocom. The American Legion Child Welfare Foundation provided most of the funding for the project.

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A COMMUNICATIONS PROSTHESIS FOR A QUADRIPLEGIC

by

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Introduction

Quadriplegics and other persons with limited motor control who are also non-verbal need a substitute for the normal verbal communication system. Some of the general aspects of the communications prosthesis design problem is selection of the subject-to-device interface, selection of input code symbols and output character sets, selection of the output device, and the specific logic design. A specific prosthetic device for a quadriplegic is described.

Interfacing to the Subject

Selecting Muscular Responses

In designing a prosthetic device to expand the communications ability of non-verbal subjects, one of the most important problems is interfacing the subject with the device. The initial step in solving this problem is to evaluate the subject's muscular control. This may be as simple a task as talking to the subject's family and physical therapist, or it may require extensive testing and training in conjunction with physical therapy.

Finger, hand and arm movements; eye and head movements; foot movements; and breath control are some of the muscular responses which have been used for applications of this type. There is some feeling that hand movements should be employed wherever possible (1). This does have the advantage of easing interface design.

Selecting Input Detectors

At the same time the subject's muscular control is being evaluated, the device to translate the movements into electrical signals must be designed. This must also be tailored to the subject; the speed, accuracy, and strength of the subject's motions must be considered.

For example, one of our subjects, a 26 year old female quadriplegic, has already been trained to communicate using head movements and Morse Code. Among the interface methods which were considered were: a pair of glasses containing a focused light source which she could direct at two photo-cells; bio-electric detectors to receive signals from her neck muscles; magnetic, optical or rf systems to detect her head position.

The system that is being used consists of two micro switches with 12 inch fiberglass levers, mounted by goosenecks to the back of her wheelchair. This solution has a number of advantages over the others considered. First, the use of fiberglass levers makes the system very safe electrically; also the lever's flexibility and padded ends virtually eleminate any possibility of injury. The cost of the switches is low, but the system is reliable. The goosenecks allow easy adjustment of the switches by her family. The system has a very low activation energy due to the use of micro-switches. Finally, no direct attachments to the subject need be made.

Input Code Selection

The first problem associated with chosing the input code is the selection of the number of symbols it employs. This choice is affected by two considerations: (1) the number of distinct motions the subject can control, and (2) the number of input symbols the subject can learn to use.

In normal individuals, it is probable that the ease of learning and speed of communication are increased as more input symbols are used in the input code. This is true for input codes that have a relatively small number, about 40, of associated outputs. For example, many people can type more than 50 words per minute, which is considerably faster than can be achieved using Morse Code.

In the case of the previously discussed subject, communication by spelling using Morse Code was a good choice. If she had had more muscular control, a code using three, four, or more switches could have been used.

Whatever input code is used, there are two important factors in selecting the assignment of input code words to output symbols: First, the code words should be designed to take advantage of the frequency of occurrance of the output symbols. Second, there must be input code words which control the output device (carriage return, space, erase, etc.) or other devices (television, radio, etc.). These two factors are virtually independent of the intellectual development of the subject and should always be considered in choosing an input code.

In the case of subjects of low intellectual capability, the difficulty of memorizing input code words suggests two types of input codes. These codes are characterized by the kind of feedback, memory of previous input symbols, and a graphic display of the code itself.

In one type of code, the input switches have a one-to-one relation to the output characters and are marked accordingly. The markings form a graphic display of the code and the subject merely needs to find the switch marked with the desired character and press it. This method can be extended to systems with fewer switches than symbols by using a scheme similar to the operation of the shift key of a typewriter.

An alternative code, for use by persons with limited muscular control, uses only two switches. When any character in the display is lighted, one switch would cause the character to the right to be lighted, and the other switch would cause the character below to be lighted. In effect the subject causes successive charactors to be lighted on the display until the desired one is reached. The symbols could also be arranged in a tree structure and the switches would determine whether the next light was lighted in the right or left branch. Obviously, these methods can be extended to more than two switches. Note that the "tree" structure is more efficient than the "right-down" moving method, since the "tree" structure results in shorter average path lengths.

Output Characters

The set of output characters is determined in part by the user's intellectual development. In the case of intelligent, educated subjects, spelling is probably the best communications method. Spelling provides a large vocabulary but requires only a relatively small number of output characters. Alternatively, character sets can be designed to represent complete words or concepts with a simple character. Such a system could be easily learned and should, therefore, be much more usable by young, uneducated or retarded subjects (2). Hieroglyphic characters with meaningful shapes are being used successfully by researchers at the Ontario Crippled Children's Center (3,4).

Output Devices

Output devices fall into two catagories -- hard-copy units similar to typewriters, and soft-copy displays of various types. In general, hard-copy devices have advantages in permanancy of record and longer character strings. On the other hand, soft-copy devices enjoy advantages in cost, maintenance, portability, and size of character sets.

Of the available hard-copy units, one of the most practical is a standard ASR33 teletype which costs about $1200 and will accept standard ASCII code. It is also computer-compatible which could permit the use of computer-assisted training programs. Its major disadvantages are noise, short life span, and small character set.

The cheapest hard-copy unit consists of a standard electric typewriter with the keyboard switches paralleled by switches in the communications device. Not only is the cost of the typewriter and interfacing small, but since it can still be used as a typewriter, it serves a double purpose.

More expensive teletypes and modefied IBM Selectric Typewriters are priced from $1800 to as much as $4500. Their advantages are primarily in the areas of higher reliability, less noise, and greater portability. A difficulty suffered by some of these devices is their use of non-standard input codes.

Soft-copy devices are generally better, but suffer from the lack of a permanent output record. The simplest soft-copy unit is capable of displaying only one character at a time, but is by far the least expensive and most flecible display device. An example of this device as presently being used consists of 62 individually lighted slides: 26 letters, 10 numbers, and 26 punctuation marks, special characters and commonly needed words. By changing the set of slides this aparatus can easily and cheaply be converted to any set of output characters.

Soft-copy devices which are presently being evaluated include multiple character displays of three types. First, displays are available from the Burroughs Corporation which are capable of displaying as many as 256 characters at a time. Their cost ranges from $260 for a 16 character display to $1100 for the 256 character unit. These devices accept a seven bit ASCII code and include a blanking or erase function. They have the advantages of low cost and small size.

One could build his own 10 or 20 character display employing 5 x 7 LED (light emitting diode) readouts. Not only could this unit be compatible with the Burroughs device, but it could be capable of a larger character set (e.g. heiroglyphics). Such a unit would cost more in single quantity purchases, but the additional expense can be defrayed by quantity buying and by the increased flexibility.

Finally, the use of CRT (cathode ray tube) displays is being considered. This approach has the advantage of the largest character set, but is also the most expensive and least portable soft-copy unit. The availability of Read Only Memories (ROM) for character generation and low cost oscilloscopes make this approach worth investigating, but the final trade-offs have not yet been evaluated.

Two general advantages of soft-copy units concern feedback and visibility. Soft-copy displays typically provide better feedback to the subject, since intermediate states can be displayed. Often the hard-copy unit will not be visable to the subject and he must depend upon other persons for correction. Also, the soft-copy units have a greater visability. While it is difficult for a large number of people to stand around a typewriter to read what is being typed, soft-copy displays can be placed so as to provide viewing to a large number of people.

Design of the Prosthesis

The prosthesis itself should satisfy several conditions. First it should be small, lightweight, portable, and possibly battery operated -- these conditions are especially important in the case of ambulatory subjects. Second, it should be inexpensive, reliable, and easy to maintain. Finally, it should be adaptable to a large variety of input codes and output character sets -- the wide range of motor capabilities and intellectual development found in persons possessing no verbal communications abilities make it difficult to employ one standard input code and output character set for all subjects.

Low cost and low power consumption can be achieved by employing integrated circuits (IC's). They are physically small and result in relatively lightweight units. Integrated circuit systems are also very reliable and easily maintained.

The adaptability of the device to variations in input and output character sets is determined by the logic design employed. Each input symbol is considered to be a single binary signal. One approach is to design a sequential machine whose outputs are equal to the machine's states. For the example of Morse Code input, the device would be designed so that after each input, the values of seven flip-flops would equal the desired output code, e.g. ASCII. This approach would require a large number of logic gates (30 to 50 TTL IC packages) and any change in the input code or output character set would require a complete and lengthy redesign. If the device were to be produced in very large quantities, though, one might employ a single Texas Instruments programmable logic array (TI TMS 2000 JC) (5). This is a 40 pin IC, which is programmed by the manufacturer to the customer's specifications. It contains 8 J/K flip-flops and a significant quantity of And/Or gating for realizing the J and K inputs.

A second approach, the one we prefer, is to convert the input symbol strings into a unique n-digit binary code, and then, use a Read Only Memory (ROM) to convert this code into a more standard one, e.g., ASCII, EBCDIC, or IBM Selectric code, or to perform a direct conversion to 2^n outputs via a matrix or grid decode structure. Such a situation is represented in Figure 1.

Morse code with a maximum string length of five symbols is the input. The presence of a dot is stored in the shift register as a zero and a dash is stored as a one. At the end of a character a unique six-bit binary number resides in the shift register. Note that the sixth bit is necessary since this is a variable length code. Two 3-to-8 decoders are used to produce an 8 x 8 array. Each of the possible 64 outputs is decoded by the coincidence of any row line and column line.

An Intel 1701 programmable and erasable ROM is employed to perform the code translation required to produce ASCII or any other codes (6). This ROM, which costs about $100.00, is extremely flexible since it can be erased by exposure to ultraviolet light and can be reprogrammed.

The logic design displayed in Figure 1 requires very few IC's. For the 64 character display, about 24 IC packages are required. If teletype output is included, then the ROM and a parallel-to-serial converter (about five additional IC packages) are required.

Interfacing to other output devices, e.g., an IBM Selectric typewriter, 5 x 7 LED readouts or CRT displays, can be achieved easily by the use of standard ROM's for conversion from ASCII to the required input codes.

Conclusion

The general problem of choosing input and output symbol sets is not a trivial one, especially when ease of learning and speed of operation are important. This problem is compounded with the need to evaluate the subject's individual motor control and intellectual development.

The communications prosthesis must provide the subject with an effective method of communicating his thoughts to others. Given that the appropriate input and output symbol sets have been chosen, a relatively low cost prosthesis can be built using medium and large scale integrated circuits. The major cost of the device is due mostly to the output device chosen.

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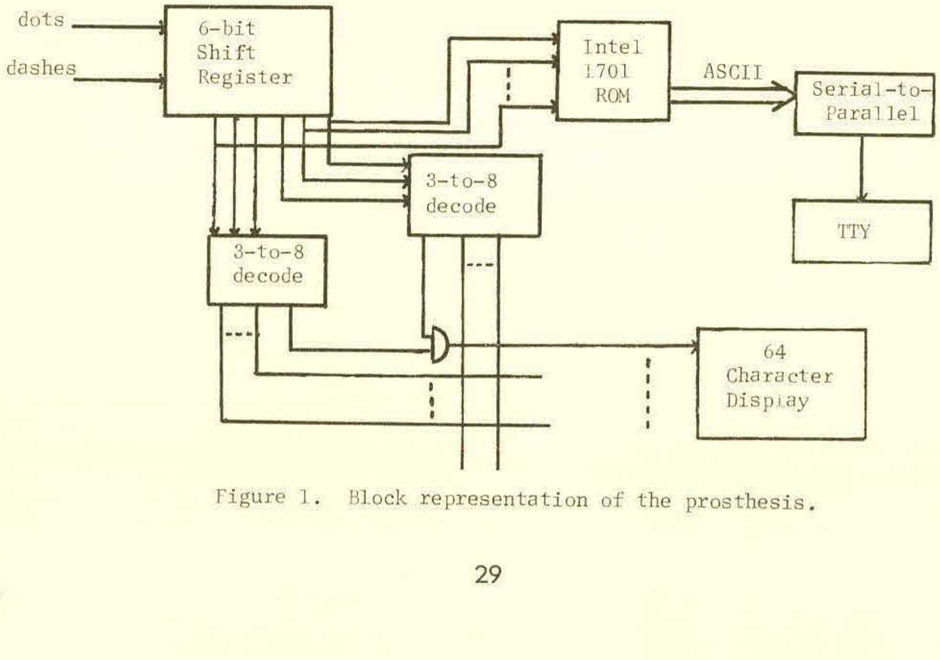

Figure 1. Block representation of the prosthesis.

APPARATUS ACTUATING AND CALL SYSTEM FOR INCAPACITATED PATIENTS

by

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Summary. This paper describes a system which enables a severely disabled person, particularly the high level quadriplegic, to call attention of attending personnel at home or in a hospital and to operate such electrical appliances as a heater, lamp, air conditioner, radio, television, an electrical door latch, or to answer the telephone. The only physical requirement on behalf of the patient is to gently nudge or puff on a sensitive microswitch.

Introduction

A small group of highly incapacitated patients cannot utilize the existing call systems for communicating in hospital; particularly spinal cord injured with high cervical (neck) injury, bulbar polio or Guillian-Barre syndrome. They frequently must remain passive and totally dependent on the frequency of visits by the nursing staff for their most vital or trivial needs. The demands on the nursing staff are great. The system described here helps both the patient and the nurse to deal with these dependent situations. It allows the disabled patient to reach a nurse at his will like any other patient. It also allows the patient to control several electrical appliances from his bedside and to answer the phone. The equipment is self-supported, requires no special installation and plugs into the existing hospital call system.

System Description

The system is comprised of four components as shown on the block diagram and photograph. These are:
1. A microswitch with appropriate support.
2. A case containing the electronics.
3. A numerical display.
4. A telephone answering attachment.

The parts are interconnected with cables and plugs, thus allowing easy transporting and refitting when necessary.

The selected microswitch has an actuating lever with an operating force of only two grams. A transparent plastic card or sail is attached to the actuating lever. Other activating means for switching electrical circuits were considered and discarded for reasons of inconvenient operation, complexity and cost. Among these were voice switching, and interrupting of an air stream (pressure switch). The support for the switch allows easy positioning at any place and orientation as needed by the patient position. It is mounted on the headboard of the bed and can be swung aside to allow unobstructed access to the patient. It may be preferable to have a separate stand by the bed similar to a microphone stand for completely independent support. It takes a slight puff to cause movement of the actuating arm and make contact.

The electronics case contains a step down transformer, a D.C. power supply, a motor-driven four-deck rotary switch, a set of latching relays, controlled electrical outlets and a jack for the telephone attachment.

The numerical display is attached to the microswitch support in line with the microswitch, within view of the patient. The numerals 1 through 9 are approximately a half inch high.

The telephone answering attachment is comprised of a metal box which fits over the cradle of the telephone apparatus and is secured in place by means of a bracket under the telephone set. A DC solenoid is mounted inside the box and a dead weight bar is attached to the solenoid plunger. The telephone receiver is placed in the cradle of a telephone loud speaker device.

System Operation

The system is activated by gently blowing on the microswitch. This starts a slow sequence. Numerals which correspond to the numbered electrical outlets appear on the display at 10 second intervals. The status of any appliance plugged into a certain outlet can be changed from "on" to "off" or vice versa if the microswitch is activated while the corresponding number appears on the display. Number 1 would be normally assigned to the

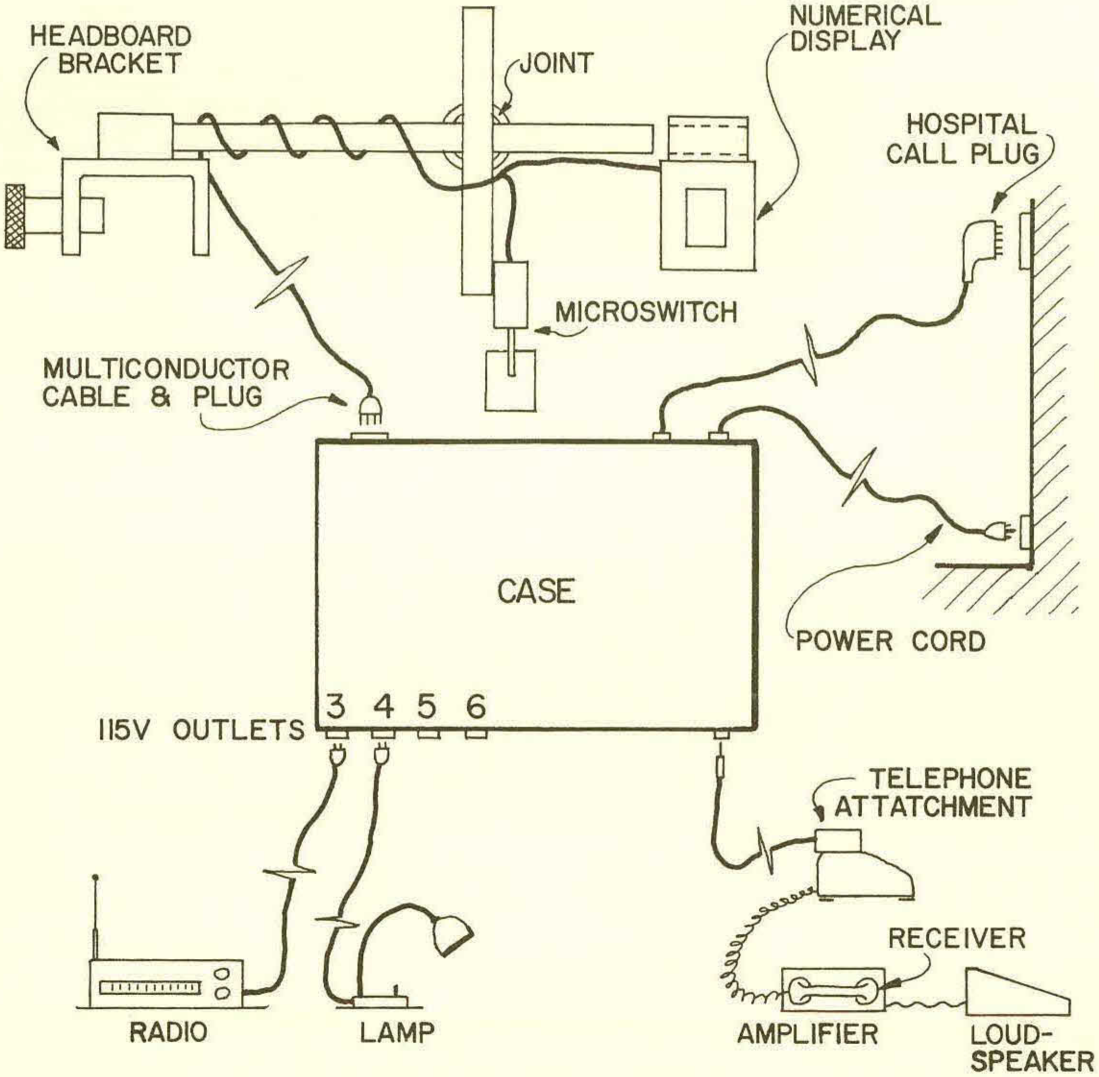

FIGURE 1. Block diagram of the actuating system.

nurse call, number 2 for answering the telephone, and the electrical outlets will be numbered 3, 4, 5, etc. The switch of each electrical appliance is left in the "on" position while the actual switching is performed in the case. The switching circuit is relatively simple. Deck number 1 on the rotary switch is allocated to driving the motor. All the contacts except the starting position are shorted and connected in series with the power supply and the motor. Deck number 2 is the sequence starting deck. The starting position is connected in series with the motor and the power supply through the microswitch. When the contacts on the microswitch close this deck will supply, the motor until the wiping arm makes contact on deck number 1. Each position on deck number 3 is connected to a latching relay. The contacts of each relay are connected to an electrical outlet on the case with 115 volts supply in series. With each additional pulse the contacts "make" or "break", thus energizing or de-energizing the outlets. A pulse is generated when the microswitch, which is disconnected now from the motor-driving deck, is closed, making a circuit from the power supply through

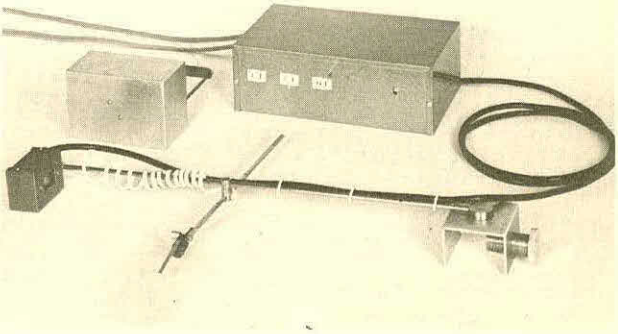

FIGURE 2. The four components which comprise the call system.

the wiping arm of the third deck into position and the corresponding coil on the relay. The positions on the fourth deck are connected to the numerical display. If numeral 5 appears on the display, that means that the wiping arm is on position number five on all four decks. If the microswitch contacts were closed now they will activate relay number 5 and change the status of outlet number 5. The contacts of relay number 2 supply low voltage to the telephone attachment jack. The relay contacts in position number 1 are connected to the hospital call cord, and perform the same switching function as does the pushing of the bell button on the regular cord.

It should be noted here that another mode of operation is possible in which the motor runs continuously and the numbers keep changing on the numerical display. This eliminates the starting circuit and allows for a faster response.

Answering the telephone is done in the following way. When the telephone rings the patient will puff on the microswitch and start the sequence. When number 2 appears on the display he will puff again, this will cause the solenoid on the telephone cradle to lift the bar off the hook. Now the conversation can proceed through the loudspeaker. To terminate the call the patient will recycle once more, wait for number 2 and puff. This will disconnect the solenoid supply and the bar will drop on the switch hook as if the receiver were replaced on the cradle.

Clinical Trial

The prototype instrument has recently been placed in trial operation at the Rehabilitation Institute of Chicago, the 76 bed physical rehabilitation hospital of the Northwestern University McGaw Medical Center, Chicago. The Rehabilitation Institute is a HEW Regional Spinal Cord Injury Rehabilitation Center.

The evaluative results* of the first patient and staff experience with the actuator are summarized here.

Subject

A 20 year old female cervical 5 level quadriplegic with 9 week duration paralysis following a diving accident utilized the actuator for 18 days. The patient had no pinch or grasp capability but could lift both forearms. Lung vital capacity was 50% of normal. The actuator provided patient control of four appliances: nurse call light, bedside lamp, television and tape player. None of these could be manually operated by the patient and nurse call was normally verbal. A circuit-use counter recorded each appliance actuation.

Actuator Use

Average 24-hour use of the actuator during the last week of clinical trial was as follows: call light, 2; television, 6; lamp, 4; tape player, 1. Hence, 13 activities per day came under the control of this patient. Eleven of these activities would have required 2 trips each by a nurse (one to turn on, one off), or a total of 22.

Patient Evaluation

The patient had never used any other mechanical device for call or appliance actuation and hence could provide no comparative evaluation. However, she indicated that the device "is much better than having to call a nurse or having someone else do it". "It's really great." She noted that the micro switch was easier to activate by moving her forearm than by blowing, because it was not always in the correct position for blowing. Further, she noted, "it is not so pleasant having it (switch sail) in front of my face".

Staff Evaluation

Three nurses and three nurses aids evaluated the device in use. Five of six (83%) staff preferred the actuator to two other mechanical hand or head activated mechanical call lights. Four (67%) noted that the actuator was saving call visits to the patient, a rather demanding and active younger patient. Thus, both staff and patient were aware of increased independence of the patient. Other nursing staff noted that the device, as currently constructed, was somewhat awkward to position and occasionally in the way. On several occasions the numeral display box was accidently displaced from its mounting. Down time for electro-mechanical reasons was minimal during the trial period.

Evaluation Conclusion

Further clinical trial in hospital and home are anticipated to determine utility and durability of this actuator system. The indications are that patient and staff can use this device to effectively increase functional independence of severely incapacitated high level spinal cord patients.

Specifications

Power requirements - 115 volts, 60 cycles 15 amps (depending on the controlled load).
Cordset - 15 amps, 3 wire, grounded.
Transformer - isolation step-down 115 into 24 volts, 60 volt-amperes.
Power supply - 24 volts DC 40 volt-amperes.
Motor - 1 rpm 24 volts AC 40 inch-ounce.
Rotary switch - 4 deck continuous rotation, 18 position make before break contacts.
Latching relay - coil 24 volts AC, contacts 120 VAC 60 Hz 10 amps DPDT (courtesy Guardian Electric Manufacturing Company).
Microswitch - normally open SPST, 2 grams actuating arm, 24 volts AC (courtesy Cherry Electrical Products Corporation).
Numerical display - 24 volts AC, ½ inch numerals.
Solenoid - 24 volts DC, pull type, continuous duty, 3/8 stroke, 10 ounce minimum lift.

Further Development

The future development of this system will provide more functions with minimum increase in complexity. The telephone attachment would permit dialing operator (0) by using a rotary solenoid on position number 3 right after the telephone switch solenoid on position number 2. Full manipulation of television controls is next. A page turning machine should be very adaptable for this system.

Conclusions

If the feasibility of the system is justified by proper evaluation of such factors as usefulness,

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*The evaluation protocol was developed by the Rehabilitation Services Evaluation Unit of the Rehabilitation Research and Training Center, Northwestern University.

cost and demand it is likely that a commercial enterprise will make it available to hospitals and individuals, bringing some relief where it is very much needed. This system means more convenience and independence to patients and less time and effort expended by nursing personnel.

SENSORY AIDS FOR THE HANDICAPPED:

A PLAN FOR EFFECTIVE ACTION

by

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Introduction

The National Academy of Engineering established the Committee on the Interplay of Engineering with Biology and Medicine in June, 1967, to delineate ways in which our national engineering capability can be synergistically linked with medical science and the delivery of health care. In 1969 the Subcommittee on Sensory Aids was formed to provide advisory services to correlate, stimulate, recommend and initiate the research, development, evaluation and deployment of sensory aids for the hearing and visually impaired.

In pursuit of these objectives the Subcommittee has organized and sponsored conference and compiled selective research, development and organization needs to aid those with sensory deficits. Publications are available from the Academy which report the proceedings of workshops on the evaluation of mobility aids for the blind and on sensory training aids for the hearing impaired. The Subcommittee's assessment of "priority projects" aimed at the amelioration of vision and audition handicaps will also soon be available, and are the topics of the next two papers this morning.

This paper addresses itself to the problem of focusing efforts at the national level and devising organizational forms which will link research and social services in order to stimulate the development and delivery of needed sensory aids to the blind and deaf. It is the result of three years of Subcommittee deliberations and summarizes the experiences we have had in working in the field, the frustrations we encounter in attempting to operate within a fractionated and unorganized system, and the proposal we offer to bring some order to the chaos.

The views expressed here today are taken directly from a position paper of the same title recently authorized for distribution by the Academy.

The Problem

There are nearly half a million blind people in this country, and more than four times as many with seriously impaired vision. The profoundly deaf number some 850,000 and an additional seven million people have seriously impaired hearing. If these people with sensory handicaps were brought together, the numbers of the blind and visually impaired would equal the populations of Memphis and Philadelphia, respectively; the deaf would fill Cleveland; and it would require Baltimore, Chicago and Los Angeles together to hold those with seriously impaired hearing.

Yet despite this multitude who are without a primary source of information, sight or hearing, relatively little effective use has been made of modern technology to provide sensory aids--devices to augment or replace the deficient senses.

Sensory augmentation for both the blind and the deaf has been less than adequate because research and development have tended to be device-oriented, poorly supported, and fragmented. Three factors have impeded progress in the application of sensory aids. First, the very complexity of visual and auditory impairments and their consequences makes it difficult to define the problems to be solved. Second, a wide disparity and lack of coordination exists among the persons and organizations that provide funds, generate ideas, and have specialized knowledge, research facilities, and rehabilitation services. Third, the market demand for sensory aids is unpredictable in an already economically disadvantaged subpopulation; such a market is unlikely to encourage private venture capital for research, development, and evaluation.

We are capable of doing much more to help these people live better lives.

To meet the needs of the blind and the deaf, a well-directed effort is required that is funded and managed on a long-term basis. We must use our advances in science and technology to provide the required basic research on information processing by humans and to develop useful devices and systems. A national program to do this could bring great benefits to the sensorially deprived everywhere. But the problems are diverse and complex, and progress will depend as much on creative management as on massive effort.

One important initial requirement is to create an effective means of communication among researchers, organizations, and workers for the impaired individuals, and the users themselves. Only with this interaction can a satisfactory balance between fundamental research and technological development be achieved. At present, development projects are often undertaken without basic knowledge of user needs and capabilities, sensory information processes, and the realities of deployment. Moreover, evaluation of the utility of specific sensory aids and the development of appropriate training procedures are practically nonexistent.

The scale of planning and organization that is needed for the overall effort calls for a substantial commitment of funds. Further, there are high costs of prototype production and field trials, and the potential for profitable sales is limited. Also, we may expect that when truly useful sensory aids become available, a large demand will be created; the organizational and funding resources that will then be necessary have yet to be estimated, planned for, and mobilized.

A unified national program can be instrumental in solving these problems.

The Needs of the Blind

Blindness limits the ability to read, to enjoy normal mobility, and to perform many everyday activities usually dependent on sight. It also precludes an enormously important means of esthetic communication, and it brings considerable economic disadvantage.

Sensory aids should, at the very least, equip blind people for reading text and for moving comfortably in unfamiliar surroundings. Such aids must extract complex information from the environment and present it to the user through his sense of touch or hearing or by making use of his residual sight. More useful aids that would assume some of the functions of the visual nervous system (thus serving as a substitute for actual vision) would obviously be still more complex and difficult to obtain, but they should be a long-range goal.

The work done so far has resulted in a relatively small and inadequate arsenal of sensory aids, largely due to the problems noted above--lack of coordination of long-range objectives, and of funding. Talking books, braille, and sighted readers (although inadequate) still are used instead of portable reading aids or automatic text-reading systems which are technically feasible and potentially more flexible. In mobility, modern technology has had no significant impact; the dog guide and the long cane remain the most effective mobility devices in use.

The Needs of the Deaf

Deafness, while not as conspicuous as blindness, is as serious. Not only does the inability to hear deny an important source of information, but in addition deafness may impair a human activity of great importance--speech--and impede the development of the most important component of thought--language. Educational retardation of from three to five years is commonplace in an intelligent child who is born deaf or loses hearing before acquiring language. Speech comes slowly (and sometimes not at all) as the deaf student struggles to produce sounds he cannot hear. Social awareness and maturity are also frequently delayed because of the child's inability to learn through listening. A deaf child has far more potential for a self-supporting adulthood if he can learn to use speech and language effectively, yet most deaf children presently do not reach an achievement level much above eighth grade. It is therefore not surprising that 80 per cent of deaf adults find themselves in unskilled, dead-end jobs. Thus deafness, like blindness, can impose severe economic penalties.

The three interrelated problems of deafness--those of speech, hearing, and language--require quite different approaches. A person who loses his hearing after learning to speak will usually retain his speech despite a tendency for the speech quality to deteriorate. On the other hand, those who are born deaf or those who become deaf very early will not independently learn to speak or perceive speech. These people require not only prosthetic aids to facilitate communication with others, but they also need some means of acquiring the abstract concepts of symbol manipulation on which all language depends. A relatively mild hearing loss can be adequately overcome with common hearing aids that simply amplify the important acoustic energy of speech. Thus, persons with such partial loss may need only a relatively simple sensory aid and some training in using it.

A variety of sensory aids for the deaf have been developed, and most of them have been directed to the problem of salvaging residual hearing. They operate either by giving as much useful sound amplification as possible or by transforming portions of the acoustic signal for use by intact parts of the hearing system or by other sensory channels. But even though the essential technology for such devices is well established, and the aids are ingeniously designed and earnestly applied, only limited utility has been achieved. For most of the devices, the design has been ad hoc, many of the user's perceptual requirements remain unknown, and training and evaluation techniques are rudimentary.

A Plan for Action

The problems of the deaf and the blind are not identical, but there are similarities. Both groups need help in dealing directly with their surroundings on a day-to-day basis. Additionally, the prelingually deafened must learn the speech skills and language concepts necessary for normal development and social intercourse.

Basic research on the role of the unimpaired senses in learning about and communicating with the environment is essential to an understanding of the kinds of aids that could be used by both the blind and the deaf. Sensory devices can be developed to give blind adults access to the printed word and to give deaf adults access to the spoken word as well as the ability to monitor their own speech production. For both, other kinds of aids could improve their mobility and safety in an environment the blind cannot see and the deaf cannot hear. For the very young deaf child, there is the urgent need for devices that will early detect a hearing impairment and for research to discover how these children can acquire language. And for all concerned, education is crucial--for training the users of sensory aids and for preparing their teachers.

Thus the needs of both the blind and the deaf have four important elements in common:

1. Communication with the environment
2. Engineering interfaces with physiological senses
3. Education
4. Synergistic organization and administration of science, technology, and human engineering.

The organizational and research strategies for such an effort will involve diverse and complex problems. Solutions cannot be expected from individual inventors or from service organizations devoted to conventional welfare. Rather, what is required is a comprehensive national program which embodies the following elements:

1. Information. Collection of demographic data; assessment of sensory needs; dissemination of information about relevant research in medical, psychological, and technological areas to planners, investigators, educators, the sensorially impaired, and the general public.

2. Research and Development. Identification of fundamental problems requiring basic research, and of sensory aids meriting immediate development. Stimulation of research and development in university, government, and private laboratories. Performance of research (especially where the complexity of the problem or scale of effort requires concentrated resources) and following through from that research to practical development.

3. Evaluation and Deployment. Assessment of prototype devices for technological, physiological, and psychological adequacy and for user acceptance. Development of systematic methods for the evaluation of sensory aids. Establishment of effective training and deployment procedures, particularly in educational settings.

4. Funding. Identifying and securing financial support for the operating program outlined above, for cooperative efforts between organizations, and for the high cost of proceeding from evaluation in the laboratory to deployment and maintenance in the field. Without such follow-through, even the best of sensory aids lies fallow and useless.

Organizational Options

Various kinds of organizational arrangements for carrying on the foregoing activities will need to be considered since each kind has merits and limitations. Although the more than 1,000 organizations currently providing service to the deaf or blind are useful, not one is adequate for the total program outlined above. New organizations are required, and it is important to determine how the existing ones will be utilized and interfaced. Although separate organizations will be needed to deal with problems of the visually impaired and with those of the auditorially impaired, the factors that affect the choice or organizational arrangement are much the same and may be considered together. Some alternatives that could achieve the desired actions are:

1. National Centers, created within the federal government to execute and to subcontract research, development, and deployment. Both intramural and extramural programs would be pursued. These mission-oriented federal centers would resemble agencies like the National Center for Health Statistics or the National Communicable Disease Center.

2. National Laboratories, existing outside the federal government and probably associated with universities. Even though established in cooperation with the government and funded by it, these centers would operate independently. They would resemble such national laboratories as Argonne, Lincoln, or Oak Ridge. The recently established Rehabilitation Engineering Centers represent a movement in this direction.

3. National Foundations, independent of the government (at least initially) and neither funded nor operated by the federal establishment. They would be supported by foundations, universities (possibly by government contracts), and industry; however, they could be planned for eventual phaseover to federal support. Small-scale models for such national foundations exist as research institutes attached to many universities; on a national scale, examples are the Woods Hole Oceanographic Institution, Carnegie Institution of Washington, and the Salk Institute.

Other organizational arrangements, less ambitious and less adequate than these national establishments, might well serve as lead-in, relatively short-range approaches. Two such possibilities, not necessarily exclusive of each other or of the national organizations, are

1. Interagency Coordinating Group(s), created within the Executive Branch of the Federal Government to guide in problem identification, to act as an information clearinghouse, and to integrate activities and reduce overlap among the many agencies serving the sensory-handicapped population, and

2. Seeding Centers, utilizing key individuals who would be deployed as nuclei in university environments or elsewhere to initiate research, development, and small-scale evaluation and deployment of sensory aids. The principal aim would be to stimulate new researchers and to encourage new pilot projects. These individuals would be identified and encouraged by an informal central directorate such as that which can be provided by the national academies.

For each of these five ways of organizing a national effort, there are advantages and disadvantages. One must consider, for example, the ease with which the present establishment would allow its formation, its ability to have an impact (particularly on federal agencies), its efficiency and its flexibility. In our Academy position paper, we have discussed some of these pros and cons in more detail.

The foregoing plans for action at the national level are only outlines. The set of possible organizational arrangements may need to be expanded, but even the five possibilities I have listed require elaboration and careful study before one could feel comfortable in recommending one over another. The conduct of such a study and the development of a rational design for an integrated national sensory aids program thus becomes an urgent and immediate challenge.

Recommendations

It is our Subcommittee's contention that a national task force should be assembled to serve as a central focal point and to perform the prerequisite study and plan. The task force would have two primary objectives:

1. To manage two major analyses which would include an extensive study of needs of the sensorially handicapped, the characteristics of existing service agencies, and alternative strategies for interfacing new organizations to those agencies to bring about the needed changes with maximum effect.

2. To examine and evaluate various organizational and funding arrangements including those suggested above, recommending courses of action with detailed plans for implementation.

These two efforts would enable the task force to satisfy its most important goal--the development of a realistic long-term plan to apply sensory aids in the amelioration of blindness and deafness. In a two-year period of time at a cost of around $600, 000, we believe that a concerted effort on the part of the task force would result in the completion of a national program plan. Further, implementation of the plan could be well underway. In addition and in parallel with the development and initiation of a coordinated national program, the task force would have other functions, including advising on research and development needs, serving as an information center, conducting topical conferences and workshops, and stimulating the evaluation and deployment of currently available devices and techniques that would have immediate payoffs to sensorially deprived people.

For objectivity, such a task group should operate outside the federal establishment, but its work would be useless if its objectives were not accepted by the agencies involved. Its output will include a recommendation to the nation; those responsible for participating in the ensuing program must be receptive to its purpose.

We in the Subcommittee on Sensory Aids are convinced that the goals presented in this Plan for Effective Action are both vital and achievable. It remains for all of us to debate the issues not much longer, for there are people in need who await our skills.

SENSORY AIDS FOR THE DEAF - KEY PROBLEM AREAS

by

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Summary. The development of sensory aids for the deaf presents an important engineering challenge, but one in which technological advances are highly dependent on developments in other areas. Among the key problem areas, are determining how the speech and language development in a deaf child differs from that in a normal child, determining the extent to which residual perceptual capacities can be used for speech reception, developing new diagnostic techniques, and improving methods of evaluation of new and existing devices. Aside from long-term basic research projects there are a number of short-term projects, which will provide immediate benefits. These include the development and widespread deployment of inexpensive teleprinters for the deaf, the development of efficient screening procedures for early detection of hearing impairments, and specific improvement to comventional hearing aids.

Introduction

The development of sensory aids for the deaf has progressed at a relatively slow rate over the past two decades. Thus, for example, despite the spectacular technological advances over this period, an auditory aid that is superior to the conventional hearing aid has yet to be developed. The last few years have seen a substantial increase in the research effort geared towards the development of sensory aids for the deaf (1-6), much of which is characterized by attempts to apply modern technology to the problem at hand. Because of the diverse inter-disciplinary nature of sensory aid development there is a danger that much effort will be concentrated in finding elegant engineering solutions to problems that in the long run may be of minor importance. The purpose of this paper is to try to provide a balanced overview of key problem areas in the development of sensory aids for the deaf.

Although most of the problem areas identified in this paper are notprimarily technological, there is an important engineering challenge in providing the means to investigate these problems. Also, the answers to the research problems listed belowwill, in turn, dictate the technology needed to produce the desired sensory aids. The last section of the paper points to a number of short-term projects using existing technology which will produce immediate benefits.

Any attempt at delineating key problem areas in the development of sensory aids for the deaf must take into account the heterogenous nature of the hearing-impaired population and the separate needs of distinct sub-groups within this population. Two of the most important groups are adult sensorineurals (mostly presbycusics) and congenitally or prelingually hearing impaired children. The former group is by far the largest and the latter group by far the most severely affected. Within each group, there are also substantial differences in the degree of hearing impairment which have to be considered because their needs are quite different. The adult sensori-neurals typically require communciation aids which will compensate a gradually failing auditory system. In addition to a communciation aid, the prelingually hearing impaired child requires substantial training to develop a speech and language capability. Because of the severity of the consequences of prelingual deafness, most (but not all) of the problem areas identified in this paper deal primarily with the development of sensory aids for the hearing-impaired child.

Although there are some technically advanced aids for use by individuals with conductive hearing impairments, these aids are not considered in detail because of the relatively small number of people who suffer debilitating conductive hearing impairments. Most conductive hearing impairments can be successfully treated by surgery or by conventional bone conduction hearing aids.

In drawing up this list of key problem areas the author has drawn heavily on the deliberations of the subcommittee on sensory aids of the National Academy of Engineering which is currently in the process of preparing a document on priority research needs in this area (8). Other important sources of information are the Proceedings of the Conference on Sensory Training Aids for the Hearing Impaired (3) and CHABA Report 65 (9). The opinions expressed in this paper are, of course, the responsibility of the author.

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* Also at the Lexington School for the Deaf.

Key Problem Areas

Fundamental Research on Speech and Language Acquisition in Deaf Children

Whereas only a modest amount is known about speech and language development of normal children, even less is known about speech and language development of deaf children. Neverless, crucial decisions on the education of deaf children are continually being made. A key assumption underlying many educational programs is that language acquisition in deaf children follows the same essential pattern as for normals, except that the time scale is considerably extended. Recent developments in psycholinguistics provide useful guidelines with which language development in deaf children may be measured. In order to better plan the education of deaf children it is important to establish whether language acquisition in the deaf follows the same hierarchy of development (albeit on an expanded scale) as in normal children, or whether basically new language forms are being developed.

The orientation of this research effort should be concerned not only with the process of speech and language acquisition and how it is affected by hearing impairment, but in determining what the remedial needs are and what can realistically be achieved. The phrase speech and language is used throughout since it is believed that the two are intimately interwined and that both oral and written forms of language should be investigated.

Quantification of Residual Perceptual Capacity

The intellectual development of the deaf child is crucially dependent on all of his perceptual abilities. This includes residual hearing capacity as well as perceptual capacity in other modalities. Methods for quantifying the information handling capacity of the visual and tactile modalities in the deaf child need to be investigated. Since the deaf child frequently also suffers from other sensory impairments, the possibility of concomitant sensory impairments needs also to be considered.

The specification of hearing impairment in terms of the audiogram only is clearly inadequate and more appropriate methods of specifying residual hearing are needed. Some research on the relation between residual hearing and speech perception is currently in progress (10) but much more needs to be done.

The future development of sensory aids is heavily dependent on the extent to which residual hearing or other modalities can be used in the transfer of information. It is possible that the potential for inter-modality transfer may be crucially age dependent and this should be considered in investigating inter-modality transfer.

The search for practical substitutes for speech should be pursued. The failures encountered in the search for acoustic, non-linguistic substitutes (11) should serve as a guide in avoiding non-productive avenues of investigation. A promising approach that merits immediate consideration is that in which key articulatory information (e.g. place, manner, voicing cues and/or prosodic features of human speech are presented visually or tactually as an aid to speechreading. The problems of automatically extracting such information from the acoustic speech signal are not trivial and need to be studied.

Improvement of Diagnostic Techniques

Closely linked to the problem of quantifying residual hearing capacity is that of accurate diagnosis of hearing disorders. This is a constantly evolving process, but at this point in time special emphasis is necessary in developing reliable audiometric procedures for very young children and in developing tests of communication ability which realistically predict the hearing impaired individuals performance in real-life situations (e.g. speech perception under noisy or reverberant conditions and capacity for handling and interpreting distorted speech signals). Methods for establishing measures of speech reception at the feature, syllable, sentence and paragraph level have been suggested by Miller (ref.3 page 78) and these techniques should be investigated.

Objective Evaluation

A major obstacle in the development of sensory aids for the deaf has been the paucity of objective evaluative data on new or existing devices. Without a body of objective data on which to build it is virtually impossible to make progress in any systematic or reliable way. The problem of evaluation however runs deeper than determining what a device can or cannot do. It is important to consider such larger issues as the potential impact of the device on the child's overall development and whether special training with the device represents a worthwhile investment of the child's time.

In order to greatly increase evaluative effort it is necessary to develop objective evaluation techniques that are both efficient and practical. One of the advantages of a computer-based training system for example, is that the childs progress with a new device may be measured objectively, unobtrusively, and with little additional effort during regular training sessions. Specific problems to be considered in the development of evaluation procedures are rate of progress, transfer of skills, after specialized training. Efficiency of evaluationis of considerable importance and the use of sequential or adaptive testing procedures should be considered as a means for terminating experiments as soon as a significant improvement (or lack of improvement) is established.

Speech Training Aids

Of the various types of sensory aid that have been developed in the past few years, speech training aids appear to have the greatest potential for success (12). The aids that have been developed and evaluated thus far cover only a limited range of speech problems. They are also used primarily for remedial work rather than aiding speech development. New aids need to be developed that will cover a wider range of speech problems as well as aids for very young children to aid speech development. Consideration should also be given to the development of semi-automated or computer-controlled speech-training aids that can be used for self-tutoring or for simultaneous, concentrated training of several children by one teacher.

Conventional Hearing Aids

Considerable research is still needed on finding the optimum electro-acoustic characteristics of hearing aids and on ways for "fitting" deaf and hard-of-hearing persons with aids that best satisfy their individual requirements. To do this, hearing impairments have first to be classified according to their origin and phsysiological nature, as well as according to the social, educational and communicative stiuations in which they offer the most serious handicap. The hearing aid requirement of each of these groups will have to be determined experimentally and clinical procedures for fitting individuals with the most suitable aid investigated. This must include investigation of the ear mold as well as the electronic device itself. A detailed review of work in this area is that of Ling (13).

A number of design improvements which could be introduced immediately are smoother frequency response curves, reduced non-linear distortion (especially when battery power begins to drop), and the development of practical directional microphones. Special consideration should be given to the problems of hearing aids for babies and young children. These include physical robustness, small size, improved earmold design for small and growing ears, and some means of monitoring externally (e.g. by the teacher) whether or not the aid is working properly.

Optimum specifications need to be developed not only for wearable hearing aids, but also for group hearing aids (wireless or loop). The latter would include consideration of factors such as frequency response, permissable distortion levels, and the relative levels of the teacher's voice, the child's own voice, and other childrens' voices.

For more detailed information on research needs for hearing aids see reference (9).

Administrative-Organizational Needs

In addition to the above problem areas all of which require substantial, long-term research efforts, there are a number of projects using existing technology which would have immediate and invaluable benefits at a moderate cost. There are (i) establish a nationwide program for screening all babies before the age of 1 year for evidence of hearing impairment or other sensory defects, (ii) get hearing aids fitted to all infants immediately they are diagnosed as hearing impaired, (iii) provide teleprinters at nominal cost to all hearing impaired who need on and (iv) Provide rehabilitation facilities for adults with progressive and sudden hearing impairment where orientation to protheses and social/vocational situations may be obtained.

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SELECTED RESEARCH, DEVELOPMENT AND ORGANIZATIONAL NEEDS TO AID THE VISUALLY IMPAIRED

by

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Summary. The National Academy of Engineering, through its Committee on the Interplay of Engineering with Biology and Medicine and Sub-Committee on Sensory Aids, is about to publish a list of projects which it is believed could significantly accelerate the progress being made toward the development of new devices and services for the visually impaired. The Academy of Engineering has earlier argued the need for a coordinated program of sensory aid development and the list of projects names some of the more important components of such a coordinated program. The items are divided into two categories -- short term projects which can be attacked immediately with the expectation of early results and those which should be initiated now with long term objectives.

The present paper points to some major features of the NAE proposals and indicates the reasons why we need a coordinated effort toward the development of sensory prostheses for the visually impaired.

Introduction

The title of my paper has been borrowed from the title page of a working paper which is about to be published by the National Academy of Engineering (NAE). Anyone wishing to obtain a copy may easily do so by applying to the NAE. My paper will describe something about the background to this document, indicated a little of what it contains and intersperse a few comments.

I think that most people here will be well aware already that the idea of using current technological accomplishments to aid the blind in reading and mobility is not new. The recently developed devices which have captured the interest of many people are not the only aids to have been invented.In fact the history of such invention dates back to the beginning of this century and perhaps even earlier. What makes many sensory devices interesting today is not their novelty so much as that current technology has made much more practical the possibility of constructing them compactly and inexpensively. However, we must ask whether technical limitations have been the only bar to progress in the design and manufacture of useful sensory devices? Can we expect that, with this single development (better technology), we can now begin to make real progress toward providing genuine assistance to the visually disabled? Many people (and I must admit to being one of them) believe that the answer to both of these questions is no. It is not merely technology which has held us back. Why then despite seventy years or so of effort do we still, for example, not have a single mobility device for our blind population that can hold a candle to the dog-guide or the long-cane? The reasons derive from a number of problems most of which are not unique to the sensory aids field but when present in combination as we find them here, they form a very serious barrier which must be recognized and removed if real progress is to be made.

Conflicts in the Development and Distribution of Sensory Aids

The problems for the most part are not difficult to see. They were reviewed in a report published by the National Academy of Sciences (NAS) in 1968 (1). Let me touch on some of these problems now. First and foremost is the enormous scope of the assignment--the development of a device which must serve as a substitute for the visual system in cerebro-motor tasks of great complexity. Too often this complexity is overlooked or underestimated and many devices (some of which are conceived over and over again) made demands on the skills of the user which go well beyond his ability to respond. Thus he is unable to operate the device at the speeds which are required in practical situations. For example he may be able to read by ear or touch using a simple acoustic or tactile transducer but so slowly that boredom rapidly sets in and the device is soon rejected except for very limited tasks.

Sometimes the quest for a simple device is dictated not necessarily by the designer's lack of imagination, so much as by his knowledge that the blind population cannot bear the cost of a more complex device and by his assumption that society as a whole will not be prepared to bear the cost either. With this fact in mind, it is indeed surprising that the blind population of the United States (more than half of which has an average income of less than \$4000 per year (2)) can still be thought of as if it constituted a market in the commercial sense--yet many would-be designers of sensory aids and devices do still think in these terms and the spirit of individual entrepreneurial enterprise is still very much alive. The paradox here is even more striking when it is realized that the overwhelming bulk of all development work being carried out today is being supported by public funds. However, the reason for this contradiction probably lies in the fact that much of the work is being supported as if the blind population was expected to eventually provide full market support through the purchase of devices, once their basic research and development has been completed. Thus the emphasis of current research is still focussed primarily on simple low cost devices--devices which can demonstrate early successes but probably having very little potential for the improvement needed for ultimate practical use by a significant number of blind people. The funds made available for research and development are consequently small and, in their turn, severely circumscribe the vision used in seeking new ways of providing potentially useful sensory devices. Limited funds from numerous agencies also lead to the setting up of small fragmented projects which are uncoordinated with one another; duplication of effort thus inevitably occurs in addition to the repetition of old mistakes and ideas. Moreover, in the event that sensory aids of some merit are developed, their deployment is severely handicapped due to a total lack of the kind of forward planning required to provide essential capital to set up manufacturing, distribution and training facilities. The prevailing assumption appears to be that these aids should be able to attract venture capital on a return on investment basis. However, as has already been pointed out, the blind population is economically weak and cannot compete with the many other markets open to an investor. Thus even useful devides tend to be ignored and the population they could serve continues to be neglected.

I have just given a brief summary of the situation described in the NAS report (1) which points to the conflicts which pervade and hinder efforts to develop sensory aids. The report makes clear that we even have no very clear definition of what the major needs are among the blind and what our priorities should be. Furthermore at the time the NAS report was released (1968) no serious study had been undertaken or was planned which could lead to such a definition of what our goals should be and the social and economic importance to our society of attaining those goals. However, in 1971 the National Academy of Engineering put forward 'A Plan for Effective Action' within which the steps of research, development, evaluation and deployment could be coordinated in an orderly and expeditious way (3). The details of this plan will be described by Mr. Garrett in his paper presented at this conference, so I will not say anymore about it now.

Projects to Aid the Visually Impaired

One of the major themes of the NAS report was that there were opportunities available for the development of sensory aids which were essentially untapped. In an effort to point out some of these missed opportunities the National Academy of Engineering's Sub-Committee on Sensory Aids recently published a working paper with the title I have taken (borrowed) for this paper. The document contains a list of projects--not an exhaustive list but a selected list of Research, Development and Organizational needs. Many of the projects are unexplored, but not all. By the standards set by current efforts some may be judged ambitious (which is not to suggest that this is a fault) but again not all have this trait. Together the suggested projects are seen as comprising many of the opportunities which should be explored in any program claiming to be comprehensive--the kind of program which must be mounted if we are to be able to say that we are making a serious effort to develop effective sensory aids without unnecessary delay.

The NAE paper is divided into two parts: short term projects which can be attacked immediately with the expectation of early results and those with longer term objectives which, in the opinion of its authors, should nevertheless be initiated now. I will briefly run down its list of contents and then describe a few selected projects in more detail.

The short-term list includes a demographic survey of reading aid needs; provisions for the exchange of information between investigators; pilot studies of the potential usefulness of automated reading services; work on the development of those services; the development of new mobility aids and new tactile stimulators; further research and development in the field of automated braille production; the formulation of better definitions of visual capability among the partially sighted and the development of special devices to aid both the blind and the partially sighted to perform certain vocational tasks.

The long-term list calls for demographic surveys of vocational opportunities; programs to inform the general public of the benefits which could be reaped from research designed to enhance the participation of the visually disabled in our society; the establishment of one or more sensory aid centers; the performance of some essential basic research on human mobility, visual pattern processing and reading and finally a feasibility study of automated reading services provided via the telephone.

I do not have the time to go into all the details which the paper provides on each of these topics. I will therefore only touch upon a few by way of an illustration.

First the proposal for a demographic survey of reading aid needs, points out that past efforts toward making reading matter available to the blind have been made in the absence of any reliable information on the reading needs of the blind public. The survey advocated in the paper would consider such variables as the type of reader (student, housewife, businessman, etc.), biographical data (degrees of handicap, education, etc.), the type of material required (type styles and size used, its variability and format, etc.) and the preferred output sensory medium (tactile, or auditory modality or a magnified visual image). The fact that this proposal appears as the first on the list is of course no accident. An accurate description of the scope of the problem must be obtained as a logical first step. It may be of interest that a survey similar to the one proposed by the Academy's subcommittee was carried out in England about eight years ago and covered both the reading and mobility habits of the blind (4).

Second the Academy paper states that radar, sonar and lasers afford an important potential means of sensing the environment. However, their promise for the blind is still largely untapped although some initial efforts have been made. The report encourages the development of a more innovative approach to the use of these media by first establishing what information about this environment the blind traveller needs to know and then seeking the means of extracting this information utilizing the best sensors now available (5).

Further research and development on automatic braille production is also advocated. The thrust of the proposals is directed toward the development of optical readers suitable for the kind of reading matter which must be transcribed into braille, the acquisition of teletypesetter's magnetic or punched tapes from publishers, the development of a centralized library of such tapes and the design and development of the necessary automated production equipment. As many of you will already be aware some motion toward automating braille production has been underway for several years. The major difference of approach proposed by the Academy committee is that a direct effort should be made to develop the necessary equipment in those areas where in the past researchers have tended to wait for technical developments inspired by the business and commercial market and funded almost entirely from that source. While keeping the costs of braille research low, this policy has caused slow progress owing largely to differences between the needs and priorities of the braille and business communities.

Yet another proposal concerns a study of the usefulness of automated reading services for the blind. These services could provide blind subscribers with tape recordings of computer generated speech from any designated printed text. Working in a similar way to the talking book service of the Library of Congress or Recording for the Blind, an automated service could provide a recording of a new book much more rapidly than is currently possible using human readers (in a matter of hours or days rather than in months). Now again, work has already begun on this project at Haskins Laboratories and elsewhere and Jane Gaitenby and her colleagues will discuss some details of this project at another session of this conference. However, despite the fact that enough progress has been made for, we at Haskins to say that we know that we could build a machine to provide a reading service, we are painfully aware that there is a large gulf between showing that a machine can be made to work in the laboratory and getting it into service outside. A small academic organization, like our own for example, simply does not have the resources in manpower and space (not to mention funds) to carry out the surveys and demonstration projects which might propel such a service into operation. The Academy proposal points to some of these important complementary programs which other organizations may be able to contribute in our own and other similar situations.

The last item I will mention concerns aids for the partially sighted who comprise about 80% of the so-called legally blind population (6). The suggestions put forward include a proposal for the better dissemination of information about existing optical aids, the setting up of standards for the closed circuit television systems which are only now becoming available for the partially sighted and the use of modular construction techniques to facilitate interconnection and thus maximize the aid as a teaching device for children.

Concluding Remarks

In conclusion, the working paper as its foreword tells us, is intended to stimulate new ideas and to encourage new people to work in the field of sensory aids. Many interesting and highly worthwhile projects are proposed for their consideration. However, the topics discussed are only suggestive and not exhaustive. The reader is urged to delve into the literature of published reports if he is to really come to grips with the details of each problem area.

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MAGNETICALLY COUPLED STIMULATION OF THE OSSICULAR CHAIN IN KANGAROO RAT AND MAN

by

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Abstract. An electromagnetic device was used to drive the ossicular chain of kangaroo rat and man. Electrical potentials recorded from the cochlea of kangaroo rat to such a drive were the same as when acoustic stimuli were used. The same device, when used to drive the human ossicular chain, initiated sound sensations which were undistinguishable from those generated by earphones.

Introduction

This research was undertaken in order to develop and evaluate an electromagnetic device to drive the ossicular chain better than the currently used hearing aids.

In 1959, Rutschmann (1) reported that electromagnetic stimulation of the eardrum provided "auditory experiences...in a band of frequencies from 2,000 to 10,000 cps" and that subjects "have listened to broadcasting programs and claim that the reproduction was satisfactory." The subjects in these studies were patients who had undergone either electroconvulsive therapy or psychosurgery. Although the findings were encouraging, no further reports were forthcoming.

Several years later, a study on the response properties of primary auditory neurons in cat was conducted using an electromagnetic drive of the eardrum (2). The objective of this research was to show (and it did) that either "attraction or repulsion" of the eardrum was sufficient to drive auditory neurons. This study used powdered permanent magnets that had been pasted on magnetic tape. Small pieces of the magnetic sheet were pasted on the eardrum and a powerful magnet was used to polarize the eardrum causing an attraction or a repulsion, depending on the polarity of the pulse. This study did not provide details about the cochlear microphonic responses for such stimulation.

The present study was undertaken in order to measure and compare the cochlear microphonic potentials generated by acoustic and electromagnetic stimulation and to use electromagnetic stimulation to transmit sound to the human ear.

Methods

Five kangaroo rats (D. spectabilis) were used in the studies in which the cochlear responses were obtained. They were anesthetized with sodium pentobarbital, following which a nichrome wire was placed near the round window of each cochlea. The animal was placed in a stereotaxic instrument and sounds were delivered through hollow ear bars which were attached to the instrument. One end of each ear bar was inserted carefully into the ear canal and an earphone was attached onto the other end. Acoustic stimuli of various intensive and frequency combinations were used. The cochlear potentials to these stimuli were recorded on magnetic tape for subsequent comparison to electromagnetic stimulation.

Following these recordings, one ear was freed from the ear bar and a small magnet, measuring less than 1 mm^3 (9.0 mg) was glued to the umbo of the eardrum with an adhesive. A coil was positioned within 1-2 mm of the magnet. The coil (Fig. 1) had a resistance of about 2.0 ohms and

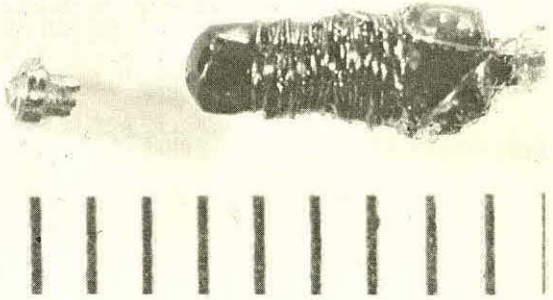

Fig. 1. Coil and magnet used to drive the ossicular chain. Vertical calibration marks are in millimeters.

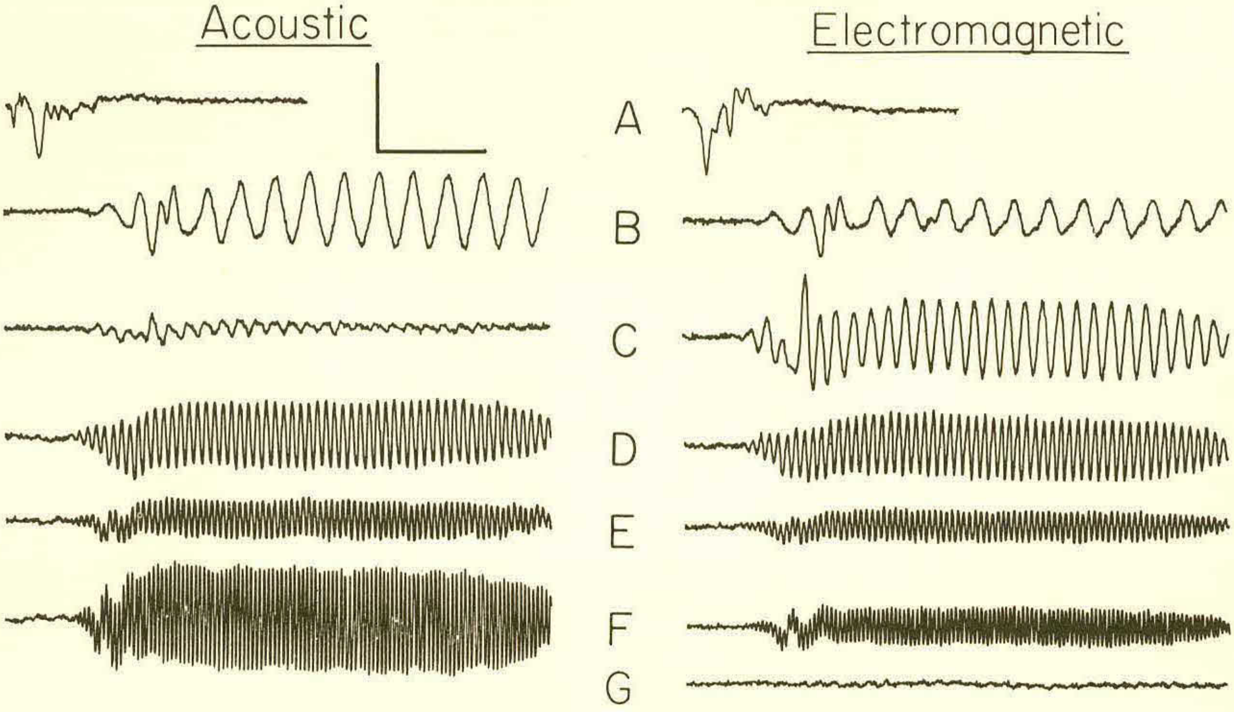

Fig. 2. Cochlear potentials to acoustic and electromagnetic stimulation. Each response is the average of 25 stimulus presentations. Clicks were generated by a 0.10-msec square pulse through earphones and coil. Acoustic tones (20-msec duration; 5-msec rise-fall) were delivered across earphones. Sinusoids into coil were also 20 msec, with 5-msec rise-fall time. Attenuations for acoustic tones are below a reference level of 125 dB (SPL) for a 1.0-kHz sinusoid measured from a 6.0-cm^3 coupler. (A) Click, -65 dB acoustic and -30 dB electromagnetic. (B) 0.5 kHz, -85 dB acoustic and -65 dB electromagnetic. (C) 1.0 kHz, -85 dB acoustic and -50 dB electromagnetic. (D) 2.0 kHz, -85 dB acoustic and -50 dB electromagnetic. (E) 3.0 kHz, -85 dB acoustic and -50 dB electromagnetic. (F) 4.0 kHz, -85 dB acoustic and -50 dB electromagnetic. (G) 1.0 kHz, -30 dB through coil without magnet on umbo. Vertical calibrations represent 100 µV and horizontal calibrations 6.0 msec. Note that the action potential response appears most distinctly in B for the acoustic and electromagnetic drive.

inductance of 33 µH. It was driven to a maximum level of 0.1 W by a 1-W amplifier and was coupled to the amplifier through a transformer network to provide appropriate impedance matching. Various combinations of frequency and intensity were used to drive the electromagnetically coupled device. The cochlear potentials to this stimulation were recorded on magnetic tape.

In the study with a human subject, the magnet was placed on the umbo of the eardrum with a thin layer of Aquaphor. The subject lay on a table in an acoustically shielded booth. The coil was positioned near the magnet and sounds--including speech--were delivered to the coil.

Results and Discussion

Figure 2 summarizes the results of one of the kangaroo rat studies. The figure shows the acoustically evoked cochlear potentials and the electromagnetically evoked potentials to a limited number of sounds. Comparison of the potentials shows that they are strikingly comparable.

The acoustic and electromagnetic stimulators were used to drive the ears over an intensive series for frequencies between 0.5 and 4.0 kHz. Trace G in Fig. 2 shows the averaged trace which was obtained before the magnet was placed on the umbo. An intense 1.0 kHz signal was delivered through the coil. It is clear the coil does not generate a response in the absence of the magnet.

The microphonic potentials generated by both the acoustic and electromagnetic stimulator varied identically as intensity was increased or decreased, at all of the frequencies we presented (Fig. 3).

In order to firmly establish that the microphonic responses to electromagnetic stimulation are real, we administered a lethal dose of sodium pentobarbital to the animal and measured the microphonic ampli-

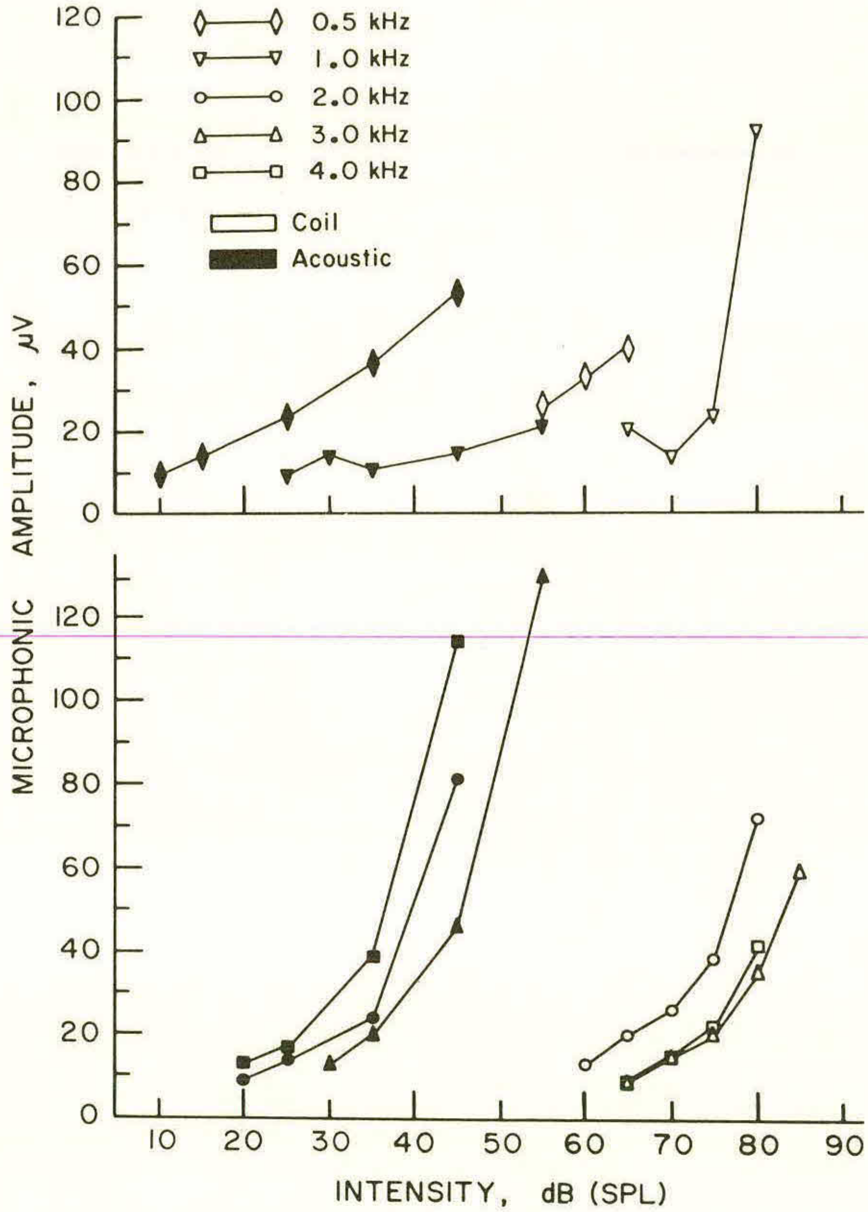

Fig. 3. Intensive functions of microphonic potential to acoustic and electromagnetic stimulation.

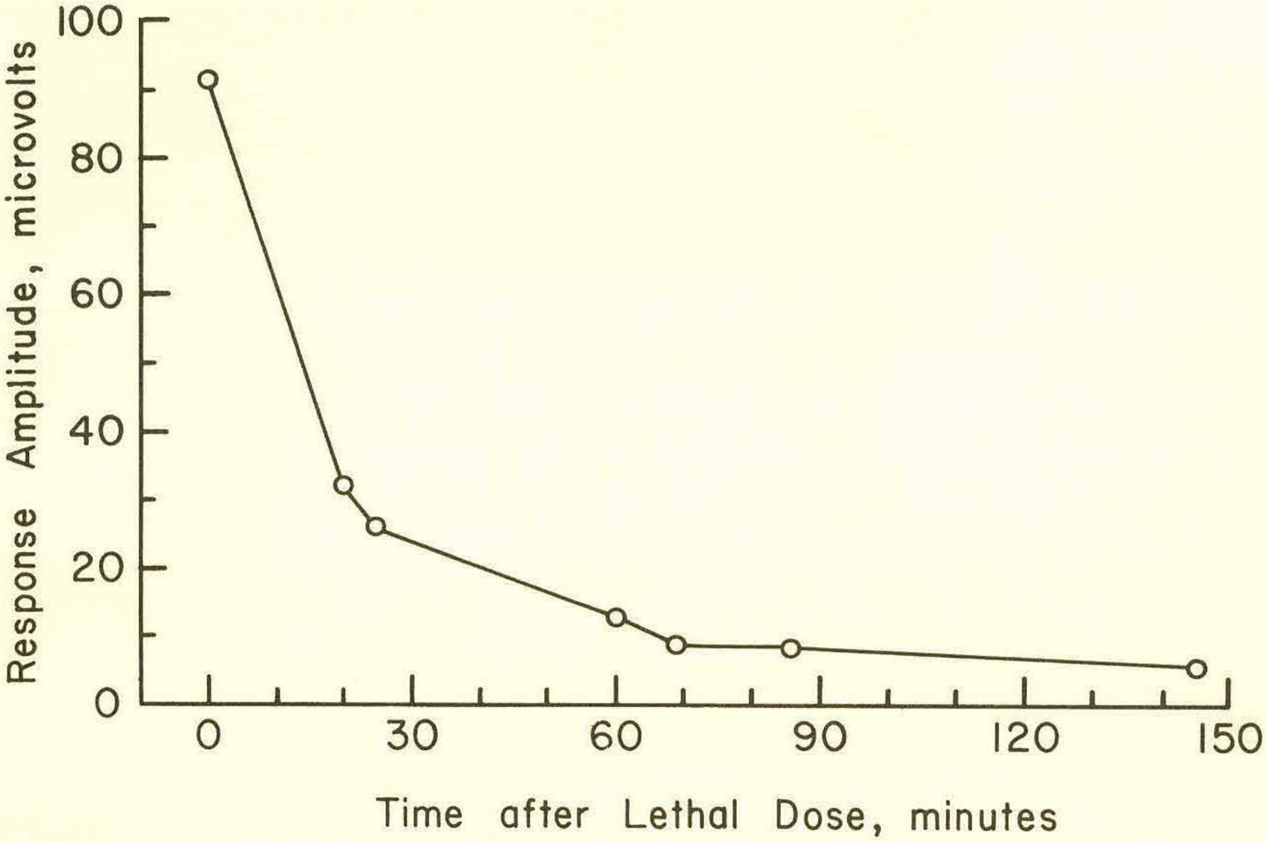

Fig. 4. Decay of microphonic potential following lethal dose of sodium pentobarbital. All data points are response amplitudes of microphonic potential to a fixed-intensity 1.0 kHz signal.

tudes at various times after the administration of the drug. Figure 4 shows the decay of the response over a 150 minute period.

The results on the human subject are preliminary but, nonetheless, striking. Through electromagnetic coupling, he heard sounds, some of which were whispers, with a clarity equal to sounds generated by earphones.

Acoustic amplification devices have peculiar disadvantages. Body aids amplify sounds produced by clothing and assist minimally in sound localization. Ear-level aids have gain limitations because of acoustic feedback.

The present study shows that the ossicular chain may be driven by a non-acoustic source. By this means, it is possible to eliminate the problem of feedback and still preserve the advantage of an ear-level aid.

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MECHANICAL SPEECH RECOGNITION FOR THE PARALYZED OR PROFOUNDLY DEAF

by

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Summary. Automatic speech recognition could serve the deaf by transcribing speech that cannot be heard to text that can be read. Or it could serve the paralyzed by providing speech control of mechanical devices. Past, present, and future trends in automatic speech recognition are discussed to shed light on the technical and economical prospects of using this tool to assist the handicapped.

Introduction

Xerox is engaged in a pilot research program investigating automatic speech recognition. At present, our efforts are not specifically intended to result in mechanical adjuncts for the handicapped. Nonetheless, we hope to contribute to a technology which, in a fundamental sense, would provide an alternate communication channel between a man and his environment, a channel requiring neither hands, nor fingers, nor ears. Automatic speech recognition will someday allow any man to cast his thoughts in writing several times faster than he could possibly type. Such written text might then control machines or be sent to a human audience. But this eventuality is several decades away and more immediate uses of automatic speech recognition (ASR) can be proposed, particularly for the handicapped. The possibility of economical voice control of mechanical devices will be explored in parallel with aids for the profoundly deaf.

The profoundly deaf may be able to learn to read "noisy" phonemic transcriptions of utterances before a machine is developed to do so. This is because of the basic inadequacies of machines compared to man in utilizing contextual cues. The "artificial intelligence" required for general continuous speech ASR will be years in coming. Meanwhile, members of the ARPA speech community, Xerox, IBM, and other organizations are developing techniques for mechanical abstraction of phonemic features from speech, as part of larger ASR projects, which might already be suitable for reading. Examples of phonemic utterance decomposition will be presented and an experimental reading program will be suggested after an examination of ASR for voice control of mechanical devices.

A Short History of ASR

Automatic speech recognition is about 20 years old. In 1952, an isolated word recognition unit was built by Davis, Biddulph and Balashek[1] at Bell Labs; they named it Audrey. It could recognize 10 digits in real time for a single speaker with 97% to 99% accuracy. The parts cost today for Audrey would probably be around $100.00. Since then over 100 independent researchers have built isolated word recognizers. Supporting institutions include such organizations as IBM, GE, RCA, Sylvania, Bell Telephone Laboratories, Bulova Electric, General Dynamics, The Royal Technicalogical Institute of Sweden, London University, Edinburgh University, M.I.T., Stanford, Bolt Beranek and Newman, Systems Development Corporation, Nippon Electric of Japan, Radio Research Laboratories of Japan, and Kyoto University of Japan, the Air Force Scientific Research Center at Rome, the Air Force Research Laboratory at Cambridge, the Maritime Electronic Laboratory in San Diego, etc. No commercially successful ASR device of any consequence has been developed in all these years. (However, this situation may be changing. A respectable product was brought out this year by Threshold Technology, Inc.) Even today, Audrey would be a strong contender among voice control units for controlling lights or bed heights for paralyzed people.

In 1958, at Bell Telephone Laboratories, Dudley and Balashek[2] built an utterance recognizer (which they didn't name) based on phonemic classifications. (The phonemic strings produced by this device looked much like the ones shown in Table 1, which were in fact produced this year by a new procedure at Xerox.) Like Audrey, it identified voiced continuants by a simple method primarily intended to measure the frequency of the first and second formants (resonances) in a speaker's voice. (In 1952, Peterson and Barney[3] demonstrated that most vowel sounds in General American English could be classified by simply measuring the first and second formants.) For Audrey, this was done by simply splitting the audio spectrum into a high frequency band (everything above 1000 cps) and into a low frequency band (everything below 900 cps). The frequency of the first formant, which lies in the low band, was found by counting zero crossings (the number of times the amplitude vs. time plot goes through zero). The location of the second formant in the second band was also found by

TABLE I. PHONEME STRINGS GENERATED FROM PRONUNCIATIONS OF TEN DIGITS.

ZERO	ZZZZZZZZFFEEEIIIIIII@@@OOOUURRRRRRRRRRRRRRRROOOOUUUUUVVV
ZERO	ZZZZZZZZFFIIIIIIIIIIIII@@UUUUURRRRRR@@@@@OOOOOUUUVVV
ONE	UUOOOAAAAA333333333@@NNVVVV
ONE	UUUOOOOAAAAAAA3333333333NNNNNVVVV
TWO	FFFFFFFFFIIIIIIIIIIII@@@EEEUUUUUUUUUU
TWO	FFFFFFFFFIIIIIIIIIIIIIEEEUUUUUUUUOOVV
THREE	FFFFFFFFFFRRRRRRRRR3333IIIIIIII@@@EEEEVVVVVVVVV
THREE	ZZZFFFFVVFFRRRRRRR333IIIIIIIIIEEIIVVVVVVVVVV
FOUR	FFFFF**OOOOOOOOOOOOOOOOOOOORROORRRRRRR
FOUR	ZZZFFFFFFFFFFVVAAOOOOOOOOOOOOOOOOORRRRRR
FIVE	VVVVFFFFFFFAAAAAAAAAAAAAAA333AAAAA3333@@RRRRRR
FIVE	VVVVFFFFFFAAAAAAAAAA333333AAAAA3333333333EEII@@@UUVVVV
SIX	SSSSSSSSSSSSSSIIIIIIII3333VVVV**********SSSSSSSSSSSSSSSSSS
SIX	SSSSSSSSSSSSSSSIIIIIIIII33IIVVVV**********SSSSSSSSSSSSSSSSSS
SEVEN	FFFFFFFFFFFFFFFFF3333333333UUNNNVV333333VVNNNNNN
SEVEN	FFFFFFFFFFFFFFFFFF333333AAAUUUUVVV33333VVNNNNN
EIGHT	IIIIIIIIIIIIIIIIIIIIEEEEFFVVV********SSSSSSVVVV
EIGHT	IIIIIIIIIIIIIIIIIIIIIIIIEEFFFVV*********SSSSSSVVVV
NINE	NNNNNN3333333AA333333333333333333EEEEEEEENNNNNN
NINE	NNNNN33333333333333333333333333333333IIEEEEEFFNNNNNNNNNN

counting zero crossings. The Dudley-Balashek device used an 10-channel, bandpass filter preprocessor which identified the two formants by the two channels with the most energy. Variations of these two forms of audio "preprocessing" (zero crossing and/or band pass filtering) have remained the favorites throughout the years, and the majority of successful systems that have worked in real time used one of them.

An interesting, inexpensive exception is "shoebox"[4], IBM's voice controlled adding machine, which was entered in the 1962 World's Fair. Simply measuring acoustic asymmetry enabled this device to run with better than 96% correct responses on its 15 word vocabulary.

An important feature of all ASR devices developed to date is that they perform well only for the single speaker for which they are tuned. Error rates increase by nearly a factor of 5 for new speakers. As a rule of thumb, the better systems over the past decade have run about 99% for the special speaker and about 94% on random speakers on a 10-word vocabulary. (Again, exceptions are beginning to emerge[5].) Furthermore, nearly all the algorithms used successfully on small vocabularies (15 words or less) have failed miserably on large vocabularies (100 words or more). There were only two systems prior to 1970 that did much better than 90% on large vocabularies (Bobrow and Klatt[6] and Vicens and Reddy[7]) and these required large scale computers. These large systems would be prohibitively expensive as aids for the handicapped.

Present and Future

Times are changing. Since 1970, the following events have occurred. Mark Medress[5] at Univac successfully demonstrated algorithms that recognized 100 words with 94% accuracy with no special tuning for the individual speakers. Threshold Technology, Inc.[8] built an isolated word recognition unit that gets 99.5% on 21 words with tuning for single speakers. (This unit is the only one commercially available in the U.S. and sells for about $15,000. It would be my first choice as a voice control unit today.) The Advanced Research Projects Agency of the D.O.D. decided to support speech research (these goals include: continuous speech recognition for a 1000-word vocabulary with near real time response) with about ten million dollars to be expended over a five-year period. (They are now one year into the project.) The Japanese government earmarked about half their total research budget for the next eight years (which amounts to over 100 million dollars) for the support of artificial intelligence research which includes ASR. Rumor has it that IBM is expanding their ASR effort in hopes of delivering a phonetic typewriter by 1980. Furthermore, IBM produced the first telephone ASR system enabling field engineers to dial up the ASR computer system in Raleigh, N.C. and to speak with a 13-word vocabulary of 10 digits,"yes",and "no" and a delimeter. No speaker adaptation is required. History was made this year in Reddy's laboratory at Carnegie-Mellon University with the first successful demonstration of continuous speech recognition. All this activity leads me to believe that this decade is destined to see some dramatic advances in ASR.

What will this do for the handicapped? For one thing, it seems likely that a single speaker 50 word, isolated utterance recognizer, running in real time at 99% accuracy, and costing less than $2000 will become a reality. I would hope that such a device would benefit the paralyzed by giving them speech control of mechanical assists.

The deaf may benefit in an unexpected and perhaps more dramatic way. ASR research may very well produce both a training aid and a communication tool. A visible phonemic decomposition of words uttered by a deaf speaker could enable him to see what sounds he has produced. Alternately he could see what his conversation mate has said.

Phonemic strings produced by algorithmic analysis of acoustic waveforms have never been very good. How good would they have to be for these applications? Recent experiments in perception provide an interesting answer.

Reading, Hearing and Perceiving

Keeping in mind that there are no natural word boundaries in continuous speech, consider the following phrase (from Broad[9]) which we may assume has been phonetically (or phonemically) encoded with no word boundary markers and given to a computer to analyze.

"THERE IS A JUSTIFIED PRIDE IN"
or is it "THEIRS A JUST IF I'D PRYED INN".
Is it THERE or THEIR; PRIDE, PRYED, or PRIED;
IN or INN; PRY DIN or PRIED IN, and so forth.

Problems of this sort don't occur for human users of English because they possess knowledge about likely meaning of language fragments (semantic knowledge) as well as a multitude of subconscious syntactic and phonological rules about phonemic sequences. A machine with no semantic or syntactic knowledge faces an impossible task when asked to reconstruct unambiguously the sentence above from its phonetic or phonemic encoding. (It is precisely this problem that stands athwart the path of progress of ASR for continuous speech.)

Evidence indicates that motivated people could read phonemic transcriptions of utterances very successfully in near real time for normal conversation.

First of all, we need to hear only relatively small fragments of speech to follow a conversation. Dennis Klatt at M.I.T. tells of an experiment wherein some tape recorded continuous speech was cut and spliced to produce isolated utterances from the once continuous speech. He found that only half the words could be recognized in isolation! Richard Warren and Roslyn Warren[10] found that a cough could be artificially recorded over an entire syllable of a word (e.g. the "gis" in "legislature") with no change in perception of the word. Listeners reported hearing a cough somewhere in the word, but were unable to tell in which part of the word the cough occurred. Furthermore, reading experiments[11] by Kolers indicates that people do not read many individual letters in words. In fact, if one were required to read letter by letter, his top speed would apparently be about 35 words per minute. Readers rely heavily on gross word morphology and (here we are again!) semantic and grammatical knowledge: Pe*ple c*N re*d w*ll w**h *h*le s*gm*nts *f w*rds miss*ng.

In summary, we neither hear nor see all that we think we do in natural language communication. Our mental eyes and ears are continually filling in gaps in words for segments that either don't exist or that are not really necessary to the message. So we could probably read poor phonemic strings. Just how poor remains to be resolved by experimentation.

For example, a good experiment might incorporate a real time phonemic transcription aparatus, a programmed language course and viewing glasses providing a split field of vision. One of the students eyes should be continuously monitoring phonemic strings produced by his conversation mate while the other eye is free to observe lip movement and other gesticulations. Training would procede more or less as in learning a foreign language. Evaluating the size the vocabulary learned in a given time period as a function of phoneme string quality should tell something about the value of such a system for the deaf.

Automated Phonemic Utterance Transcription

Table 1 contains phoneme strings generated in our laboratory from pronunciations of the ten digits, each repeated twice. Our research goal is to develop a complete ASR computer system, and so these strings were produced somewhat as an afterthought to illustrate the concept of phonemic string reading.

Our isolated word ASR system achieves 99+% for 10-word vocabularies for a single speaker in real time using only phonemic character strings such as those in Table 1!

Speech input is band passed filtered into 6 octave channels, the highest frequency passed being 10 kHz. The voltage in each channel is summed up for 10 ms digitized and sent to the computer. This process is repeated every 10 ms. The computer is a 16 bit/word, 32K Sigma 3. When a new speaker first approaches the Sigma 3, the computer requests that he pronounce EVE, AH, MET, IT, OH, TWO, RRR, NNN, SSS, FFF, ZZZ, VVV, HAY, (and sometimes other words). From these words the computer abstracts templates (reference points in the 6-D filter space) for each of the primary sounds in each word and then labels them with the characters E, A, 3, I, O, U, R, N, S, F, Z, V, and @. There is nothing special about the choice of prompt words or their character codes. They can be altered at will, and we frequently increase and decrease their number.

Inspection of the strings reveals that similar words produce similar strings. (What else?) Clearly more phonemic detail needs to be incorporated for general word recognition, but to the unaccustomed eye, this would only obscure the patterns that do exist; so, the detail was omitted for this presentation.

These strings would probably be too long for reading at the typical speaking rate of 200 words per minute since the average reader only covers 250 words a minute where each word has an average length of 5 characters (not 50). Experience suggests that these phonemic character strings could be reduced to average length 10 with little loss of information.

In considering written phonemic strings as a general communication tool, a severe problem not to be neglected is the variability in the phoneme strings from speaker to speaker. Most algorithms known today would require some sort of speaker adaptation. Difficulties in "speaker normalization" should be investigated early.

Conclusion

Automatic speech recognition has taken a long time to approach the minimal requirements of cost, vocabulary size and accuracy for even the most ideally suited tasks. But it seems likely that the art has advanced to a point of having utility for such applications as speech control of machines for the bedridden or paralyzed. If ASR is not yet useful, the field should nonetheless be watched because utterance recognizers can be expected to improve at an accelerated pace for the next decade.

Automatic phoneme recognizers can be built today that transcribe spoken words into phoneme strings. Given adequate instrumentation, it seems likely that people could now (or will shortly) be able to read these phoneme strings fast enough that they could be of considerable assistance to the profoundly deaf in following normal verbal conversations.

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TOWARD OPTIMUM SYNTHETIC SPEECH FOR THE DEAF

by

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Summary. Communication theory, and in particular modulation theory, is used in conjunction with nonlinear transformations on instantaneous voice envelope and frequency for the purpose of matching the synthetic speech to the mapping of an individual's region of hearing. The process is straightforward electronically. An example is given which yields an approximately linear frequency mapping and an expression for the resulting mean and spread of the synthetic voice spectrum. The introduction includes a review of the literature which discusses the importance of various properties of speech, defines speech as an envelope and angle modulated signal, summarizes types of non-conventional hearing aids such as the transposer, and discusses the information capacity of the ear.

Introduction

Although not a few efforts have been made toward advancing hearing aid technology, little agreement is discerned in the field as to which method is best in all or even in most cases. Aids for speech perception include not only auditory but also visual and tactile (1). Hearing loss may sometimes be corrected by surgery, but other than this, residual hearing is usually utilized with the aid of some type of hearing device. Among the users, choice of hearing aid should depend upon the recommendations and diagnosis of the audiologist. However, "the hearing specialist lacks a reliable means of prescribing a hearing aid with performance characteristics similar to the ones he wants for his patient" and " a hearing aid dealer has little way of relating those specifications to his own wares" (2). In addition, 70% of the wearers omit the audiologist and go directly to the dealer. Thus the typical commercial hearing aid is not only a simple amplifier, emphasizing some or most audio frequencies, but it also comes in hundreds of models from which the consumer hopefully chooses or has had chosen for him the best for his particular need. Beyond the "typical" hearing aid, several researchers in the past ten years have theorized, developed, and even gathered objective data on various nonconventional auditory aids. Among the best known of these is the frequency transposer developed by Johansson (3). A recent overview of the history of the development and results of this and similar aids is given by Pickett (4) of Sensory Communications Research Laboratory, Gallaudet College, Washington, D. C., who also has suggestions for open research areas. He states that, "It appears from the present test results with transposers that considerably more research will be necessary before we know how best to design transposer hearing aids. It will be necessary to solve some very difficult problems, as discussed earlier. It will probably also be necessary to take into account different individual hearing capacities at various frequencies and for different time patterns" (4, p. 7). What is meant by hearing capacities was indicated by R. Mazeas (5), who divides the hearing region into least distinguishable amplitudes and frequencies and uses the time constant of the nervous system to formulate an individual's maximum hearing capacity in bits per second (bps). The number might range from 200 bps to 40,000 bps in a severely handicapped case to a normal case, respectively. A device called "Le Bitmetre" has been manufactured by a French firm to measure this capacity. It allows measurement not only of puretone hearing thresholds but also of amplitude (ΔI) and frequency (Δf) difference thresholds and time resolution ($\Delta \tau$), indicated by the ability to distinguish two successive impulses. Modern hearing aid design should take into account such data from each individual wearer.

The first step in this direction has been taken by several devices which at least have moved the speech spectrum into a narrower, lower band. Results of various aids using transposition are reported in several articles in American Annals of the Deaf, Vol. 113, 1968 (6) - (9), and Bulletin D'AudioPhonologie, Vol. 1, No. 2, 1971 (10). The results are varied and even contradictory. For example, the Lafon amplifier (10) is reported to yield results in lip-reading which "could never have been achieved by the classical methods," according to a teacher of 26 years experience. Levitt (11) distinguishes between two forms of results of the newer aids, noting their apparently marginal success for perception but moderate success for speech training.

More specifically, types of audio aids with other than pure amplification, include the following:

1. amplification of low frequencies with superposition of a transposition of high frequencies onto the low band (3), (6);
2. amplification of low frequencies with superposition of amplitude modulation of selected medium tones by the envelope of selected narrow high bands (6), (10);
3. amplification of low frequencies with superposition of frequency-divided versions of selected higher frequency bands (7); and
4. pure synthetic speech generation by means of vocoding, or amplitude modulating low frequency tones with the envelope of higher frequency narrow bands with a one-to-one correspondence between tones and bands (12).

As of yet, there has been no hearing aid built which maps all instantaneous speech frequencies and amplitudes into a narrower band of hearing on a one-to-one basis for the specific purpose of aiding either speech perception or training, although the concept

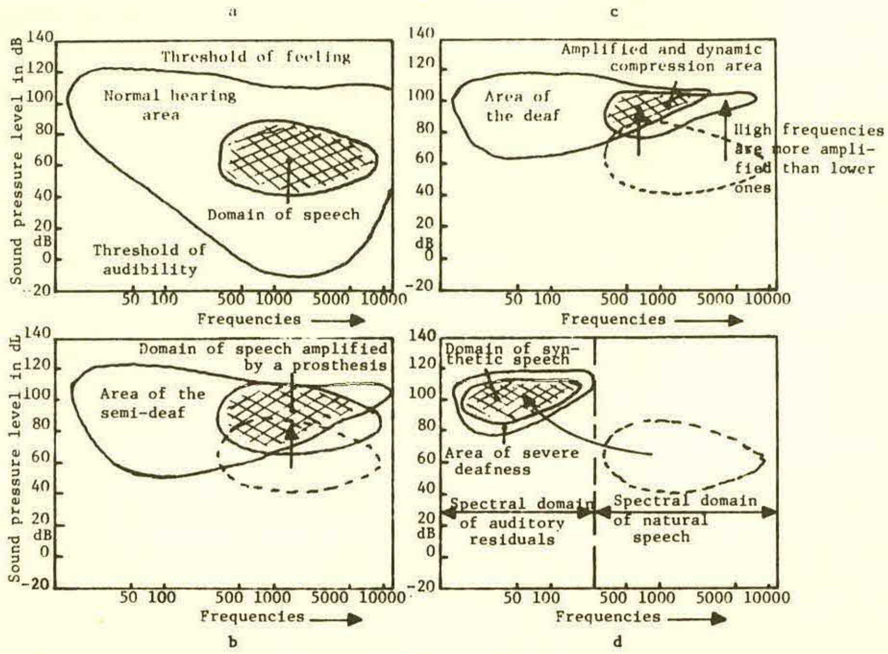

FIGURE 1. (Duplicated from Pimonow (12)):

Part a. The normal hearing area and the range or domain of speech (crosshatched).

Part b. Hearing area of the semi-deaf. By means of a conventional prosthesis the domain of speech can be adapted to the hearing area which is reduced by disorders, through amplification, that is to say by a vertical shifting.

Part c. Hearing area of the deaf. The range of speech is partially adapted by selective amplification and dynamic compression. All these methods which act exclusively on vertical shiftings of the range of speech are at present used in most of the school for deaf-mutes.

Part d. If losses are very large, a vertical shifting is not sufficient. It is necessary, not only to act upon amplitudes, but also to shift the domain of speech along the frequency axis. Any such adaptation amounts to a conversion of spoken language into synthetic speech.

is not new and is displayed in Fig. 1, reproduced from (12). (However, Dr. Richard Carr of Raytheon has proposed a mapping of zero-crossing information using digital electronics, and Dr. George Haspiel at Penn State University computerized and verified the utility of a similar system in 1969.) The aids which use envelopes of high narrow bands to remodulate tones of lower frequencies do not, unfortunately, make direct use of the information in the zero-crossings of speech, which are known to contain most of the information (13). In addition, the envelope spectrum of speech in octave bands has been found to have significant frequency content only between 0.25 and 25 Hz (14), and thus probably contains very little information. Morris (13) has explained why real zero-crossings contain most of the information.

On the other hand, the adaptability of the ear to interpret synthetic or even coded or scrambled speech is impressive. Kahn states (15), "Beginners in the study of (speech) privacy systems never fail to be amazed at the difficulty of scrambling speech sufficiently to destroy intelligence. The ear can tolerate or even ignore surprising amounts of noise, non-linearity, frequency distortion, misplaced components, superposition, and other forms of interference." An example of such distortion compensation was shown by Blesser (16) who employed a system that totally inverted the speech spectrum so that high frequencies became low and low became high; and by which listeners learned to communicate adequately. He thus proved that speech perception could not be tied to phoneme characteristics.

The method of speech compression that seems most desirable is one which compresses instantaneous frequencies and also operates on the envelope such that the resulting synthetic or distorted speech bandwidth fills the reception band of the deaf individual. A scheme for performing these operations is indicated by M. R. Schroeder and J. L. Flanagan of Bell Laboratories (17). By dividing instantaneous frequency by two and taking the square root of the envelope and combining the results, they showed by computer simulation that speech bandwidth had been reduced by a factor of two, and were encouraged that the possibility of higher compression ratios might be feasible. The spectral results of frequency dividing and filtering hard limited speech are shown by Bogner (18) to give acceptable results for bandwidth compression, with some possibly objectionable phase ambiguities upon decompression.

The extraction of a voltage proportional to the instantaneous zero-crossing frequency is no longer a difficult hardware problem due to the manufacture of complete phase-locked loops (PLL) on a single electronic integrated circuit component, and either the linear or non-linear but monotonic mapping of that instantaneous frequency to another is a simi-

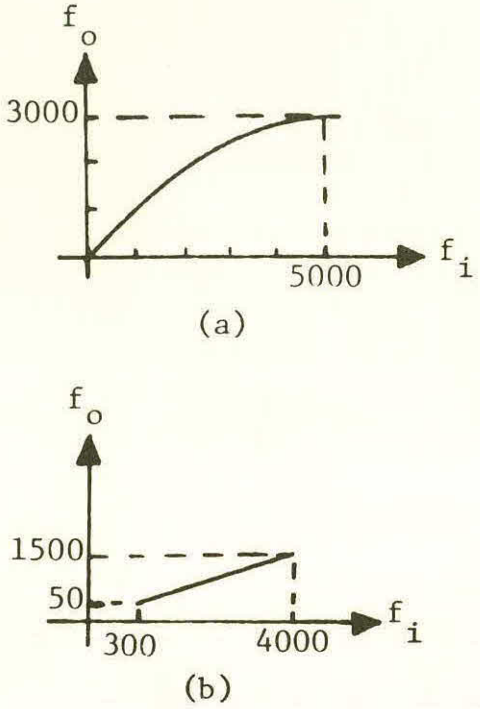

FIGURE 2. Possible non-linear frequency compression characteristics. Output frequency f_o vs input frequency f_i.

larly simple process. Miniaturization of digital circuits provides another method. The resulting spectrum could also be amplitude shaped or frequency distorted as desired with some custom, but simple, tailoring in the analog case. For example, someone with normal hearing which has deteriorated at high frequencies may be fitted with a gradual compression and/or amplification at higher frequencies. This would be the frequency transformation shown in Fig. 2a. The keys to any serious attempt to optimize synthetic speech are threefold: (1) measuring the hearing capacity of each individual with a device or technique such as the "Bitmetre," (2) extracting the instantaneous envelope $a(t)>0$ and frequency $\dot{\phi}(t)$ from voice $v(t)$ for generation of a new signal $s(t)$ with envelope $b(t)$ and frequency $\dot{\gamma}(t)$ which are matched to the individual, and (3) trading theoretical possibilities of receiving "information" with the practical difficulties of re-learning new speech sounds. (For example, a person with old-age hearing loss should obviously not be required to relearn a totally synthetic speech; only that necessary part of speech which he can no longer discern should be recoded.)

Such remodulation implied by (2) above might be optimized through the use of the theory of simultaneous envelope and phase modulation as presented by Kahn and Thomas (19). This requires first that the statistics (power spectral densities, autocorrelations, amplitude densities, cross correlation, covariance function) of $a(t)$ and $\dot{\phi}(t)$ be found. To this author's knowledge this has not been done. Other useful statistics would be those of the zero-crossing rate $Z_1(t)$ of speech and the zero-crossing rate $Z_2(t)$ of the derivative of speech. The amplitude densities and autocorrelations of voice and $Z_1(t)$ have been found, however (20), and the spectrum of the envelope of voice in octave bands has also been found (14).

Optimum Modulation for Synthetic Speech

Assuming that the above statistics are known and that the envelope $a(t)$ and frequency* $\dot{\phi}(t)$ of voice $v(t)$ are available in the form of an analog voltage (or an analog-to-digital converted form), a voltage-in-voltage-out transformation can be synthesized to yield new envelope $b(t)>0$ and frequency $\dot{\gamma}(t)$. For example analytic signal rooting (17) yields

$$f_{1/n}(t) = a^{1/n}(t) \cos[\phi/(t)/n] ,$$

which is a signal having approximately (1/n)th of the bandwidth of $v(t)$. While bandwidth has been reduced, however, it has not necessarily been reduced optimally. Before any such "optimum" $s(t)$ could be synthesized, knowledge of its spectrum would be necessary. To begin, let voice be single-sidebanded to ω_c:

$$v_1(t) = a(t) \cos[\omega_c t + \phi(t)], \tag{1}$$

and let

$$s(t) = b(t) \cos[\omega_c t + \gamma(t)]. \tag{2}$$

The positive frequency components of $s(t)$ around ω_c are given by

$$x(t) = \tfrac{1}{2} b(t)\, e^{j\gamma(t)} , \tag{3}$$

which is not usually a real function of time but in general complex. The bandwidth of $s(t)$ around ω_c is the same as that of x around the origin and may be defined by (19):

$$\Omega_x = \frac{||f[\Phi_x(f)]^{\frac{1}{2}}||}{||\,[\Phi_x(f)]^{\frac{1}{2}}||} , \tag{4}$$

where $\Phi_x(f)$ is the power density spectrum of $x(t)$, and

$$||X(f)|| = [\int_{-\infty}^{\infty} |X(f)|^2 \, df]^{\frac{1}{2}} .$$

In terms of the autocorrelation $R_x(\tau)$ of x, the bandwidth is

$$\Omega_x = \left[\left(\frac{\frac{\partial^2 R_x(\tau)}{\partial \tau^2}}{R_x(\tau)} \right) \Bigg|_{\tau=0} \right]^{\frac{1}{2}} \tag{5}$$

which is also equivalent with

$$\Omega_x = \frac{E\{|\dot{x}|^2\}}{E\{|x|^2\}}^{\frac{1}{2}} \tag{6}$$

where E denotes expectation. Assume now that the root mean square bandwidths of $b(t)$ and $\gamma(t)$ are known and are denoted Δ_b and Δ_γ, respectively. (That is, for example,

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*From (17), $a(t) = [v^2(t) + \hat{v}^2(t)]^{\frac{1}{2}}$, and $\phi(t) = \tan^{-1}[\hat{v}(t)/v(t)]$, where $\hat{v}(t)$ is the Hilbert transform of $v(t)$.

$$\Delta_b = ||f[\Phi_b(f)]^{\frac{1}{2}}||/||[\Phi_b(f)]^{\frac{1}{2}}|| \text{ .)}$$

Then Kahn and Thomas (19) show that

$$\Omega_x{}^2 = \Delta_b{}^2 + E\{b^2\dot{\gamma}^2\}/E\{b^2\} , \tag{7}$$

and further, that if b and γ are independent,

$$\Omega_x{}^2 = \Delta_b{}^2 + E\{\gamma^2\}\Delta_\gamma{}^2$$

$$= \Delta_b{}^2 + E\{\dot{\gamma}^2\} . \tag{8}$$

The spectral mean is also given:

$$\mu_x = E\{b\dot{b}\dot{\gamma}\}/E\{b^2\} \tag{9}$$

Expressions (7) - (9) may be used to determine the bandwidth and position of any synthetic speech formed by transforming the envelope and instantaneous frequency of real voice. Such a system is shown in Fig. 3, where voice is first single-side-banded to produce $v_1(t)$. The envelope $e(t) = a(t)$ and instantaneous frequency $f_i = \dot{\phi}$ are then extracted. The voltage analogous to frequency passes through an attenuator or nonlinearity to frequency modulate a carrier which is also amplitude modulated by the original envelope. The resulting angle-and-amplitude modulated (AAM) signal may then be beat down to a new desired center frequency in the band of residual hearing. In this example, $b(t) = a(t)$, and $\dot{\gamma}(t)$ may be simply proportional to $\dot{\phi}(t)$ or perhaps related by $\dot{\gamma}(t) = k \log(1+\dot{\phi})$ where k is a constant.

In practice $\dot{\phi}$ may not be easily obtainable, but $z_1(t)$, the zero-crossing rate, is easy to produce. The zero-crossing rate $z_2(t)$ of the derivative of voice is also easy to produce and may be even more desirable to work with due to the greater intelligibility of differentiated and clipped speech to normal ears (21). If no amplitude remodulation is performed, i.e., if $b(t) = 1$, the synthetic speech will have a spectral width given by only the second term in expression (8).

Having determined roughly where the synthetic speech frequencies are for given transformations of a(t) to b(t) and $\dot{\phi}(t)$ to $\dot{\gamma}(t)$, the question is, "What transformations are desired?" If we had complete control of the demodulation (the human brain) we would consider the ear and its nervous system simply as a channel through which we would like to communicate n bits per second, and the signal could be designed optimally according to the channel characteristics. In particular, if we considered the ear a linear channel with only a threshold (the threshold of hearing), a saturation level (the threshold of pain), and an ideal passband (indicated by the intersections of the above two threshold curves vs frequency), then in the presence of a fixed gaussian noise level we would distribute the transmitted information evenly within those boundaries. Thus, ideally, the joint probability of each envelope amplitude and instantaneous frequency would determine their information content and we could so code b and $\dot{\gamma}$ to yield a uniform distribution across the usable portion of the frequency-intensity characteristics of the ear.

However, the true situation is not nearly that simple, and synthetic speech must take into consideration several facts:

1. The ear channel has a non-uniform "noise" amplitude in the form of least-distinguishable-difference thresholds of intensity ΔI and frequency Δf at every point in the usable hearing region (5).
2. The threshold of hearing vs frequency curve is usually determined by pure tone testing, which in some cases means that although the deaf ear might not linearly respond to that tone, distortions may be sensed due to a high enough input level.
3. Natural hearing indicates that some monotonic mapping of $\dot{\phi}(t)$ onto $\dot{\gamma}(t)$ seems reasonable; i.e., a gross shuffling of input vs output instantaneous frequencies by the synthesizer does not seem appropriate.
4. Time-distorted speech is also not practical for obvious reasons.

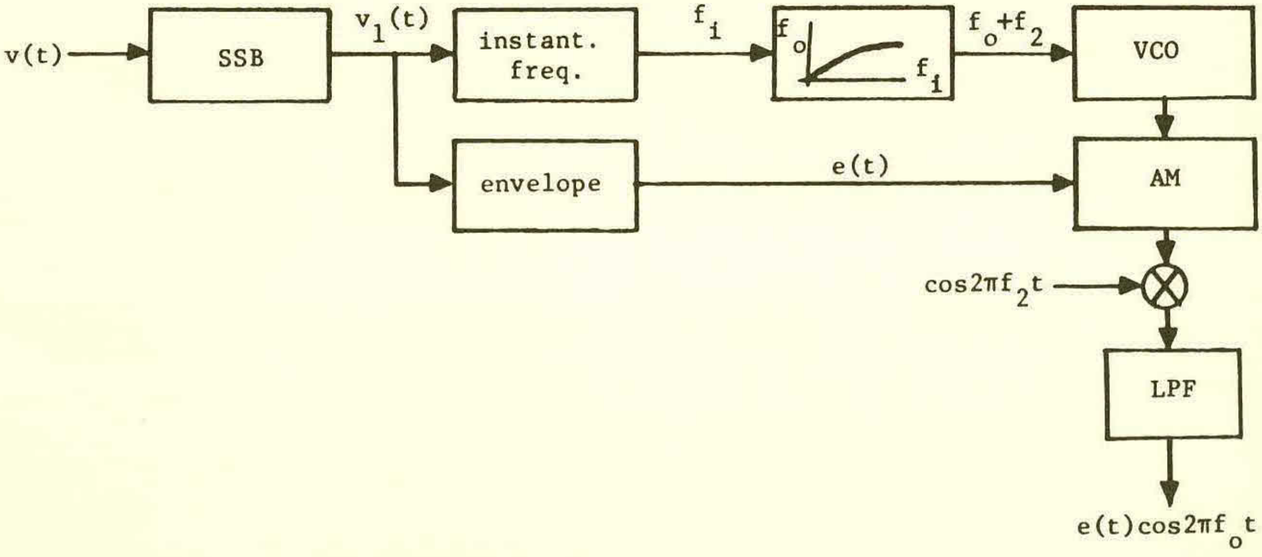

FIGURE 3. Production of frequency compressed speech by extracting envelope e(t) and instantaneous frequency f_1 from voice v(t), aided by single-side banding.

5. Many hearing problems are of the high frequency hearing loss type, and the low frequency portions of speech have already been learned.

With the exception of item (2) above, which cannot be accounted for with linear system theory, a reasonable solution seems to be as follows. Let the mean of the envelope lie in the mean of the acceptable intensity region, and the amplitude density of b(t) be essentially confined to acceptable intensities. Thus let

$$b(t) = k_1 a(t) + I_o \ , \qquad (10)$$

where I_o is the mean acceptable intensity.

At this point, note that the frequency content of b(t) is small, on the order of 0.2 to 25 Hz (14). This means that the spectral width of s(t) will be due essentially to $\gamma(t)$. If an individual's Δf is particularly large near frequencies f_i, $i = 1,2,\ldots,m$, let the mapping of $\dot\phi$ to $\dot\gamma$ "avoid" those frequencies, thus compressing $\dot\gamma$ into only regions with smaller Δf. (See Fig. 4). If the nonlinearity in $\dot\gamma(\dot\phi)$ is not too great, $\dot\gamma$ is approximately given by

$$\dot\gamma = k_2\dot\phi + f_x \ , \qquad (11)$$

where f_x would often be negative, assuming all $\dot\phi$ are positive and a down-shift of frequencies is needed. Using (10) and (11) in expression (8) gives the approximate bandwidth; note that

$$E\{\dot\gamma^2\} = k_2^{\ 2}\, E\{\dot\phi^2\} + f_x^{\ 2} + k_2 f_x E\{\dot\phi\} \ .$$

If $\Omega_x(k_1,k_2)$ is too large, a smaller k_2 may be chosen.

More ideally, an amplitude transformation would be designed similar to the frequency transformation such that amplitudes b(t) would lie in regions of large ΔI only with small probability. With computerization, a joint mapping would shape the joint probability density of b and $\dot\gamma$ such that only rare combinations would occur in a region of both large ΔI and large Δf.

For the person with a high frequency hearing loss, a gradual nonlinear transformation of frequencies might prove best. For example, let

$$\begin{aligned}\dot\gamma &= \log(1+k_3\dot\phi)\\ &= k_3\dot\phi - (k_3\dot\phi)^2/2 + (k_3\dot\phi)^3/3 - \cdots \ . \qquad (12)\end{aligned}$$

This transformation allows low frequencies to remain nearly unaltered, but compresses the highs. With an analog implementation a simple control would allow the individual to vary k_3 to his liking. Although such a device has not been tested, it seems that the resultant synthetic speech would be perceived to be more natural than that of the transposer, which is not a one-to-one mapping of frequencies, but an overlapping of highs onto lows.

In addition to the mapping (12), pre-differentiation of speech or post-high-frequency emphasis should be useful for the high-frequency loss user.

Conclusions

It is realized that the major obstacles in determining the utility of synthetic speech devices are not in their engineering, but in their application to humans, and it will be the field and educational testing that will prove their worth. Nevertheless, this paper has attempted to introduce more technically sound approaches toward synthetic speech generation. These approaches not only compress the voice spectrum, but do so with an attempt to match the synthetic speech with more detailed information about the capacity of the individual's ear other than bandwidth and hearing threshold, and in addition, take into account the human learning

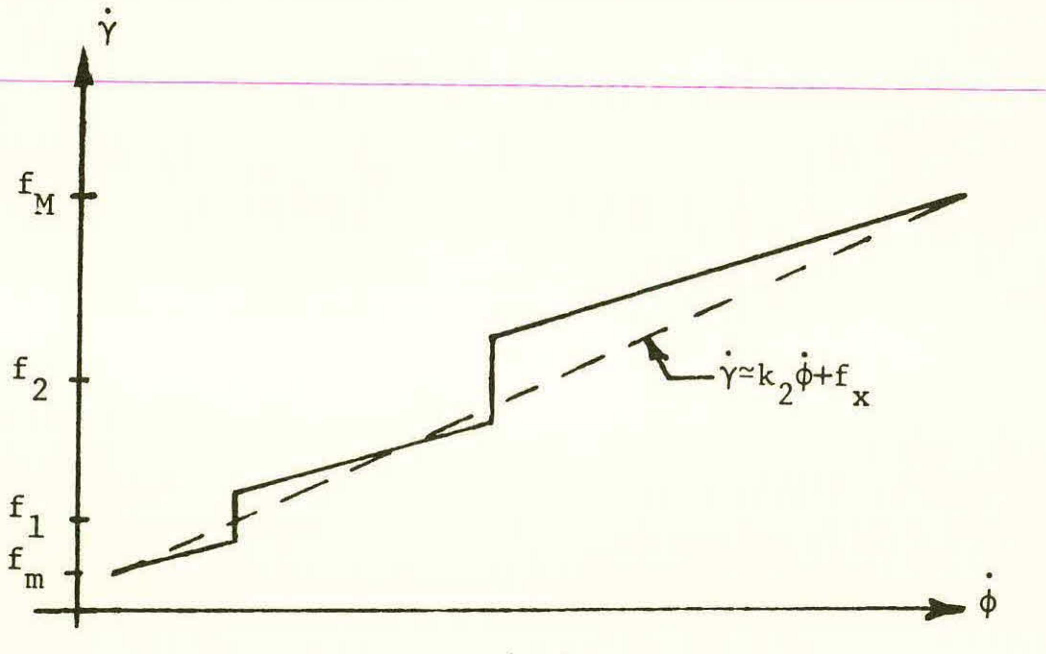

FIGURE 4. Transformation of $\dot\phi$ to $\dot\gamma$ which is compressed into the reception band ($f_m \le f \le f_m$) and avoids frequencies f_1 and f_2 which have large frequency difference thresholds Δf.

process. It is also assumed that previous advancements in hearing-aid technology would be incorporated into any newer devices. For example, automatic volume controls, noise level thresholds, and even directional "phased array" microphones should also be used to advantage. The trade-offs between theoretical and practical gains in information reception must be studied as well. This implies not only building devices but designing and implementing objective programs whose results allow feedback for redesigning the device's functions and directing their use to individuals with a higher potential for adaptation.

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TRANSPORTATION FOR THE SEVERELY DISABLED; DESIGN PROBLEMS IN A PERSONAL CAR

by

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Abstract. Two problem areas are discussed in the development of a practical road vehicle to be driven by a severely disabled person. A unique wheelchair lift to facilitate entry and exit from the vehicle is described. The lift can be operated safely and independently by the disabled person in a large variety of parking situations.

An electro-hydraulic full power control system is proposed which would allow control "handles" suitable for a wide range of disability. Unusual control transfer functions are considered as a means to produce adequate performance with reduced dexterity and help filter out "manual noise", as well as make possible improvement in reliability and cost. A discrete rate steering transfer function which could provide these advantages is proposed, and a computer simulation to investigate its suitability is described.

Introduction

The development of a highway vehicle for independent use by a severely disabled individual involves several problem areas, two of which will be discussed in this paper. The work presented is by no means the final result, but represents the initial efforts on a project that it is hoped will yield a practical vehicle.

Classifying the Driver

For purposes of this paper, a severely disabled driver will be considered as one who is unable or only marginally able to operate existing commercial mechanical controls of the type commonly installed in automobiles for the disabled. Many specific causes of disability may produce manifestations which require new approaches in order to allow independent use of a highway vehicle. High level traumatic quadriplegics and polio quadriplegics are two common types of persons needing extended techniques. For these drivers problems other than operating the vehicle driving controls will exist. A power operated wheelchair will be needed for effective short distance mobility and thus must be available for use at the destination of a trip. They will generally not be able to independently transfer themselves into the vehicle. They will be sensitive to inertial forces while driving and thus require a means for restraint.

The Mobility Problem

Short distance mobility needs for the severely disabled are usually met with some form of power operated wheelchair. Though considerable mobility is afforded, many limitations exist with commercial wheelchairs. For the able-bodied, medium range independent travel may involve the use of a bus, a train, or a car. But, these modes are not available to an individual who requires a powered wheelchair. By imposing on firends or relatives it is possible to get from place to place with a car or van type vehicle, but considerable physical effort is often required of the person helping. No satisfactory means for independent medium range mobility is available at present. With but two notable exceptions, the BART system and the Washington, D. C. subway, urban mass transit is not usable and will be such for many years. Several commercial taxi services have been established for the disabled. While these may provide a partial solution particularly for the very severely disabled, they tend to be expensive and not able to give sufficient mobility for everyday affairs. One solution to the medium distance mobility problem would involve the use of a highway vehicle with special features that permit independent operation by a severely disabled person. Two research topics in the design of such a vehicle will be discussed in this paper, the entry-exit system and the characteristics of the vehicle control system.

Entry-Exit System

Since the driver considered in this paper is unable to transfer himself from his wheelchair seat onto a conventional car seat without assistance and many severely disabled would prefer not to leave their personalized wheelchair(1), driving from a wheelchair is assumed. A vehicle which will accommodate the wheelchair and a means for entering the vehicle must then be specified. Because of problems with headroom and space to position the wheelchair, a small step-in van is one of the few practical vehicles available. Though a step-in van lacks many of the handling and esthetic quantities of other vehicles, modification of existing structures is minimized.

Lift Philosophy

A practical wheelchair lift for a severely disabled person must satisfy a number of constraints. Because of the driver's general lack of strength, all mechanisms must be power operated. While it is true that certain individuals may be able to manually accomplish specific tasks such as closing doors, there are parking situations where these tasks cannot be done or may be dangerous. To be truly practical the lift should function reliably under a wide range of parking situations, such as uneven terrain when the entering wheelchair may not be at the same attitude as the vehicle.

The wheelchair must be restrained and maintained level or tipped slightly back to insure safety of the driver. This requirement results from a common inability to balance found with the severely disalled. Good engineering practice requires that all conceivable failure modes be such that adequate warning is given. It is thus assumed that the driver will periodically inspect the physical condition of the mechanism. The construction techniques and components used should be of a type that allows ready maintenance without the need for special equipment.

Lift Designs

A ramp is the simplest means of access to a van and many designs are available commercially, some with a power folding feature(2). But, a ramp has many obvious disadvantages for a severely disabled driver.

The application of a platform lift to the problem of vehicle entry allowed for a measure of independence for those with sufficient strength and motion to operate conventional hand controls. These platform lifts are adaptations of the familiar tailgate lift used on delivery trucks. The lift is powered by an electric motor or hydraulically through an electric motor driven pump or a pump on the vehicle engine. Several common commercial platform lifts use a cylinder and chain to elevate the platform, which is guided by two vertical channels. A cylinder and swinging arm linkage are also used occasionally.

In use the wheelchair is rolled onto the platform, which extends out from the vehicle. The platform is raised to floor level, and the wheelchair is rolled into the vehicle. The platform is then stowed by folding it up against the side of the vehicle. This folding process must often be done manually, unless power operation is added by the owner after purchase. At least one manufacturer calls for mounting the entire lift mechanism externally where it may easily be damaged and can become a hazard.

A variation on the platform lift is used by the Rehabilitation-Education Center at the University of Illinois on their fleet of buses, which operate on a regular schedule year round. The platform is actually part of the floor which moves out and down supported by four arms as shown in Figure 1.

The platform type lift has several disadvantages. A practical problem results when the entering edge of the platform is not flush with the ground, producing an effective step which the wheelchair must negotiate. This condition can occur for example with a heavily crowned road or an obstruction such as a rock or accumulated snow. Adequately restraining the wheelchair while it is being lifted may pose a problem. The physical dimensions of the mechanism itself may be difficult to accommodate in a personal size vehicle without obstructing vision or movement, although visibility when the lift is stowed can be improved somewhat by using a platform composed of two channels for the wheels.

Another approach to entering a vehicle involves lifting the wheelchair from the back with a mechanism that engages the structure of the wheelchair itself. This approach was developed at the Coordinated Science Laboratory (CSL) and will be described in detail in the next section. A group at the University of California at Berkeley is developing, under an HEW Grant, the concept of a lift which will place a uniquely designed

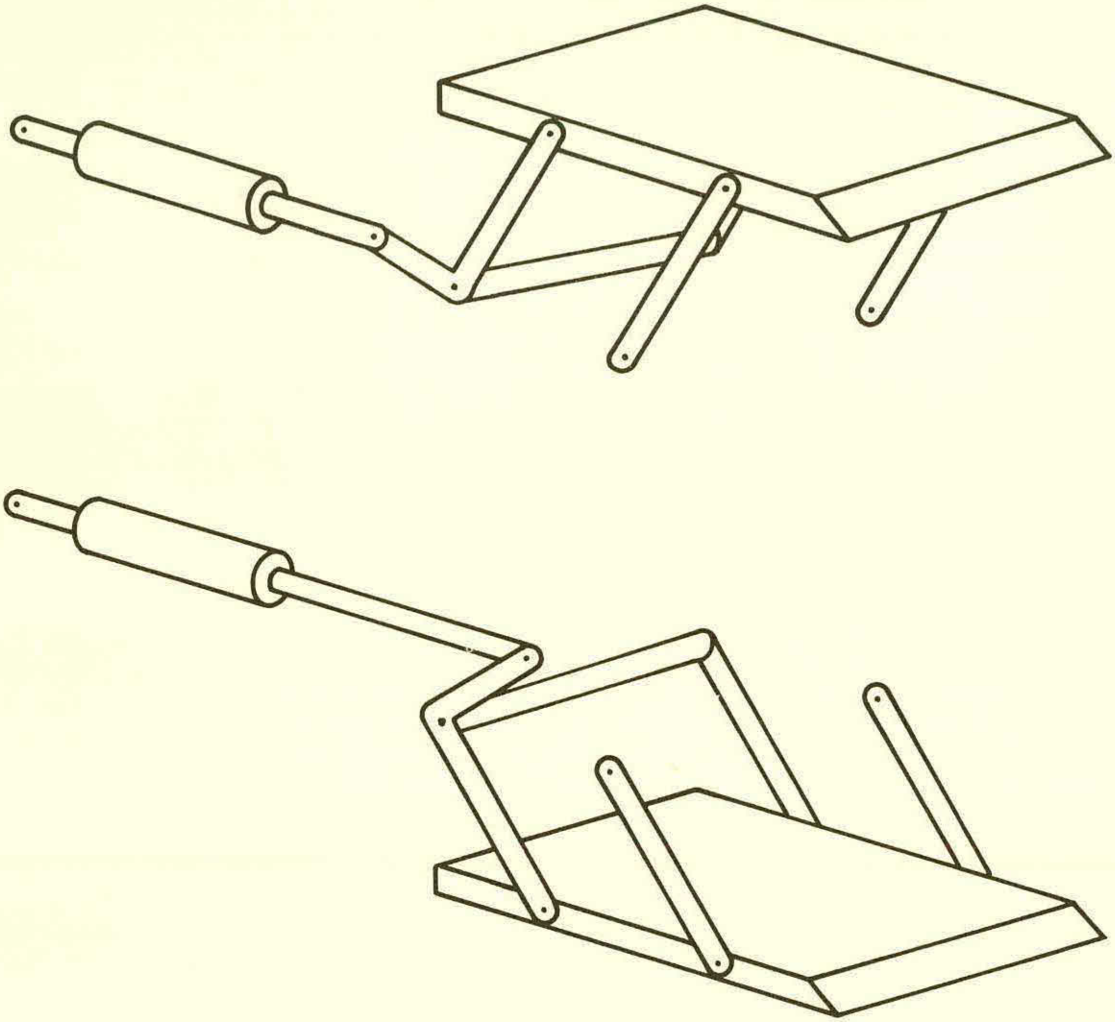

FIGURE 1. University of Illinois Rehabilitation Center lift mechanism.

wheelchair into the driver's position of a standard size auto (1,3). This design transfers the wheelchair, which has engaged two forks on the lift and then raised its wheels, backward from the passenger door side into the vehicle, over the drive tunnel and into the driver's location. The Berkeley lift as outlined would require a complex and expensive mechanism, and no prototype development has been attempted to date.

CSL Lift Design

The CSL lift design is an attempt to meet the needs outlined above without the disadvantages of a platform lift.

In operation the CSL two bar lift mimics the technique used to manually pull a wheelchair up a series of steps. The hand grips on the back of the wheelchair engage a bar on the lift. The chair is tilted back, rear wheels resting against another bar. Then the chair is pulled up.

The manner in which the lift holds the wheelchair is shown in Figure 2, where the arrows indicate the direction of the forces applied to the chair. The center of gravity (c.g.) shown will vary with the model wheelchair and the individual. All calculations in this paper are based on the dimensions of an Everest and Jennings Model 840 Adult Power Drive wheelchair. The lift will function with other models including manual wheelchairs, but may need slight dimensional adjustment for best operation. An adjustment capability can be easily provided in the hardware design.

The lifting sequence is shown in Figure 3 (a)-(c) where the lift is mounted on a van door, which is opened 90 degrees. Note that the wheelchair is automatically aligned with the lift during the engagement phase, Figure 3 (b). This feature permits safe use of the lift when the chair is not at the same attitude as the vehicle. In the extreme case the chair

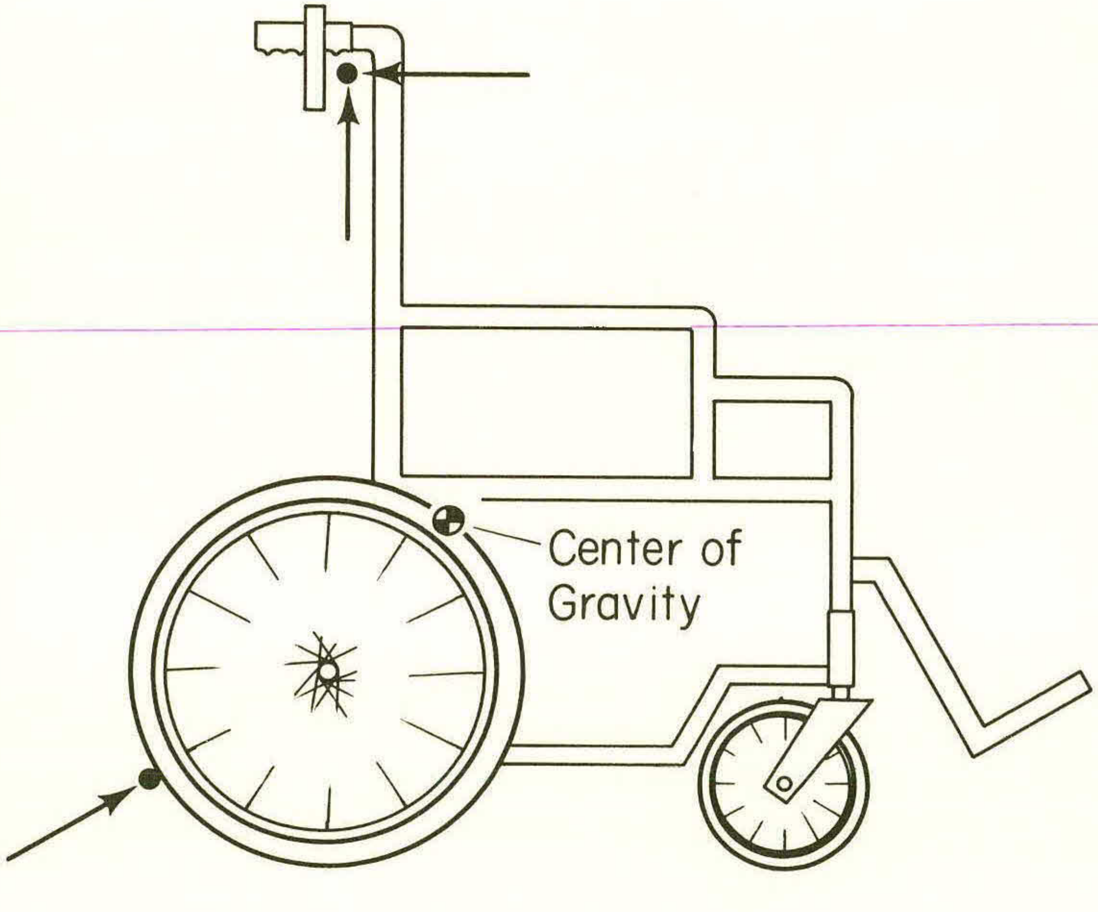

FIGURE 2. Two bar lift engagement points.

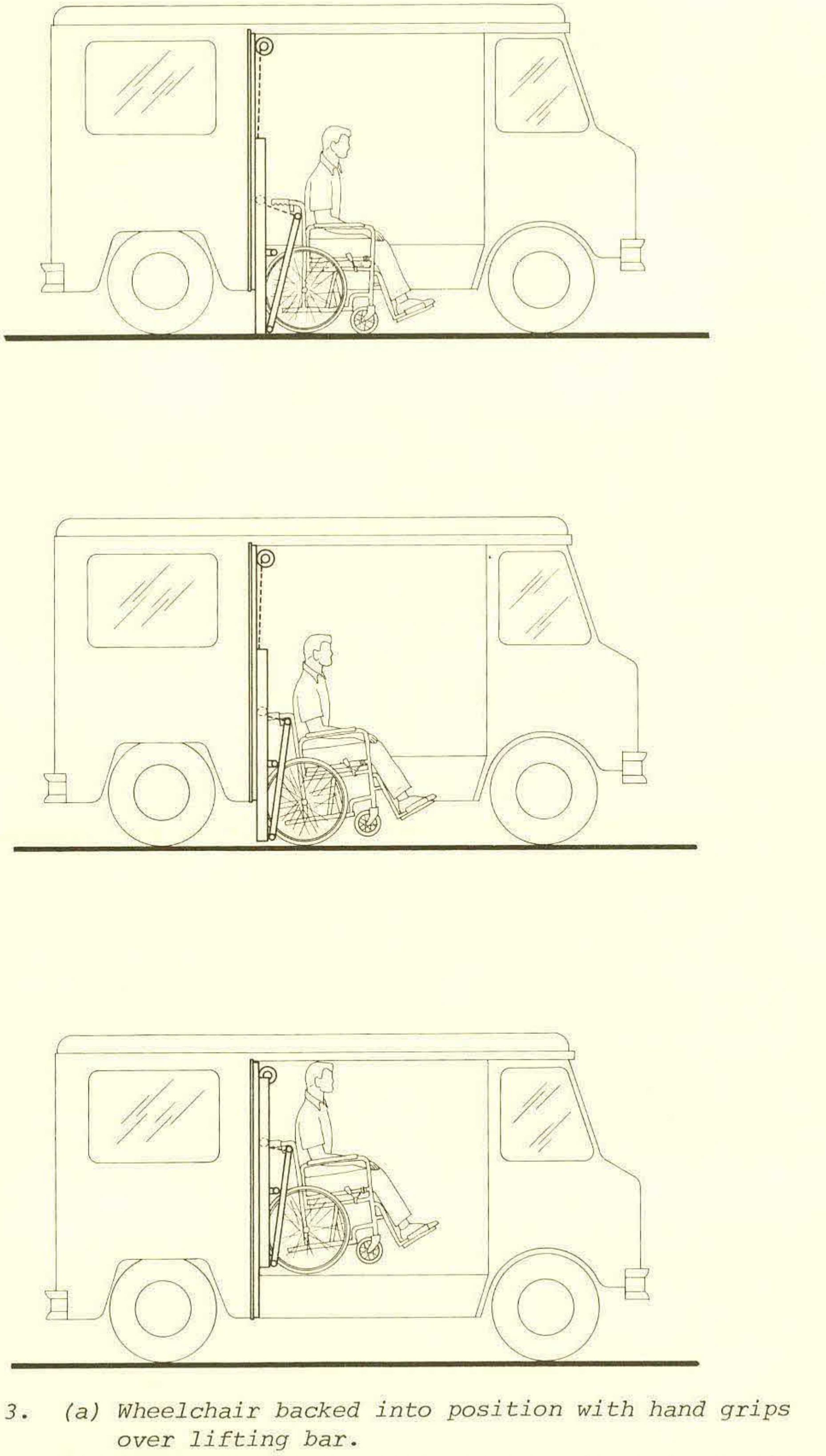

FIGURE 3. (a) Wheelchair backed into position with hand grips over lifting bar.
(b) Tension of lift cables raises slide rails until bar contacts hand grips. Additional tension pulls bar back, tilting chair.

can be lifted with only one hand grip engaged if necessary, as long as both hand grips are between the vertical pivot arms. It is possible to lift from a level below the road level or to pull the chair up a small curb or over an obstacle. If the engagement condition for safe lifting is not met, the resultant tilt will provide immediate warning. Engagement from and release onto uneven surfaces are slow, and thus do not introduce sudden imbalance problems for the occupant.

The forces on the wheelchair were calculated using Figure 4 in order to set the design dimensions for the lift. Consideration was given to

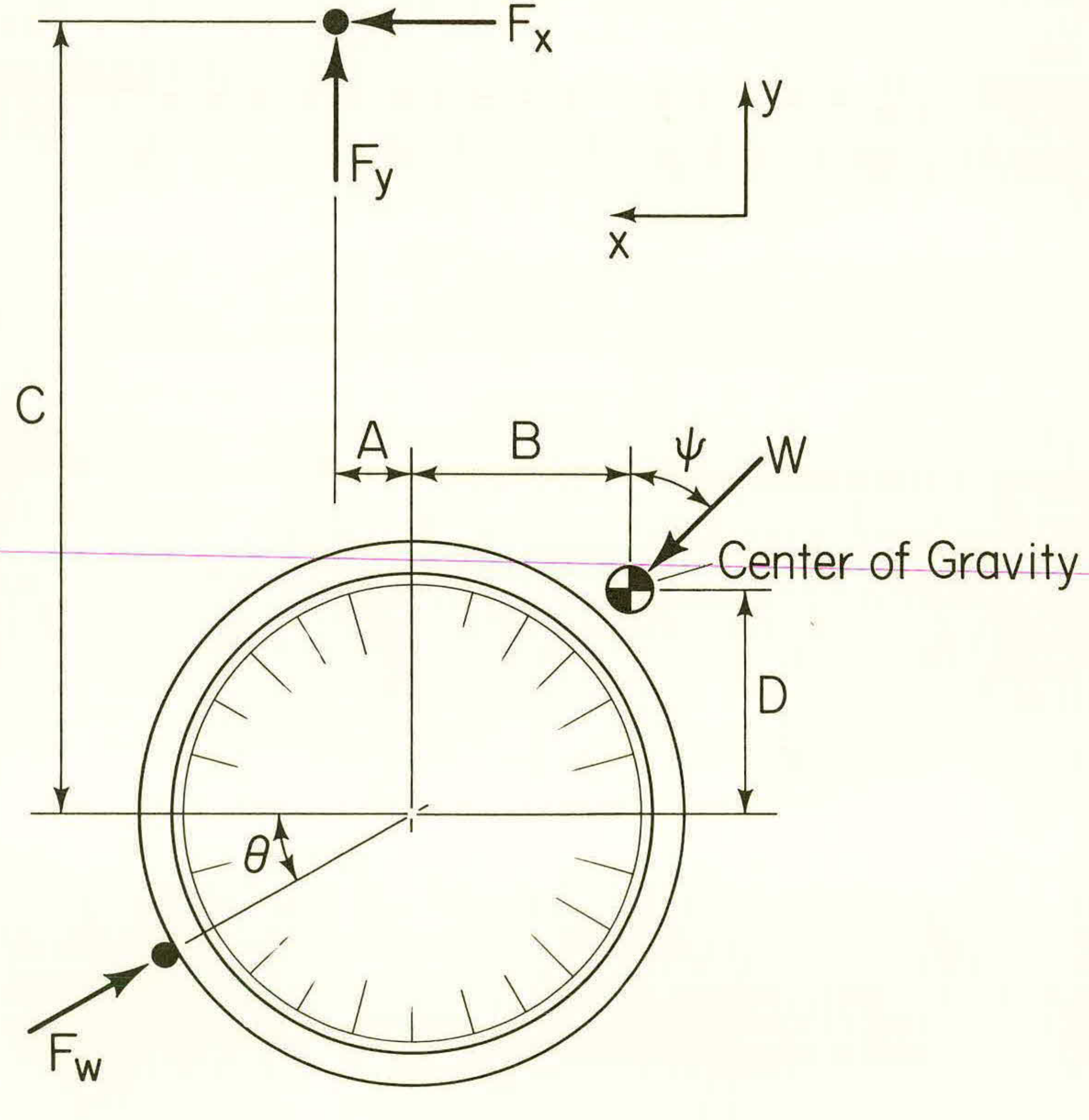

FIGURE 4. Two bar lift forces on the wheelchair.

the magnitude and ratio of forces on the wheelchair hand grips in order to insure reliable engagement of the lift and minimize strain on the backrest frame. For a specific wheelchair and occupant, these forces are determined by the tilt angle, Ψ, of the chair from vertical and the angle, θ, made by a radial line through the lower bar contact point on the wheel and a line parallel to the x axis of the chair (see Figure 4).

Straight forward analysis yields the following relations

$$F_x = \frac{W_y(A+B)\cos\theta - W_x(A\sin\theta+D\cos\theta)}{A\sin\theta + C\cos\theta}$$

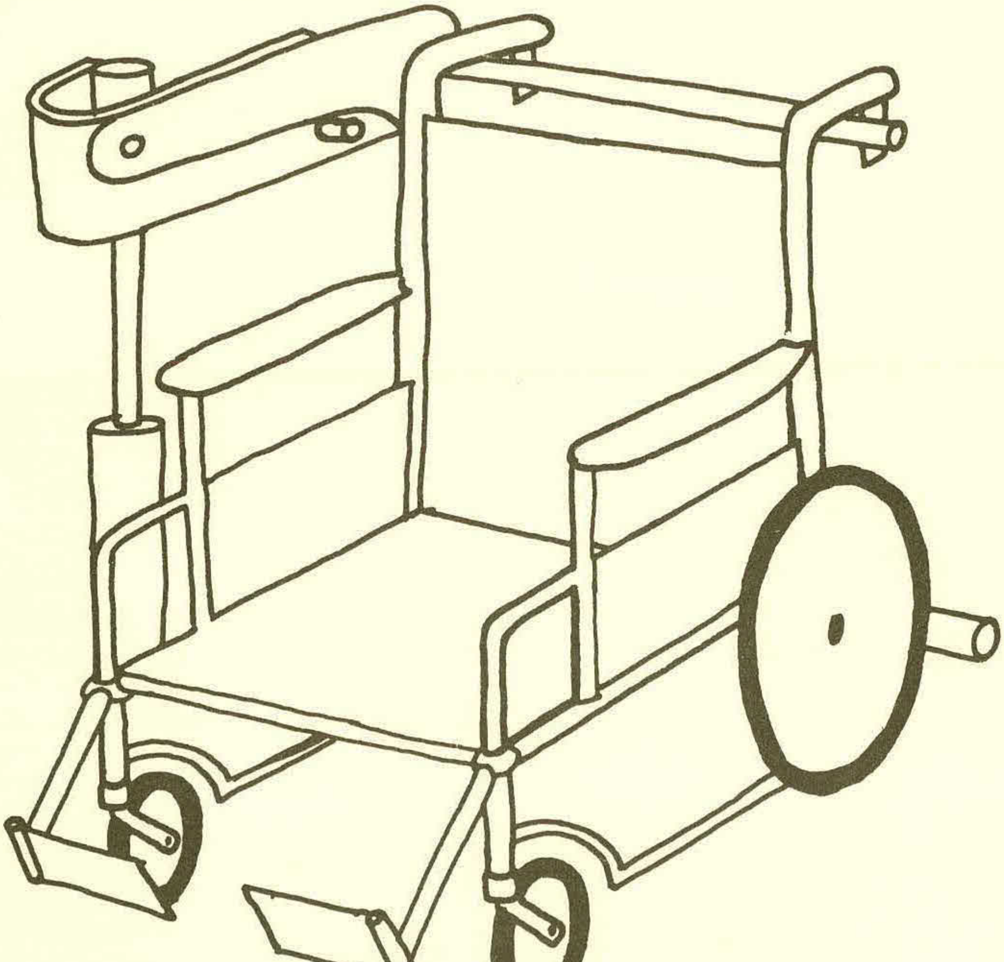

FIGURE 5. Basic two bar post lift.

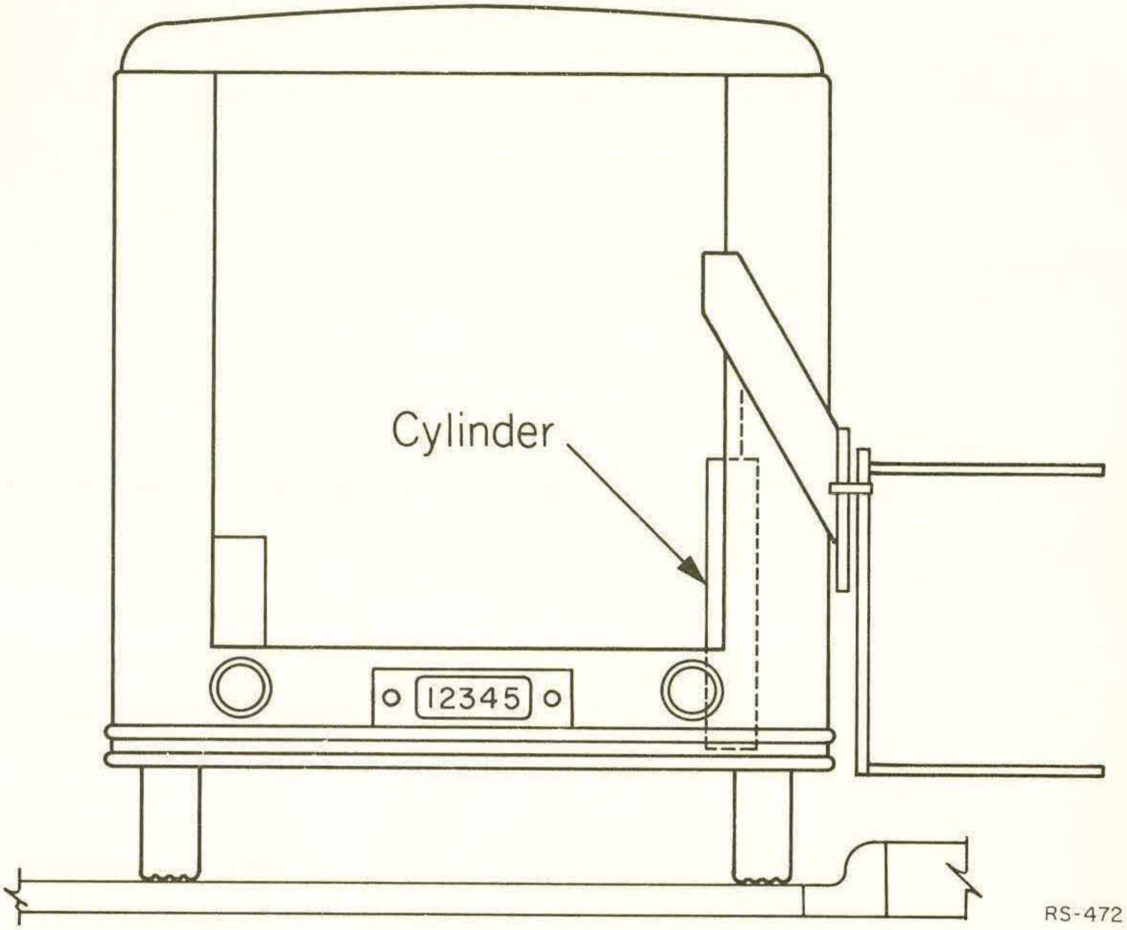

FIGURE 6. Two bar post lift installed in a van.

$$F_y = \frac{W_x(D-C)\sin\theta + W_y(C\cos\theta - B\sin\theta)}{A\sin\theta + C\cos\theta}$$

and

$$F_w = \frac{W_x(C-D) + W_y(A+B)}{A\sin\theta + C\cos\theta}$$

where

$W_x = W \sin \Psi$

$W_y = W \cos \Psi$

W = weight of wheelchair and occupant

Two Bar Lift Prototypes

Two prototypes of the two bar lift have been constructed. The first and simplest mechanically was intended for mounting on a vertical post such as a hydraulic cylinder rod in a vehicle. The basic mechanism is shown in Figure 5. Note that the two bars are rigidly connected and pivot about a point above and forward of the wheelchair center of gravity. The bars are normally held up against a stop by a spring. During engagement of the chair, weight on the upper bar causes the two bars to pivot pushing the lower bar forward against the rear wheels. As the upper bar assumes more weight, additional pivoting of the bars gives the chair a rearward tilt until a stop is encountered whereupon the chair is lifted. When a suitable height is reached, the lift and chair are swung into the vehicle, and the chair disengaged. A possible installation is shown in Figure 6. With this configuration entry would be possible from the street behind or from the sidewalk next to the vehicle. The prototype post lift shown in Figure 7 was permanently mounted on a column in a garage and manually operated. It is shown here being used to enter a step-van.

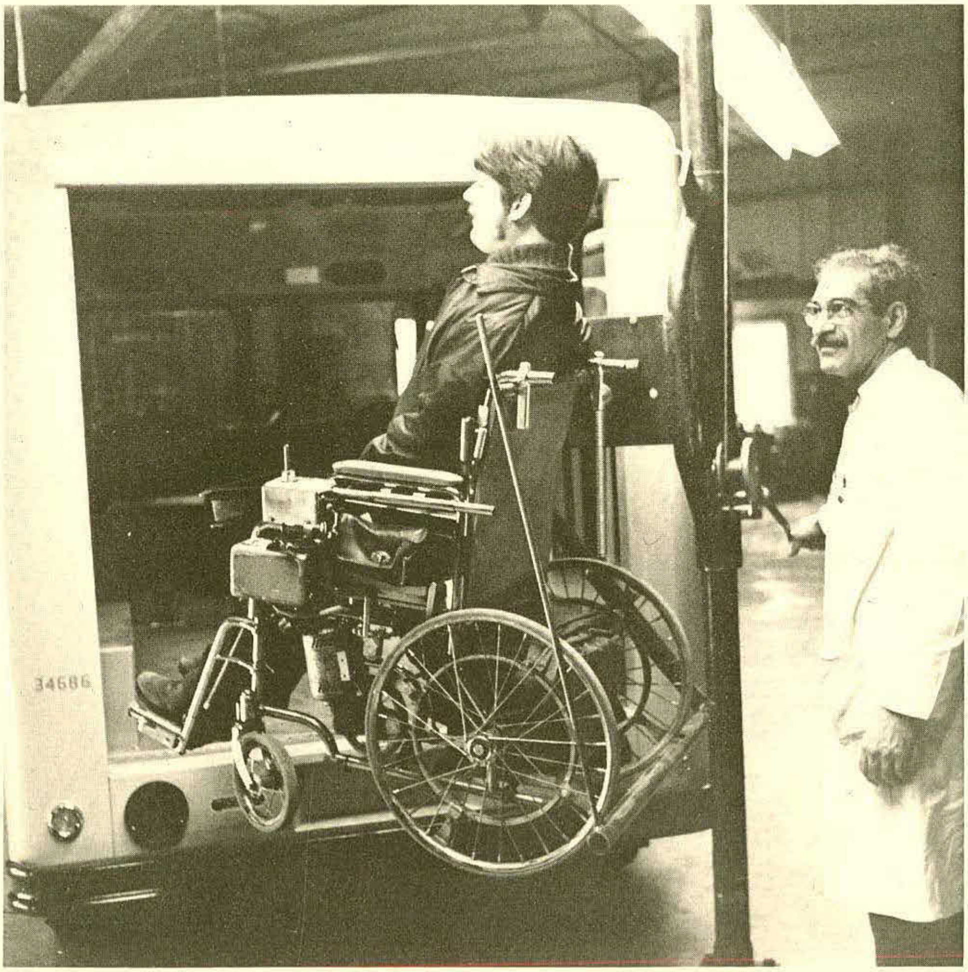

FIGURE 7. Prototype two bar post lift.

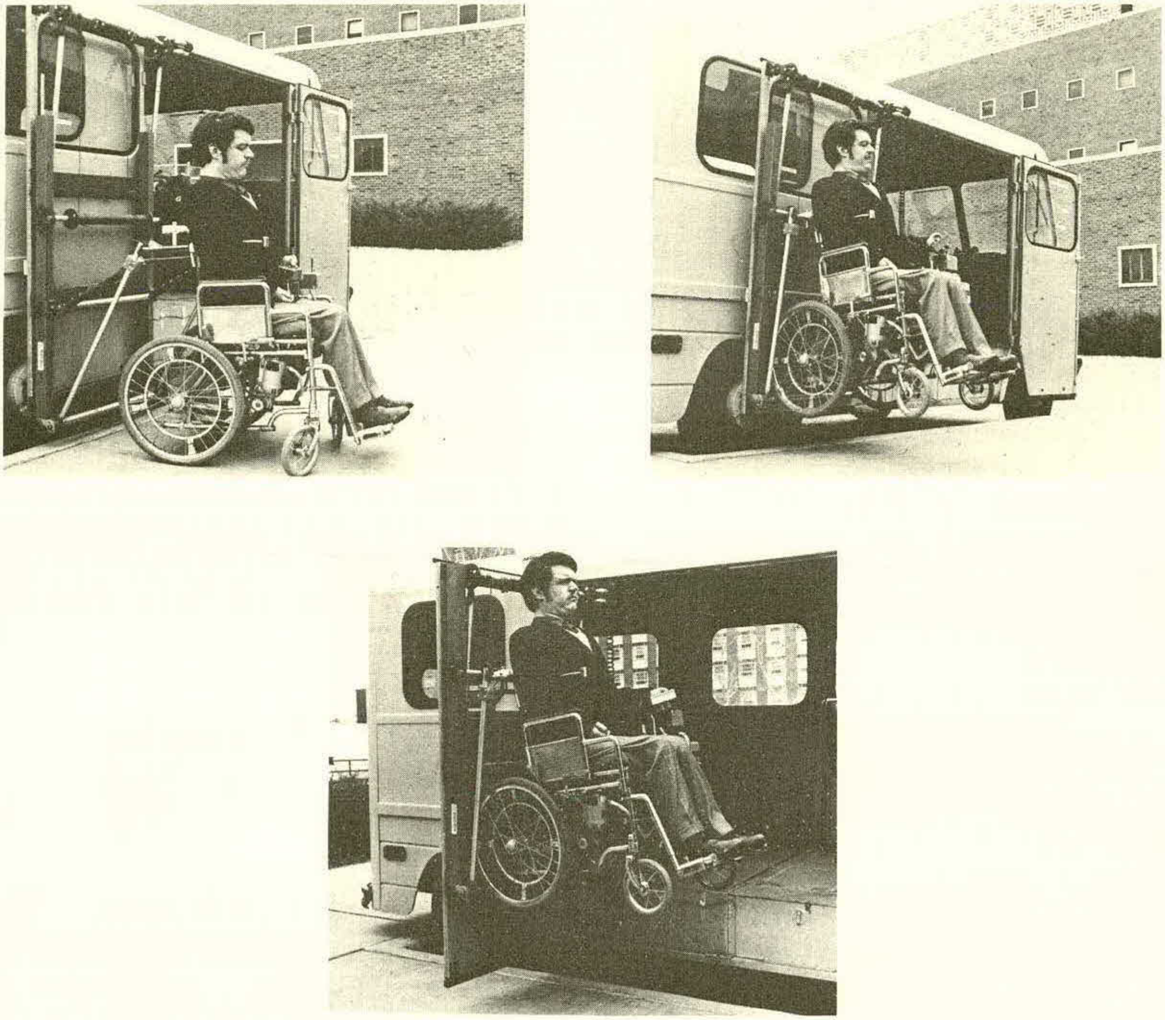

FIGURE 8. Two bar door lift being used to enter a van.

The second prototype two bar lift, like the design in Figure 3, was mounted on the right side door of a van. The entry sequence is shown in Figure 8 (a)-(c). In Figure 8 (a) the chair is being backed into place. The upper bar, held away from the door by springs that counteract the weight of the lift frame, is positioned under the hand grips. A button on the remote control box is then pushed causing the lift cables to be wound up on a drum. The lift raises on the door until the weight of the chair begins to bear on the upper bar. As the cables continue pulling, the weight of the chair is transferred to the upper bar causing the bar to pull back as the springs are compressed, thus aligning and tilting the chair. Note that with the door lift the chair tilts about its rear axle. The chair is being raised in Figure 8 (b). When floor level is reached another button would be pushed closing the door as in Figure 8 (c). The door closing mechanism has been designed but has yet to be installed. After the door is closed, the chair is lowered and disengaged by reversing the sequence above. The lift is then stowed by winding the cable up until the upper bar has been pulled against the frame.

The typical time required to enter the vehicle is under a minute and a half, with the lift itself needing fourteen seconds going up and ten going down. The mechanism is compact when stowed, being thirty-one inches wide and less than nine inches deep (this can be reduced to about six and a half inches with slight changes). It will accommodate chairs with tires up to twenty-six inches apart and will lift chairs from three inches below road level. It will also lift the driver up over a parking-lot curb as much as six inches out from the lower bar.

Power for the entry system is supplied by a commercial electrically driven hydraulic power unit connected to the vehicle battery. The lift cable winding drum actuator is a small hydraulic motor on the door. The door closer mechanism will use a cylinder mounted under the floor. Solenoid valves, mounted in the old step-well along with the pump, control fluid flow. These are operated by an umbilical control box or alternately in the future by a wireless hand held unit. A diagram of the hydraulic system is shown in Figure 9.

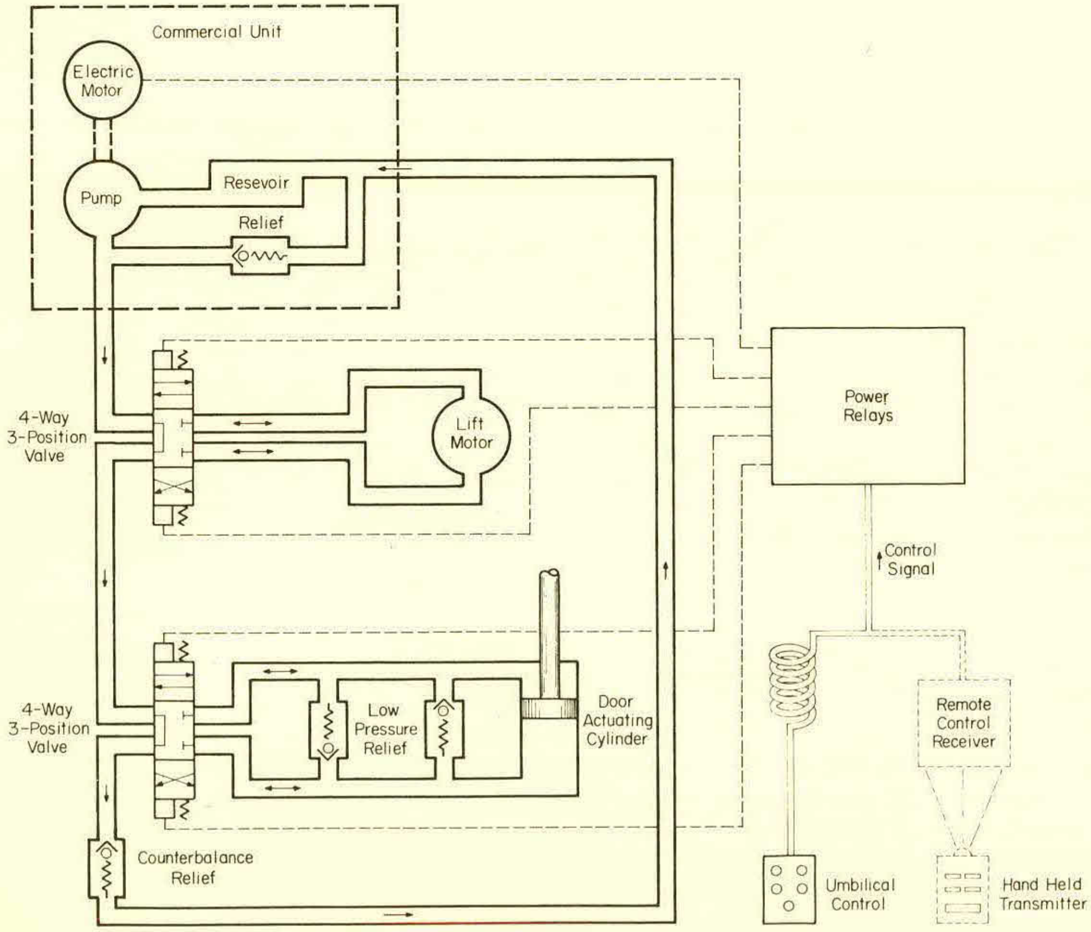

FIGURE 9. Hydraulic and control system of prototype door lift.

Considerable attention was given to reliability and safety in the door lift prototype. The dimensions are such that a three and half degree backward tilt of the chair occurs on level pavement. Under these conditions a vertical force of two hundred thirty pounds and a horizontal force of sixty-five pounds would be applied at the hand grips producing a relatively small bending moment on the backrest with the chair and occupant shown in Figure 8. Calculations indicate that the forces produced on the grips would be acceptable for over fifteen degrees of tilt in either direction; however the occupant may not be stable for forward tilts. The hand grip stops are securely clamped to the steel tubing but could be welded for permenent installation. These stops can be quickly attached by removing the plastic grip and tightening the clamp. The materials used were conservatively rated and of a readily available type whenever possible. The vehicle door was strengthened with another hinge and two horizontal plates. Hydraulic system features include (see Figure 9) a counterbalance relief valve to support the lift load against falling under any condition of valve or pump operation. The door actuator will be relieved at low pressure to prevent damage and allow manual opening of the doors if the power system fails. Manual operation of the valves is possible permitting the lift to be lowered by someone else.

Vehicle Control System*

Driver Capabilities

As stated earlier the driver being considered would be unable to effectively operate the mechanical hand controls now available. There may be several reasons for this functional limitations. Insufficient strength may be available to provide the forces needed to operate the mechanical linkages. Only a small range of motion may be useful making movements such as turning a standard steering wheel impractical. Involuntary motions may interfere with voluntary actions. The driver can be modeled as a system with inputs, outputs, and some form of transfer function. Here a full range of inputs, visual, aural, and kinesthetic, are assumed; though the kinesthetic input may be limited in information capacity with some disabilities. The outputs are sharply limited in capacity and may contain some noise such as involuntary motions or inertially generated signals. The outputs may also have small dynamic range or low resolution. The true form of the transfer function is complex and beyond the scope of this paper; though it is expected that work will be done in this area in the future. Here only a simple form will be used, thus the theoretical results obtained may be inferior to the performance of a human driver.

A Steering Control System

The control system must be able to account for the limitations above and still allow adequate performance for driving. Many possible approaches are available. Full proportional control is commonly used in aircraft and auto systems. A hydraulic servo with electronic augmentation has been used to increase the dynamic range of control handles. Though a proportional

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*Taken largely from a Master's thesis by George Stupp system of this type is capable of very good performance, the servo valve used introduces reliability as well as cost problems (4). Thus a proportional servo system was rejected as a candidate for the vehicle steering system.

Another approach which has been used successfully in other applications and has advantages due to hardware simplicity is a discrete rate control. The inputs to a road vehicle steering control could be like those in Figure 10a with the resulting steering angle response shown in Figure 10b. The choice of discrete input from a given set of discrete values determines the rate of angle change in the front wheels. A specific wheel angle is achieved by allowing the motion to integrate for a sufficient time period. Thus by choosing the rate from a fixed set and picking the corresponding length of time for that rate, any angle may be traversed. The hardware advantage results from the replacement of the precision servo valve of the previous approach by five simple solenoid valves and two flow control restrictions. A possible two rate system is shown, Figure 11. Because these valves produce only an on-off action and do not require the precision necessary for throttline, it is expected that an order of magnitude increase in reliability and a similar decrease in cost might be achieved. The system can be simplified even further by replacing the five valves with two 4-way, three position valves plus flow control restrictions. It is recognized

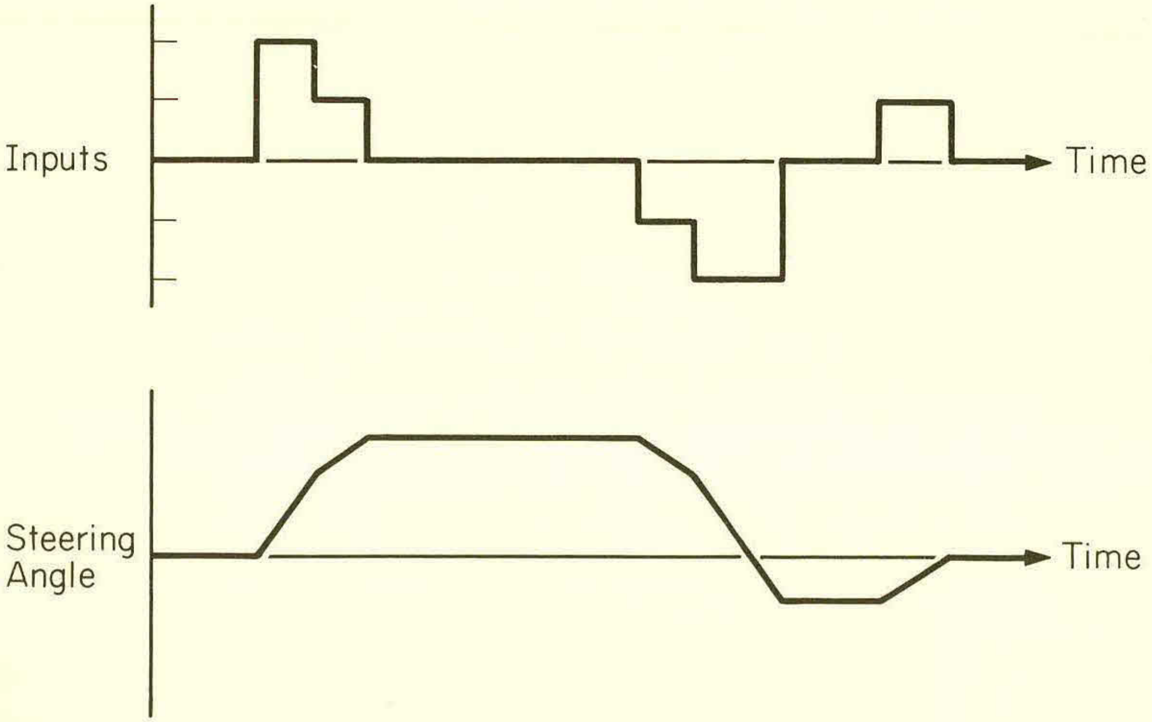


FIGURE 10. Response of a discrete rate control system.

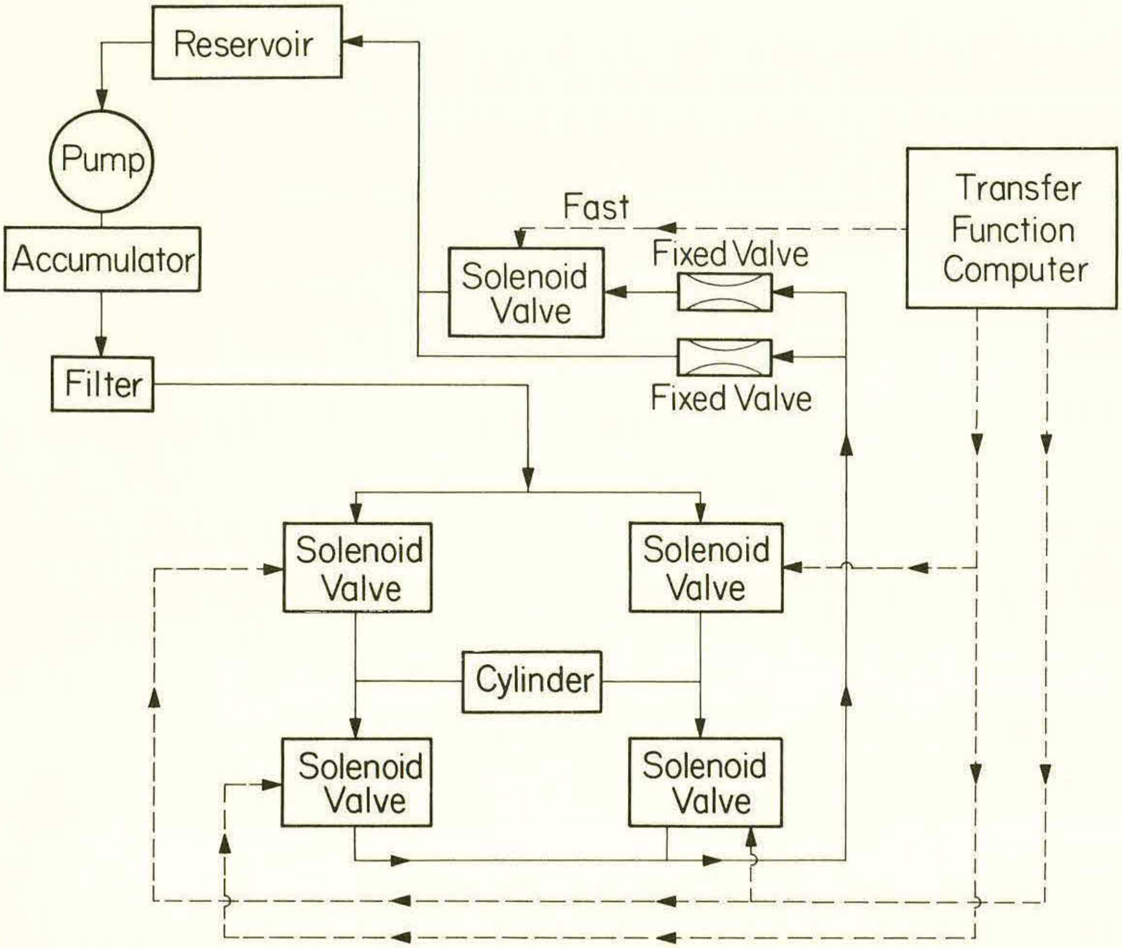


FIGURE 11. A possible two rate control system.

that a discrete rate system will produce a response inferior to that of a proportional system; however the improvement in reliability and cost made this type of system of interest.

The feasibility of a two rate control in steering an automobile was tested using an electric motor driven mechanism attached to the steering wheel of a 1967 Buick stationwagon with conventional power steering. The rate and direction of steering wheel rotation were chosen by applying voltage to the motor through a five position joystick. The values of voltages, and thus the steering wheel rotation rates, were picked subjectively by trial and error for the driving situations encountered. Though the mechanism was crude with backlash and slippage, adequate control of wheel motion was achieved over several runs using two experienced able-bodied drivers and one inexperienced disabled driver. The experienced drivers reported adequate control of the vehicle was easy in city driving. The most difficult driving occurred at high speed where the magnitude of the slow rate limited the maximum drivable speed, though one driver claimed good control up to 70 mph. The inexperienced driver though not provided with a control for braking and acceleration was able to effectively steer through city streets and park in a head-in situation. The only difficulties encountered resulted from not being accustomed to the size and turning radius of the vehicle.

The positive indications from this crude test along with the potential benefits noted above prompted an attempt to optimize the design of a discrete rate steering control system for the vehicle. The problem then reduced to finding the number and magnitudes of the steering rates that would allow adequate performance over the range of driving expected. The subsequent optimization produced an initial result for the two rate case using a simple man-vehicle model.

Driving Performance Index

A figure of merit or performance index must be defined in order to indicate in what sense performance is to be evaluated. A measure of error was used as the index and thus was minimized. For simplicity the performance index was applied only to describing a single turning maneuver. Data was taken of the front wheel angle versus time for several able-bodied male drivers executing turns in normal city and expressway driving with a 1970 GMC step-van donated for the project. Inspection of the data showed a close fit to a function composed of a fixed combination of constant segments and time varying segments of the form:

$$\theta = A[1 - \cos(Bt + C)]$$

where θ = front wheel angle

A = one half the maximum angle

B = the frequency (rate) of motion

C = a constant

t = time

Figure 12 shows a comparison of the idealized function with data from an actual turn. The performance index judged the performance of the modeled system against the idealized function for the turns specified by the A and B values taken from the actual driving data.

A subjective evaluation of desirable performance yielded an index of the form:

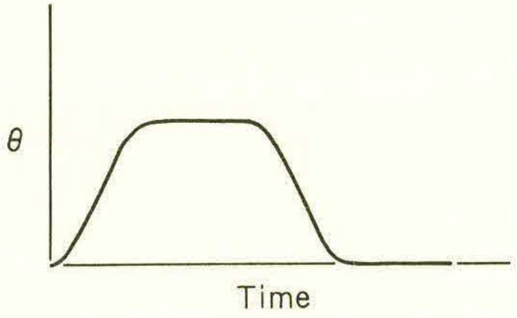
$$J(\underset{\sim}{x},\underset{\sim}{y}) = W\epsilon^2(T) + Pe^{(\epsilon_{max} - 2.)} + Re^{R(A_{max} - 0.1)} + S\left(\frac{N}{T}\right) + Q\int_0^T \epsilon^2(t)dt$$

where $\underset{\sim}{x}$ = set of parameters to be adjusted

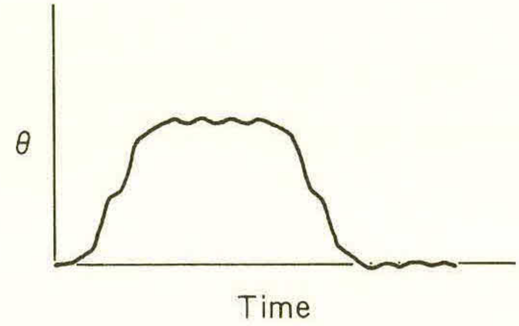
$\underset{\sim}{y}$ = set of parameters describing the turn

$\epsilon(T)$ = final lateral position error

ϵ_{max} = magnitude of the maximum lateral position error



Idealized Wheel Angle Function



Actual Wheel Angle Data

FIGURE 12. Idealized and actual front wheel angle function.

A_{max} = magnitude of the maximum lateral acceleration error

N = number of control inputs in time T

W,P,R,S,Q = weighting constants

The error function $\epsilon(t)$, A, and N were generated by a computer model of the man-vehicle system executing an idealized turn with parameters $\underset{\sim}{y}$. The choice of the performance factors and their penalties was motivated by the following arguments. If one considers the situation of turning into a narrow space, then deviation from desired position at the completion of the turn can be significant. An exponental penalty was applied to the maximum deviation from the desired path for errors over two feet since keeping the vehicle in its lane may be of paramount importance.m Lateral acceleration can be a measure of smoothness of control and must be kept within bounds to eliminate skidding. The maximum deviation of the lateral acceleration from the desired value was then given an exponential pentalty for errors over 0.1G, where the vehicle model speed for all turns used was set to allow a maximum lateral acceleration of 0.2G. The number of distinct driver motions per unit time was included as a consideration for driver effort. Lastly, the integrated square of the error was used to help reduce wandering or oscillation about the desired path.

For the type of control system being developed the steering rates must be set to some fixed values, yet they must permit adequate performance over a continuum of curves from a slow speed street corner to a high speed expressway lane change. Thus the rates must be optimized such that the worst performance over the range of turns is as good as possible, in other words a minimax optimization procedure is needed (5).

Driver-Vehicle Model

Because the minimax optimization required considerable computer time to run, a reasonably simple but adequately descriptive model was needed to allow a practical solution on the computer available, a CDC 1604. Two models were developed and the most descriptive, the threshold model, used in the optimization.

As shown in Figure 13, the threshold model describes the driver's judgement in terms of set of error level thresholds. A continuous decision is made on the composite error using the nonlinear error thresholds shown, the driver picking a steering rate from the available set which is appropriate to the error conditions observed. The selected rate is held for T_p min (0.05 seconds) which is the minimum pulse length that a driver might reasonably produce, based on the shortest dot produced by a telegraph operator sending at 20 words per minute. The resulting steering rate command is the input to the vehicle dynamics, where V is the vehicle velocity and W is the wheelbase. Note that no reaction delay is included, as a trained driver's prediction capabilities are assumed to make delay errors insignificant (6). The front wheel angle response of the threshold model is shown in Figure 14 with two possible steering rates. Though it is recognized that this is somewhat crude by the standards of current research, it was felt that a suitable approximation to observed behavior could be made using a simple threshold model, thus avoiding more complex approaches such as estimation theory models (7).

The optimization of the model performance involved minimizing the performance index with respect to the rates, error thresholds, and time constant τ and maximizing over the range of probable turns.

Minimax Algorithm

In a typical minimax problem it is desired to find the solution vectors, $(\underset{\sim}{x}^*, \underset{\sim}{y}^*)$, such that

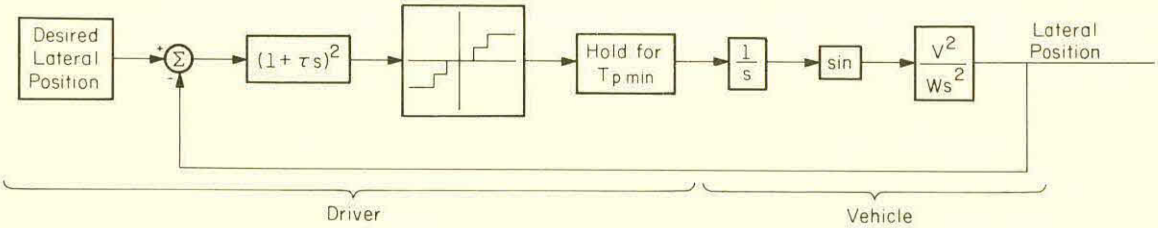


FIGURE 13. Threshold model of driver-vehicle system.

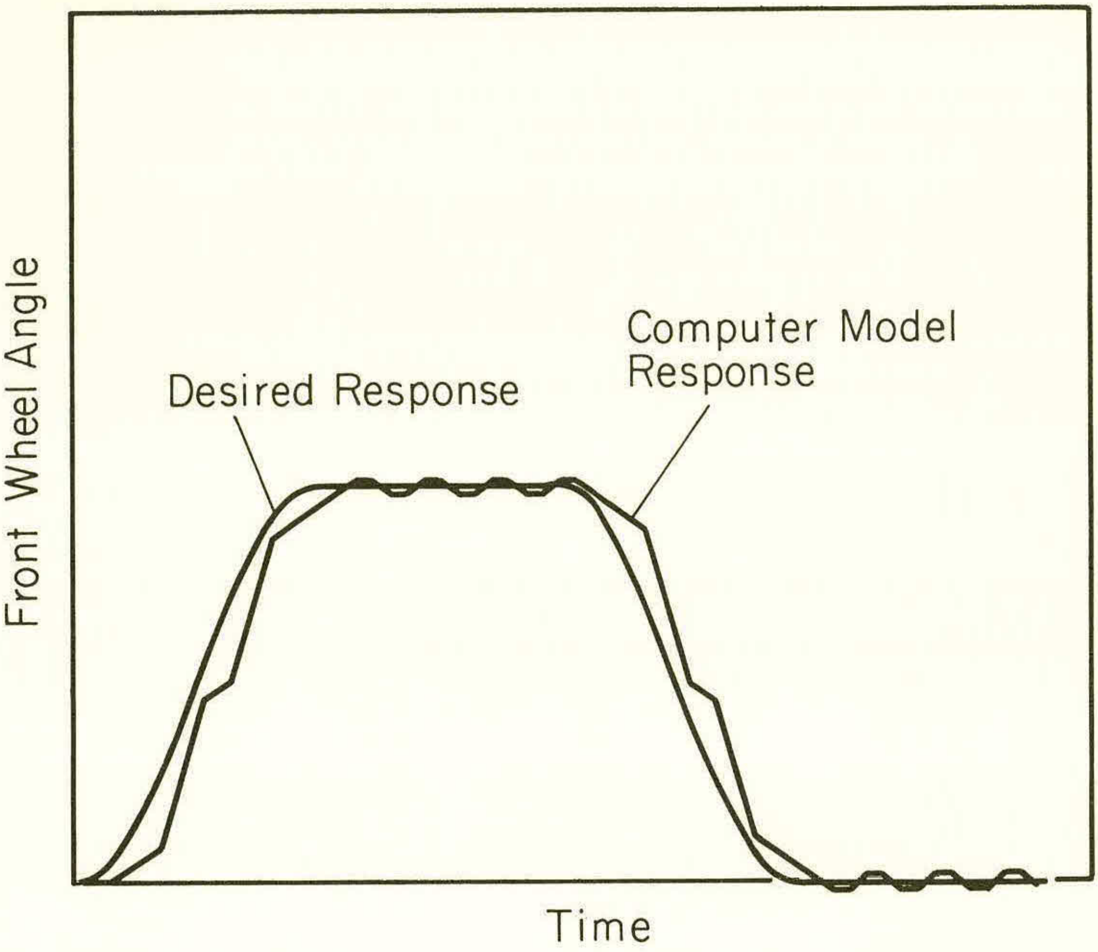


FIGURE 14. Response of threshold model for a two rate control system.

$$J(\underset{\sim}{x}^*,\underset{\sim}{y}^*) = \min_{\underset{\sim}{x}} \max_{\underset{\sim}{y}} J(\underset{\sim}{x},\underset{\sim}{y})$$

where $J(\underset{\sim}{x},\underset{\sim}{y})$ is the performance index of the system. In an attempt to solve this problem with reasonable convergence and reduce the effect of discontinuities with respect to $\underset{\sim}{x}$ in $J(\underset{\sim}{x},\underset{\sim}{y})$, a straight forward minimax routine was developed using an available modified Rosenbrock rotating coordinate minimization subroutine (8).

A simplified block diagram of the logic of the algorithm is shown in Figure 15. The minimax routine begins by prescribing the finite admissible space of $\underset{\sim}{y}$'s, Y, the upper and lower componentwise bounds for $\underset{\sim}{x}$, $[a,b]$, and a minimization parameter, Δ. The initial value of $M(\underset{\sim}{x},\underset{\sim}{y})$ is then calculated for the initial guess $\underset{\sim}{x}_o$, where

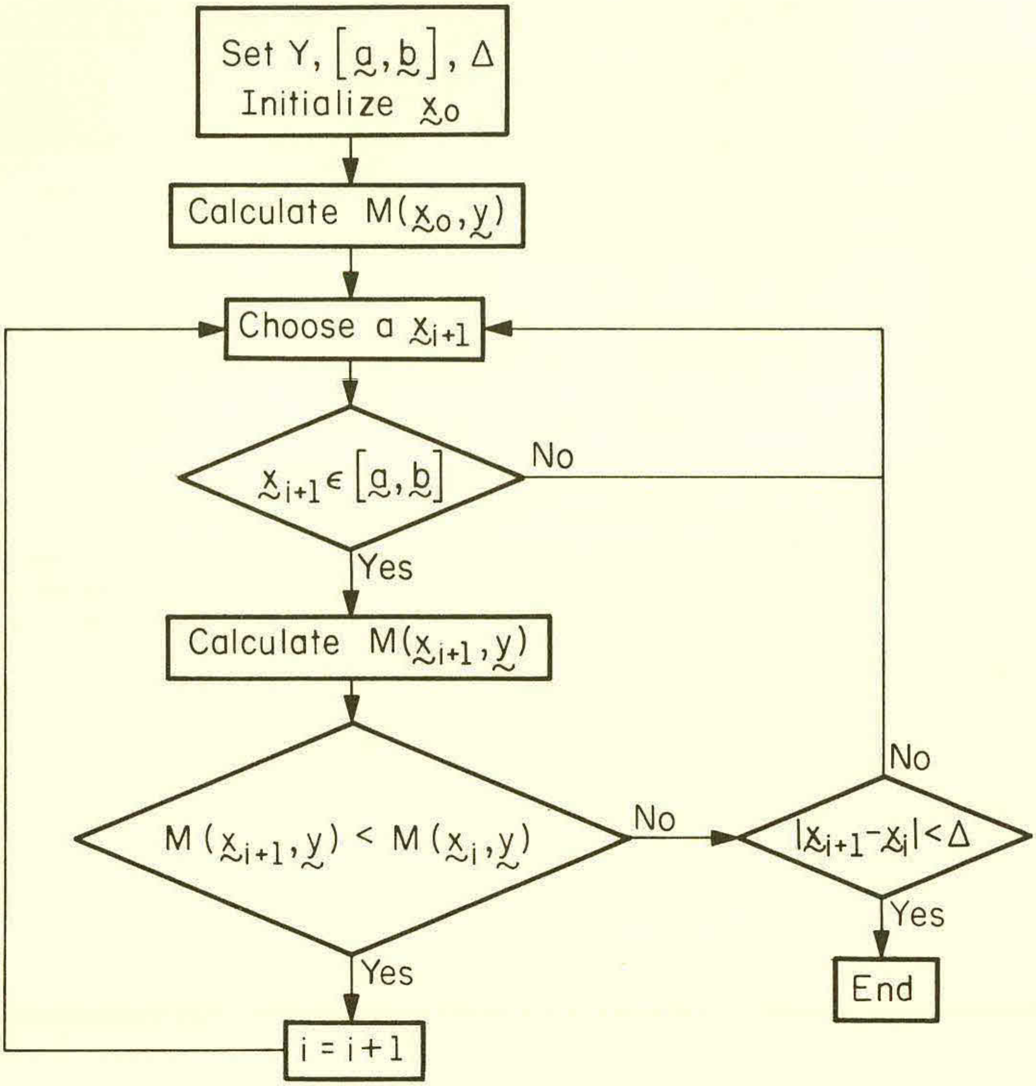


FIGURE 15. Simplified minimax algorithm.

$$M(\underset{\sim}{x}_i,\underset{\sim}{y}) = \max_{\underset{\sim}{y}} J(\underset{\sim}{x}_i,\underset{\sim}{y}),\ \underset{\sim}{y}\epsilon Y.$$

A new guess for $\underset{\sim}{x}$ is made using the modified Rosenbrock algorithm and checked for satisfaction of the given boundary constraints, [a,b]. An admissible guess is then used to calculate $M(\underset{\sim}{x}_{i+1},\underset{\sim}{y})$. If this new guess decreases the maximum, it is used in choosing the Rosenbrock coordinate directions and thus future guesses for $\underset{\sim}{x}$. If it does not decrease the maximum, the difference of this guess, $\underset{\sim}{x}_{i+1}$, and the current point, $\underset{\sim}{x}_i$, is compared with the minimization tolerance, Δ. If the difference is less than Δ, the routine ends with $\underset{\sim}{x}_i$ as the minimax solution. If the difference is not less than Δ, a new $\underset{\sim}{x}_{i+1}$ is made with $\underset{\sim}{x}_i$ unchanged.

Results of the Optimization

The set Y contained eight turns specified in the form

$$X = \begin{bmatrix} A \\ B \end{bmatrix}$$

where A and B are parameters of the turns. Discontinuities in $J(\underset{\sim}{x},\underset{\sim}{y})$ and a considerable number of local minima in $M(x,\underset{\sim}{y})$ were encountered during execution of the routine. These resulted largely from the discrete Y and the discontinuous nature of the driver-vehicle model. Several initial points were tried and decreasing sequences of Δ's were used to broaden the region of the Rosenbrock search. However there is no assurance that the minimum point selected is even the regional minima.

The solution for the two rate case is the best of the minima found. For this solution the weighting constants in $J(\underset{\sim}{x},\underset{\sim}{y})$ were

$$W = 500.$$

$$P = 20.$$

$$R = 10.$$

$$S = 750.$$

$$Q = 1.$$

The initial point was

$$\begin{aligned} x_o &= (9.0,\ 20.0,\ 0.3,\ 1.0,\ 50.0 \\ &= (E_1,\ E_2,\ R_1,\ R_2,\ \tau) \end{aligned}$$

where E_1 and E_2 are the error thresholds corresponding to the rates R_1 and R_2 respectively and τ is the feedback time constant. The minimax solution was

$$x^* = (22.83,\ 95.04,\ 0.2191,\ 1.139,\ 50.00).$$

Thus a rate set of 0.2191 rad/sec and 1.139 rad/sec of front wheel rotation results in a local minimax solution for the threshold model. Though it may be possible to find a better solution, this solution could be considered a "suitable candidate" for a system if it can be shown that satisfactory performance is produced (9).

The performance of the modeled control system at the above solution point can be seen in Figure 16 for two turns. The upper left plot is the front wheel cngle response for a sharp turn at 7.7 mph and the upper right plot is the corresponding lateral position error. The jagged line in the

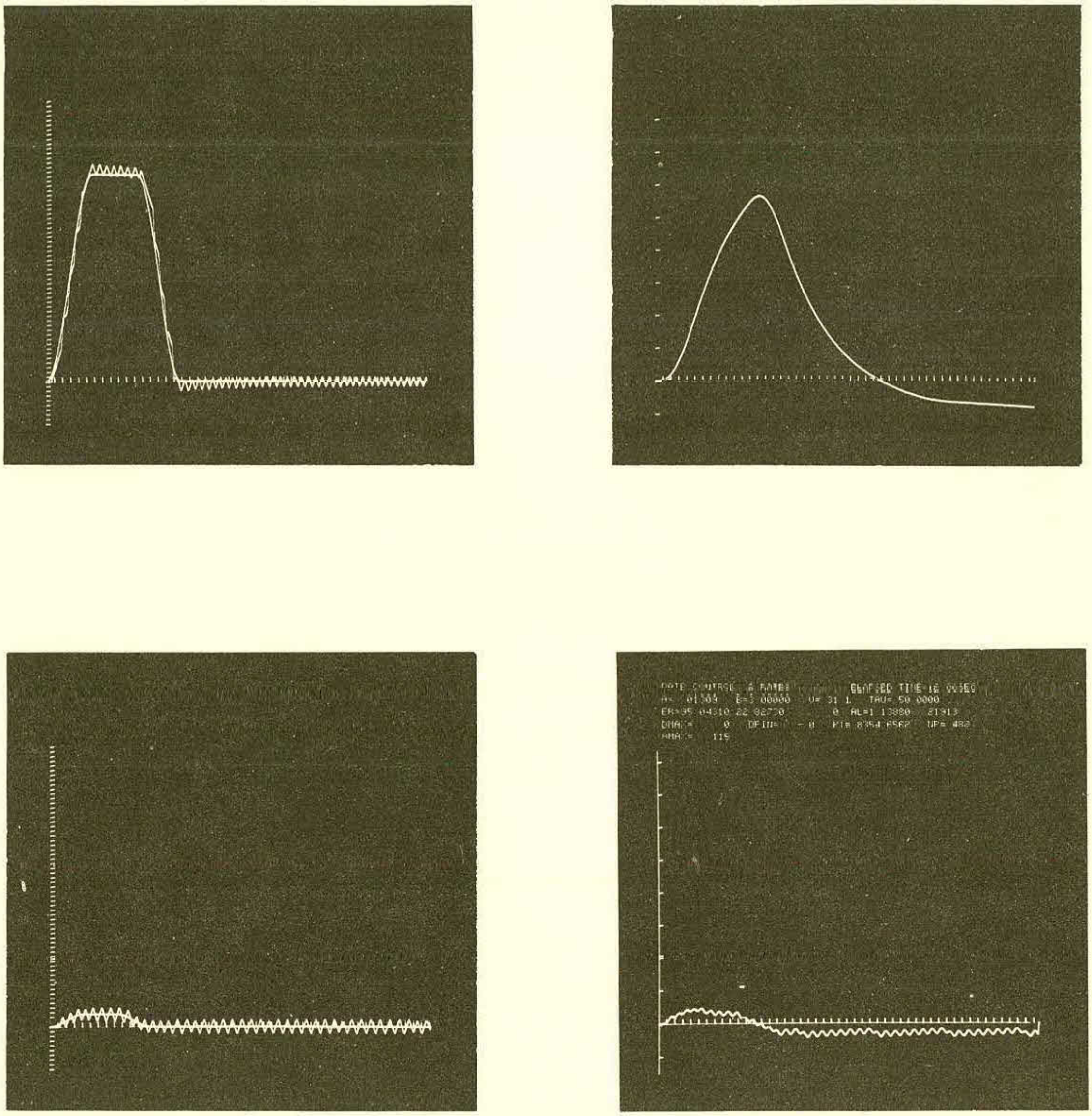


FIGURE 16. Response of driver-vehicle model for the optimal two rate case.

left plot is the system response while the smooth line is the idealized response. The maximum lateral position error during this turn was 0.6 feet and the maximum lateral acceleration error was 0.025G. The lower left plot shows the wheel angle response for a shallow maneuver at 31.1 mph with the corresponding position error on the lower right. Here the maximum position error was less than a tenth of a foot while the acceleration error was 0.115G. The other turns used in the optimization produced similar results with the largest position error being 0.9 feet.

In general the performance of the locally optimal two rate control is considered adequate for conservative city driving. However, higher speed expressway driving performance may be marginal at times with considerable driver fatigue possible as a result of the large number of small corrections needed combined with the reduced physical capabilities of specific drivers. Additional rates could be provided to improve performance here. It is hoped that additional work may be done to determine the optimum number of rates and their magnitudes.

Conclusion

Two design efforts have been presented on aspects of the development of a practical highway vehicle for independent use by a severely disabled person. Neither of these can be considered as the final result as additional refinements are needed.

While an operational prototype of the two bar lift exists and has shown its functional usefulness, additional design work will allow increased function and improved mechanical integrity.

Though the theoretical work above indicated that a discrete rate steering control would allow adequate driving performance, more detailed analytic techniques and real world driving tests are needed to truely validate this approach in view of the difficulty in fully simulating the driving environment in the laboratory.

It is hoped that this work may be continued along with an integrated study of the total vehicle including areas such as driver restraint, control console design, and potential driver evaluation and training.

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A DIGITAL PITCH-SENSITIVE CONTROLLER FOR AN ELECTRIC WHEELCHAIR

by

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Summary. The use of the voice as a control signal for mobility aids to the quadriplegic has been the subject of much research. This paper describes the design, construction, and evaluation of a digital control system that responds to the variations in the pitch of a hummed or whistled tone. This controller has been attached to a standard electric wheelchair, providing a wide range of directional control. Films of the prototype control system in action will be shown. The system offers a relatively wide control capability (7 or more discrete functions) at low cost. This project has been supported, in part, by the Veterans Administration. Two controllers are now being evaluated by the VA.

Introduction

The selection of control signals available from the quadriplegic with a high-degree of disability is quite limited. Eye, ear, and tongue switches have been used, as will as breath control (puff and suck, etc.) The most obvious choice is the voice, however, but the myriad difficulties inherent in voice recognition have severely limited the use of spoken commands for mobility aids.

As a compromise, one of the authors developed a prototype wheelchair control system[1] that responded to the pitch of a hummed tone, rather than to words or syllables. This original controller demonstrated the feasibility of a pitch-controlled system. This paper describes the further development of the original pitch-control concept, and the subsequent design of a digital pitch-sensitive controller.

The Digital Controller

The new digital controller was designed with several goals in mind. Among these were social acceptability (implying unobtrusive hardware and control action), responsiveness, ease of adjustment to various uses, relatively wide control capability, repeatability, and, hopefully, low cost (about $200). We feel that most of these goals have been realized in the control system as it now stands.

A block diagram of the digital controller is shown in Figure 1. Vocal input to the controller is derived from a small clip-on throat microphone. This eliminates almost all extraneous noises. The signal from this microphone is amplified and filtered by a simple three-stage amplifier and then sent to a Schmitt trigger for "squaring" prior to imput to the digital portion of the controller.

The digital logic operates in a four-state sequence designated as COUNT, COMPARE, STORE, and RESET. During the COUNT period the zero-crossings present in the hummed input signal are accumulated in a decade counter. The length of the COUNT period is controlled by a reference oscillator which is adjustable to fit the comfortable frequency range of the user. Control frequencies from 50 to 450 Hz can be recognized.

At the end of the COUNT period the contents of the decade counter are compared with the counted value that was accumulated during the previous count period. The previous value is stored in a set of registers for this purpose. The comparison is used to differentiate between hummed control

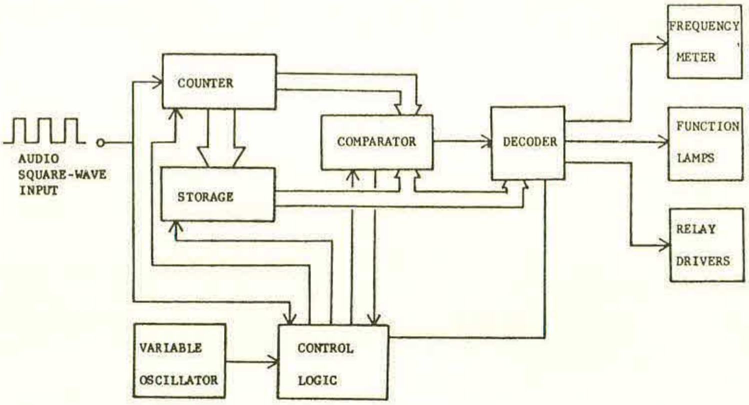

Figure 1: Block Diagram of the Digital System

signals and other sounds (talking, coughing, etc.). The digital control logic requires that the counted value, i.e., the hummed frequency, compare within a relatively narrow margin for three consecutive COUNT periods prior to initiating any control action. Thus, since speech and other sounds produce widely different counts during consecutive intervals, the controller responds only when the operator produces a hummed signal.

The COUNT interval is nominally 0.27 seconds. Thus, the operator must maintain a relatively stable pitch for about 0.8 seconds (three COUNT periods) in order to initiate movement. Once started, however, the controller remains energized until the operator stops humming, allowing him to shift from one control signal to another with only a 0.27 second delay.

At the end of the COMPARE period the current counted value is transferred into the storage register for use during the next comparison. Then the RESET period allows the decade counters to be cleared, after which the COUNT operation begins again.

The various control signals are derived by decoding the high-order digit as it is stored in the register following each COMPARE period. In the case of the wheelchair controller, seven different signals are decoded, corresponding to the high-order digits from 3 to 9. These control bands correspond to signals that produce from 30 to 39 counts during the COUNT period, 40 to 49 counts, and so on. The width of these "bands" allows the operator some latitude in each control frequency. The typical bandwith of a control band is about 35 Hz.

The control bands of the wheel chair controller are arranged as shown in Figure 2. The center band (50-59), when detected, energizes both wheelchair motors in the forward direction. The next higher and lower bands cause one of the motors to be cut off, thereby producing a veering to the left or right. The next two higher and lower bands cause the "off" motor to go into reverse, thereby producing a left or right spin or rotation. Following an unused guard band, the highest control band initiates a reverse movement.

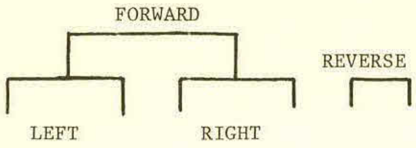

Figure 2: The Overlapped Control Bands

The overlapping of these bands allows the operator to make dynamic course corrections by shifting his pitch slightly upward or downward from the center (FORWARD) frequency.

Visual feedback is provided to the operator by a frequency meter that is marked in accordance with Figure 2. Function lights indicating FORWARD, LEFT, RIGHT, and REVERSE are also provided. With a little practice, however, most operators are able to relate frequencies and movement without needing visual feedback.

As the controller is now designed, movement continues only as long as the operator continues to hum. Whenever humming ceases, a detection circuit disables the chair's motors within 0.02 seconds and the chair coasts to a stop. This serves as a fail - safe feature, stopping the chair whenever the hummed input stops, as it would if the microphone slips out of place.

Conclusions

The controller described above seems to satisfy most of the original design goals. Its components cost approximately $200. It is not without problems and possible improvements, however. The necessity to maintain humming at all times is an inconvenience, although quite desirable for safety, and some type of fail - safe method to allow the operator to continue motion without continuing humming seems desirable. Also, braking (mechanical or electrical) seems desirable for stopping and for holding the chair in place when stopped on an incline.

Two controllers have been sent to the Veterans Administration Prothetics Center in New York for evaluation. It is expected that this evaluation will point to further need for improvement in the controller.

Acknowledgements

This project has been carried out jointly by the Departments of Bioengineering and Electrical Engineering at Texas A&M. Funds for the construction of the controllers were obtained, in part, from the Veterans Administration. Personnel from the Texas Institute for Rehabilition and Research, in particular Dr. Lewis Leavitt, have contributed valuable expertise to the project.

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A RECLINING WHEELCHAIR THAT PROVIDES WEIGHT SHIFTING MOBILITY FOR THE QUADRIPLEGIC

by

Donald E. Rugg
Charles E. Eppinger

Background

Damage to the human spinal cord produces disability which is somewhat predictable in extent--the effects correlating fairly closely to the vertical location of the injury. Within this general truism, however, the precise degree of paralysis is found to vary from individual to individual. These differences must be recognized as having extreme importance to the person living with them. Therefore, although a general class of equipment (such as wheelchairs) is needed by nearly everyone with high spinal cord injuries, variations in the physical abilities of each must be carefully accommodated, in order to successfully fill the specific needs of each.

Experience has taught that in rehabilitation, real and usable solutions are most reliably achieved when real and individual problems are confronted; that is, a solution which may entail the development of new hardware or modifications to existing items, will probably produce true success if the efforts are directed only at the major problem of a single disabled individual. Fortunately, many times it is found that, following success on the original problem, a moderate amount of additional work will tailor the solution for use by a number of others. However, when the initial thrust is made against a general problem (or a nonproblem imagined to be possessed by a class of people), it should be no surprise when the results are less than satisfactory, and the bill exorbitant.

The Independence reclining motorized wheelchair, as described in this paper, was developed to answer the needs of a single quadriplegic: author Donald Rugg. The purpose of the paper is to relate its development--from the position of the severely disabled person requiring it. To help understand the motivation for the development of this wheelchair, a brief discussion of his physical disability and overall needs will be presented.

Permanent paralysis resulted from spinal cord lesion at the C-4 and C-5 levels; the biceps, anterior deltoids, and middle deltoids remained functional, providing a reasonable range of arm motion. Although no wrist or hand motion remained, the problem of grasping objects was solved through appliances fitted to the forearm and hand. At this point, mobility was provided by a traditional electric wheelchair.

The Weight Shift Problem

Within four years following the injury, most of the general problems faced by quadriplegics had been solved. However, the ordinary electric wheelchair proved unsatisfactory, due to lack of physical ability to shift weight while in a sitting position; this obviously imposed serious limitations on activities. In addition, the prolonged periods of sitting had resulted in repeated pressure sores, requiring surgery five times during this four year period. They could be prevented by being lifted from the wheelchair every three or four hours and placed in a supine position, in order to redistribute the pressure. But, this necessity made full time employment impossible; it also complicated daily home care. It became obvious that this problem--the prevention of pressure sores which would almost certainly develop from overlong sitting--was the limiting factor; with its solution a satisfying, productive life and a high level of independence seemed achievable. It was clear that in this case, the positive prevention of pressure sores could be accomplished without the need for an attendant, only if a means were available for shifting body weight while in a wheelchair.

Past experience had shown that the pressure relief afforded by reclining periodically would successfully prevent pressure sores, while the use of various special cushions, including an alternating air cushion, had failed. Therefore, the concept of a powered wheelchair which would provide for full reclining (or perhaps more accurately a powered reclining mechanism on wheels) would allow occupying of the wheelchair all day without the need for an attendant.

Desired Functions

The size and maneuverability of a standard electric wheelchair were to be maintained. But it was obvious that it would not be feasible to simply add a reclining mechanism to a standard electric wheelchair; a fresh start was going to be required. With this decision made, a listing of the desired functional characteristics could be begun. Since the needed device was intended for use by only one individual, these characteristics could readily be defined, in the necessary detail. Adequate mobility, indoors and out, and the availability of enough energy to ensure all-day operation, were required. Speed capabilities to accommodate both close quarters and long straight runs, and high maneuverability were also musts. The chair would be required to negotiate, among other obstacles, a 30-inch doorway and all ramps commonly encountered. In addition to providing for full or partial reclining, convenient, once-a-day transfer was desirable. All of these would have to be achieved with a device that would be sturdy, reliable, easily cleaned, and pleasant in appearance. Finally, all desired functions must be capable of control, utilizing the remaining body functions.

Design Decisions

In translating the desired functional characteristics into a mechanical design, it is convenient to consider the device to be composed of a reclining chair mechanism mounted upon a lower framework having wheels and drive motors. The geometrical limitations imposed by the parts of the reclining mechanism, the rather massive storage batteries, and the drive motors, were found to be tight indeed. Since the chair was not ever to be hand-propelled by its occupant, the drive wheels chosen were of 10-inch diameter. They were located at the front of the chair with casters at the rear, because the clearance circle required for caster swivelling could not conceivably clear the occupant's legs without thrusting the whole of the lower reclining frame much too far rearward. The independent powering of each of the front drive motors allowed for steering, through a provision for energizing the motors separately or together, in either direction. For tidiness and easy cleaning, all possible frame members were fabricated from steel tubing which would later be chromium plated.

The seat and footrest elements were dimensioned in an attempt to satisfy the proper upright position of the occupant, a height that would accommodate work at a

FIGURE 1. The Independence Reclining Motorized Wheelchair.

standard desk, and adequate floor clearance. The seat depth was chosen to provide support for the upper leg along a maximum length, in order to prevent the leg from slipping off the side of the chair; the seat width was chosen to fit the body fairly snugly, in order to assure correct side-to-side positioning. Seat cushions were of vinyl covered rubber foam, slightly concave, so as to present greater surface area for weight distribution. For this occupant, the back height was kept low so as not to further impede the limited shoulder motion retained.

Design of the reclining mechanism, which was after all the chair's reason for being, received particular attention. A fully horizontal position was desired, and yet the position of the center of gravity relative to the chair base had to assure that the chair would not tip over--at every degree of recline. In order to assume the horizontal position, it was necessary to raise the footrest, to lower the back, and to bring a headrest into position for head support since it was undesirable for the seat back to be that high. With the degree of disability involved, it was essential that the chair return the occupant to his original position on the seat, no matter how many cycles were gone through.

A motor-driven lead screw provided motion for the chair back, footrest, seat, and headrest through a mechanical linkage arrangement. A spring in the mechanism which raises the headrest furnished a counter force to assist the lead screw in returning the chair to its upright position. A close following of the occupant's motions by the chair elements, in order to assure repetition of his original position as mentioned above, was furnished by providing the seat with a fore and aft motion, tied to the reclining position. Therefore, as the back moves downward and the footrest and headrest begin to change their positions, the seat also slides rearward slightly. It thus lengthens the distance from footrest to seat, and shortens the distance from seat to back. This motion is vital to the chair's success because it allows the occupant to be returned to his original position, time after time, without assistance.

Since the initial wheelchair was designed for a quadriplegic with a reasonable range of arm motion, simple and functional controls were selected. A joystick, which allows for eight sectors of directional control, directed power to the two drive motors, and provided steering. Slightly behind the joystick, a three-position switch was provided for selecting high or low motor speed, or power off. A third switch at the same location controlled the reclining operation. These hand-operated controls were selected because of their simplicity, reliability, low cost, and minimum interference with other body functions--and in preference to the several more sophisticated approaches which might have been used. All switching functions were accomplished with ordinary relay circuits.

Concluding Remarks

The original objective has been accomplished; the chair has supplied mobility without the recurrence of pressure sores, through the weight shifting provided by reclining. The user remains in the chair about sixteen hours each day and has been employed on a full time basis now for over twelve years. The home care by others, formerly required, has been greatly reduced.

This instance of pressure sore prevention is not unique. Many, if not most, high level quadriplegics who do not retain the physical ability to shift their weight, while sitting in a wheelchair, suffer from that problem. The benefits provided by the first Independence wheelchair were, quite naturally, sought for other individuals in similar circumstances. At this date, through a licensing agreement with the Falcon Research and Development Company of Denver, nearly a hundred users have achieved similar self-sufficiency--have been able to continue their education or return to work on a full time basis, and greatly reduce the amount of home care required.

However, each user is an individual case and requires individual consideration. First of all, the seat, back, footrest, and armrest dimensions are tailored to the individual's physical size and weight. The means required to control the wheelchair are even more sensitive to the individual and his own degree of disability. With a reasonable amount of arm motion, a joystick control box as previously described can be utilized--mounted either upon one of the armrests or, in some cases, in a special location immediately in front of the occupant. When insufficient arm motion remains, good head motion is usually available. This has been exploited through the use of a chin control unit which is mounted immediately in front of, and slightly below, the user's chin. As before, this choice is based upon maximum simplicity and reliability, and noninterference with other necessary motions and functions; it is preferred to other, nonmechanical signals for these reasons. It is out of the line of vision, and away from the mouth. When the user wishes to move away from the unit slightly, he merely reclines the back an inch or two. In all cases with the chin control, and in some cases with the hand-operated joystick, the on-off, high-low speed, and recline functions are available through three neck switches located around the user's collar, and activated with the chin by nodding the head.

Some electric wheelchair controls provide for speed variation as a function of joystick position (proportional control). However, most of the candidates for the Independence wheelchair do not possess sufficient hand and arm dexterity to successfully manipulate this type of control. It would merely add complexity and cost without solving a major problem, and has therefore not been used.

The Independence wheelchair has solved the major problem of a large number of severely handicapped persons throughout the country, because it was designed through the observance of (1) careful identification of a specific problem before reaching for solutions, (2) a bias toward simple and reliable measures in preference to those of higher sophistication whenever possible, and (3) the application of combinations of tailored dimensions and special purpose accessories to one basic or standard item, which allows it to be furnished with reasonable economics.

A SURVEY OF ELECTRIC WHEELCHAIR POWER SUPPLIES*

John Molnar**

Abstract. The severely handicapped are dependent upon electric wheelchairs for mobility. Many of the handicapped are young quadruplegics. Whether or not these people can achieve any degree of self-sufficiency depends upon their ability to get about.

Electric wheelchairs are being examined for possible improvements through recent engineering advances. The electric wheelchair can be divided into convenient subassemblies for study. One of the subassemblies is the power supply. A detailed presentation of power supplies is made. The universally used lead-acid battery is compared to fuel cells, alkaline batteries, and new high energy density batteries. It is shown that for the present it is necessary to continue to use the lead-acid battery. Techniques to achieve maximum utilization and lifetime for a lead-acid battery are described.

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Introduction

The nation contains a growing number of severely handicapped citizens. A large percentage of them are young adults. The veterans who are quadruplegics due to war wounds have recently received national publicity [1]. Less publicized is the steady increase in the number of quadruplegics due to diving and other sports-related accidents. The modern road systems and high performance automobiles have combined to produce increasingly destructive automobile accidents. The survivors of high-speed accidents are often partly or completely paralyzed. A few years ago, quadruplegics had a short life expectancy due to high vulnerability to urinary infection and decubitus ulcers [2]. Modern antibiotics and patient care have solved these problems, and the patients can expect normal life spans. The group is not limited to spinal-cord injuries. People with severe cases of cerebral palsy are also included. The patients want to become self-supporting, but lack mobility. The electric wheelchair is the key to helping the severely handicapped achieve independence.

The adaptation of the response of the wheelchair to the desires of the user is a direct function of the amount of money the user is willing to invest in his chair. The available wheelchairs can be categorized into two groups: indoor wheelchairs and outdoor wheelchairs. The former tend to be standard folding wheelchairs that have been fitted with drive motors, battery, and a control unit, usually of the "joystick" type. The latter tend to be motorized tricycles or golf carts and are generally too large and heavy to facilitate indoor usage. The indoor chairs are portable, but require the removal of a 50-pound battery before folding. The typical indoor electric wheelchair weighs approximately 150 pounds with battery.

The wheelchair can be conveniently divided into subassemblies. The subassemblies are: the power unit, the power supply (the suspension), the control unit, and the overall chair configuration. Each of the subassemblies is being examined for improvement.

This paper is concerned with the power supply. The need for a portable power supply is felt in many areas, including prosthetics. Lead-acid storage batteries are used to power electric wheelchairs. The lead-acid storage battery as a power source is heavy and requires nightly recharging; however, it is mass-produced which makes it inexpensive and readily available. In the following paragraphs the lead-acid battery is compared to alkaline batteries, high energy density batteries, and fuel cells. Detailed lead-acid battery data is presented to acquaint the reader with the variety available. Finally, information is presented on how to attain the best service from a lead-acid battery.

The capacity of a storage cell may be expressed in two ways: as the amp-hour (Ahr) or the watt-hour (Whr) capacity [3]. Battery Ahr and Whr ratings are relative quantities. The actual capacity of any given battery is greatly affected by the manner in which the battery is used. The discharge rate, temperature, and final voltage all affect battery performance. A battery that is rated to give a current for eight hours at the normal discharge rate will only function for about one hour at four times the normal discharge rate. Likewise, the battery will give one-fourth the current for about 56 hours [4].

Another comparative number that is cited is the energy density. The energy density is computed by dividing the battery Whr rating by the battery weight. The energy density is an indication of battery efficiency in terms of the amount of material required to store electrical energy. High energy density batteries are desired.

Alkaline Batteries

The first energy storage devices to be examined can be collectively referred to as Alkaline Batteries. Included are batteries using Nickel-Cadmium, Iron-Cadmium, Silver-Cadmium, Silver-Zinc, and Manganese-Zinc for electrode materials. The batteries are commercially available and manufactured in sealed and cell form. The Nickel-Cadmium (Ni-Cd) and Iron-Cadmium (Fe-Cd) batteries are examined here for possible use in powered wheelchairs [5].

The primary advantages of Ni-Fe and Ni-Cd batteries are their ruggedness and long life. A comparison of lifetimes is presented in Table 1. The life of a Ni-Cd battery is usually given either as the number of charge and discharge cycles that can be delivered by the battery, or as the total lifetime. It is difficult to give definite figures, since battery life will vary a great deal with different operating conditions. The Ni-Fe battery has a history of delivering one of the longest periods of useful capacity of any battery system. Vibration does not cause loss of active material from the plates. Neither Ni-Cd nor Ni-Fe batteries are damaged by overcharging, short-circuiting, or reverse charging. Ni-Fe batteries have been reported to last from seven years (in heavy duty service) to more than 25 years (in stand-by and floating applications).

Typical energy densities and weights for Ni-Fe batteries are presented in Table 2, and for Ni-Cd batteries in Table 3. The energy density of Ni-Cd sintered plate and Ni-Fe batteries is comparable to lead-acid batteries. The energy density of Ni-Cd pocket plate batteries is less than for lead-acid batteries. Powered wheelchair manufacturers recommend 100 Ahr capacity weighs 63 pounds and has an energy density of 19.4 Wh/lb. Typical alkaline battery dimensions are listed in Table 4. Two lead-acid batteries have been included for comparison. It is seen that alkaline batteries tend to be larger than comparable lead-acid batteries.

Alkaline batteries cost more than lead-acid batteries. Nickel and Cadmium are very expensive materials. A 12-volt, 100 Ahr Ni-Cd battery would cost approximately one-thousand dollars [6]. A comparable lead-acid battery would cost approximately sixty-five dollars.

In order to obtain long life from alkaline batteries, careful servicing is required. The batteries must be periodically flushed. The user here encounters an unexpected hazard. Alkaline batteries are not in wide usage. The person doing the battery maintenance may well add sulfuric-acid-based electrolyte. The sulfuric acid will ruin the battery.

Thus it is seen that while alkaline batteries last longer than lead-acid batteries, the increased lifetime is outweighed by greater weight, higher cost, and lower energy density for alkaline batteries. Alkaline batteries are neither readily available nor servicable, and therefore are not recommended for use with powered wheelchairs.

TABLE 1

COMPARISON OF BATTERY LIFETIMES

Battery	Number of Deep Discharge Cycles (>70% discharge)	Total Lifetime in Years
Ni-Fe	2000 - 4000	7 - 25
Ni-Cd (Pocket)	500 - > 2000	8 - 25
Ni-Cd (Sintered)	300 - >2000	3 - 10
Pb-Acid	200 - 700	3 - 6

TABLE 2

SELECTED ENERGY DENSITIES FOR NICKEL-IRON BATTERIES

Cell Type	Capacity per Plate Pair Ahr	Weight per Plate Pair Lb	Total Battery Capacity Ahr	Total Weight Lb	Energy Density Whr/lb
A3	37.5	3.5	112.5	105	13.5
C2	56.25	5.1	112.5	102	13.2
D2	75	6.85	150	137	13.2
EB	100	7.45	100	74.5	16.1
EB2	100	7.45	200	149	16.1

TABLE 3

TYPICAL VALUES FOR Ni-Cd SINTERED PLATE BATTERIES (SONOTONE)

H $\underline{\Delta}$ High-Rate
M $\underline{\Delta}$ Medium-Rate
L,K $\underline{\Delta}$ Low-Rate

Cell Type	Cell Capacity Ahr	Cell Weight Lb.	Total Battery Weight Lb.	Energy Density Whr/lb.
60L 420	70	5.19	52	16.2
81H 120	80	6.6	66	16.7
100M 220	111	11	110	12.1
100M 320	121	11	110	13.2
210L 420	230	19.8	198	14.0
HIP-10	100	19.4	194	6.2
HIP-14	125	26.2	262	5.7
HIP-15	150	3.17	317	5.7
HI-10	100	20.9	210	5.7
HI-14	125	26	260	5.7
MDP-10	100	12.8	128	9.4
MDP-13	130	16	160	9.75
MDP-14	140	20.2	200	8.4
MD-14	140	20.1	200	8.4
KAP-10	95	10.6	106	10.7
KAP-13	125	13.4	134	11.3
KAP-18	175	16.9	169	12.4
KA-12	120	13.4	134	10.7

TABLE 4

TYPICAL ALKALINE BATTERY DIMENSIONS

Battery Type	Battery Capacity Ahr	Dimensions Length	Width	Height
Lead-Acid	102	13 9/16	6 13/16	9 13/16
Lead-Acid	105	17 15/16	7 1/8	9 5/8
Nickel-Iron	75	24 3/4	32	29
Nickel-Iron	100	24 3/4	26	23
Nickel-Cadmium*	80	20	5 1/8	8 1/2
Nickel-Cadmium*	111	27 1/2	6 3/4	8 3/4
Nickel-Cadmium	100	40	6 3/4	15 1/2
Nickel-Cadmium	100	30	5 3/8	12 3/8
Nickel-Cadmium	120	29	6 3/4	16 1/8

*Nickel-Cadmium batteries with sintered plates--other Nickel-Cadmium batteries listed have pocket plates.

High Energy Density Batteries

High energy density batteries for use in electric automobiles are being developed [7]. The goal is production of a battery with a 100 Whr per pound energy density at a cost of one dollar per pound. Two types of batteries are being developed. Both the Ford Motor Co. and the Dow Chemical Company have developed experimental sodium-sulfur (Na-S) batteries. A lithium-sulfur (Li-S) battery is undergoing tests at the Argonne National Laboratory. While both batteries are in the developmental stage, indications are that the energy density and cost goals are achievable. The work on the Na-S battery is more advanced than the Li-S battery. Also, the Na-S battery will require less money than the Li-S battery to set up demonstration hardware. The successful demonstration of a Na-S battery may well lead to stopping work on the Li-S battery. Both batteries are high temperature devices that operate at temperatures over 300°C.

During the period of July 1970 to June 1971, approximately fifty experimental Li-S cells of various designs were tested. Cycle lives of over 800 discharge-charge cycles have been demonstrated. Current and energy densities have been achieved that indicate that a battery consisting of Li-S cells can meet the energy density goal. An energy density of 150 Whr/lb has been predicted for a Li-S battery which is much greater than the 16 Whr/lb for a lead-acid battery [8]. Except for the lithium, which is less than ten percent of the cell by weight, the materials needed for a Li-S cell are plentiful and inexpensive. The potential cost of a mass-produced cell would appear to meet the design goal.

Ford Motor Company has developed a Na-S cell that has a molten-sodium anode, a crystallite ceramic electrolyte, and a melt of sodium sulfide and sulfur for the catholyte. The Ford cell uses a ceramic membrane made of beta-alumina. The theoretical energy capacity of a sodium-sulfur battery is 360 Whr/lb while the estimated practical energy density is 100-150 Whr/lb.

Work is progressing to develop high energy density batteries that operate at room temperatures. The results thus far are encouraging and indicate the possibility of high energy batteries that would be operable at room temperature, although maximum power might occur at a higher operating temperature.

Practical lithium-sulfur and sodium-sulfur batteries can be expected to be developed before low-temperature batteries. The high energy density batteries that are being designed for the automotive market should be applicable to powered wheelchairs. The commercial appearance of the high energy batteries described above is some time away. The batteries are predicted to become available during the early 1980's [9].

Fuel Cells

The fuel cell merits consideration for use with powered wheelchairs. Most of the engineering work for developing fuel-cell power systems has been done in the past ten years [10]. The elimination of long recharging periods makes the fuel cell attractive for use with powered wheelchairs. The same feature makes comparison with conventional batteries difficult [11]. Batteries are compared by means of their energy densities as given in Whr per pound. Such an energy density figure of merit does not apply to fuel cells. A fuel cell consists of two parts: the reaction apparatus and the fuel supply. Electricity is produced as long as fuel is supplied. Thus, the energy capacity rating is open-ended.

The only successful fuel cell to date is the hydrogen-oxygen cell. Hydrogen is the fuel, oxygen is the oxidant, and potassium-hydroxide is the electrolyte. The hydrogen and oxygen react to produce the byproducts of electric current and water. The production of water has been useful to the space program, where hydrogen-oxygen fuel cells have been used extensively.

As larger current is drawn from a fuel cell, the terminal potential will drop. The loss of potential is known as polarization. To minimize the effects of polarization, platinum, palladium, and silver have been used for the electrodes. The result is very expensive cells that only the space agency has been able to economically justify. In 1968 a commercially available cell was announced by Yuasa Battery Company in Japan [12]. The price quoted at the time was $2775. The cost alone disqualifies the hydrogen-oxygen fuel cell from consideration for use with powered wheelchairs. Another bad feature of the hydrogen-oxygen fuel cell is the potential explosion hazard. Also, the hydrogen and oxygen are supplied and stored in liquid form, which is not practical for a wheelchair. Suppliers of liquid oxygen and hydrogen are not readily available.

Much developmental work has been done on hydrocarbon fuel cells.

In a hydrocarbon fuel cell, a more convenient and less expensive fuel such as natural gas or propane, reacts with air to produce electricity [13]. Direct hydrocarbon fuel cells have not reached a useful stage of development, primarily due to slow rates of electro-chemical reaction for organic fuels. The best simple catalyst found so far is platinum. The most successful hydrocarbon fuel cells actually convert the fuel into hydrogen which is then used to produce electricity. When a re-former is used to generate hydrogen from a hydrocarbon fuel, the overall system efficiency falls. The re-forming process is only about 50 to 70 percent efficient and introduces an increase in system hardware and complexity.

In summary, fuel cells are expensive, because of costly fuel. Their lifetime and ease of maintenance for extended operation have not been proved. The future outlook for fuel cells does not look promising at this time [14]. No one is willing to pay the cost of making fuel cells a practical reality.

Lead-Acid Batteries

From the preceding, it is seen that due to the lack of competitive alternatives, it will be necessary to continue to use lead-acid batteries in electric wheelchairs. The primary disadvantage of the lead-acid storage battery is the weight. The capacity of a storage battery is dependent upon the amount of material in the plates, the plate thickness, and the design of the plates. High capacity batteries require many large, heavy battery plates [15].

Typical battery characteristics [16] are presented in Table 5. It is seen that both the battery weight and number of plates increase as the battery capacity increases. While the physical battery size does not greatly increase with higher capacity, the weight and cost do. Comparing the 80 and 375 Ahr batteries, it is seen that for a 470% increase in capacity, the weight and cost increase by 634% and 566$, respectively. The Whr capacity and energy density for each of the batteries in Table 5 are listed in Table 6. It is recommended that the smallest capacity battery that would satisfy the individual requirements be used. The increase of running time does not justify the increased weight of a higher capacity battery unless such a battery is actually needed. The truely high capacity batteries would require extensive bracing of the wheelchair in addition to an initial battery cost out of proportion with the useful gain.

The performance and reliability of powered wheelchairs can be improved through better education of the users. With proper care, a lead-acid automotive storage battery can last for two or three years. However, the users receive very little instruction on how to care for the battery. Only recently have some manufacturers started recommending battery capacities. Often users have purchased inadequate batteries due to financial restraint and lack of knowledge about power requirements. More detailed instructions, including a preventive maintenance schedule, should be furnished by manufacturers. Writing such instructions would be challenging, for the users often have a meager technical background. The procedures necessary to get the most efficient usage from a battery are described next.

The powered wheelchair user needs to know how much energy remains in his battery. This is especially true if he operates the wheelchair out of doors. An amp-hour meter would give a visual indication of charge status. One type of amp-hour meter that could be used on powered wheelchairs is basically a mercury microcoulometer. The microcoulometer is a glass capillary tubing filled with two columns of mercury separated by a small electrolyte gap. Application of a direct current to electrodes inserted in the mercury causes mercury at the anode to be electrochemically transferred across the gap to the cathode at a time rate proportional to the current. The gap moves along the tube length which can be calibrated to indicate the amount of battery charge remaining. A typical tube-type amp-hour meter would measure 1.87 x 0.37 x 0.39 inches with a one-inch scale, weigh eight grams, and cost approximately ten dollars [17].

The maximum capacity of a lead-acid battery is obtainable only through complete charging. Complete charging can be obtained only by knowledgeable use of carefully selected equipment. Powered wheelchair users must be educated in the why and how of battery charging. An ideal charging cycle consists of a high initial surge of charging current, followed by a steady charging current, and finished with a charging current that is slowly reduced [18].

Many battery chargers are available commercially. One retailer has a selection with prices varying over a range of nine to thirty-five dollars. As the price increases, more features are added. It is recommended that the powered wheelchair user not stint on purchasing a battery charger. The high priced model mentioned above initially delivers a short 50 amp booster charge. The charger then switches to normal 10 amp charging rate which is tapered to five amps towards the end of the charging cycle. All switching and turn off are automatically controlled. Less expensive chargers deliver smaller charging currents, which means longer charging times are required. The low cost chargers must be monitored and manually shut down to prevent excessive battery gassing.

Once a week the battery should be given an overcharge, known as an "equalizing charge." The purpose of the equalizing charge is to bring all the cells in the battery to the same level of charge. The equalizing charge is accomplished by continuing to charge the battery at a low rate with the cells gassing freely until three consecutive readings of the specific gravity and voltage show no increase. If the wheelchair user is unable to check the specific gravity, he should make arrangements for an attendant to do so. It may be necessary to rewire the battery charger to permit overcharging.

Once every three or four months, the voltage and specific gravity readings of each cell should be recorded. Trouble such as sulphation or leakage is indicated by a progressive change in specific gravity readings. The specific gravity of the cells must be adjusted whenever electrolyte has been added to the cell. Specific gravity adjustment should be done at the end of the equalizing charge. The specific gravity should need adjusting only if the electrolyte has been spilled. The electrolyte level should be monitored. Excessive gassing during charge will remove water from the electrolyte leaving a more concentrated solution of sulfuric acid. Should the level be low, water should be added. The water should be added before charging to permit mixing with the electrolyte during charge.

The battery connections must be kept tight at all times. The battery terminal posts should be given a light coating of petroleum jelly to prevent corrosion. A battery case is recommended to protect the battery from the elements, should the wheelchair be used out of doors.

TABLE 5

TYPICAL 12-VOLT LEAD-ACID BATTERY RATINGS

Ahr	Weight Lbs.	Number of Plates	Cost Dollars	Dimensions (In.) Length	Width	Height	Design Use
80	48	78	46.45	12 7/16	6 5/8	8 15/16	Automotive
95	53	90	51.95	12 7/16	6 5/8	8 15/16	Automotive
95	69	66	70.45	11 7/8	6 7/8	10 15/16	Tractor
100	70	138	91.95	10 29/32	10 3/16	9 1/16	Ordnance
102	63	90	63.95	13 9/16	6 13/16	9 3/16	Commercial
105	77	78	77.95	17 15/16	7 1/8	9 5/8	Heavy Duty(Truck)
135	99	90	81.95	16 1/2	7 1/16	11	Tractor
155	122	114	109.45	20 3/8	8 11/16	9 3/4	Heavy Duty
174	141	138	115.45	20 3/8	9 13/16	9 3/4	Heavy Duty
204	154	150	129.45	20 3/8	10 15/16	9 3/4	Heavy Duty
275	212	162	183.45	20 3/8	10 7/8	11 7/16	Mine Car
375	304	114	247.45	20 1/4	10 7/8	14 7/8	Mine Car

TABLE 6

ENERGY DENSITY FOR TYPICAL LEAD-ACID BATTERIES

Ahr	Whr	Weight Lbs.	Energy Density Whr/lb.
80	960	48	20.0
95	1140	53	21.5
95	1140	69	16.5
100	1200	70	17.2
102	1225	63	19.4
105	1260	77	16.4
135	1620	99	16.4
155	1860	122	15.2
174	2090	141	14.8
204	2440	154	15.2
275	3300	212	15.5
375	4500	304	14.8

Conclusions

Various energy sources have been examined. It has been seen that technology is not far enough advanced to permit use of fuel cells or high energy density lithium-sulphur batteries. Alkaline batteries are seen to have lower energy densities and higher costs than lead-acid batteries. It is not felt that the longer life justifies the out-of-proportion cost increases. Thus, probably for the next decade, it will be necessary to continue to use lead-acid storage batteries, with their disadvantages of high weight, frequent charging, and required maintanance.

It is felt that powered wheelchair users should be better trained with respect to battery care. Charging procedures and general battery maintenance have been described.

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A VOICE-CONTROLLED TELEPHONE FOR THE MOTION HANDICAPPED

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Summary. This paper describes an experimental voice-controlled telephone developed at Bell Telephone Laboratories and discusses preliminary results of a small, informal field experiment.

Introduction

To make it possible for people to use the telephone unassisted, despite loss of finger and arm function, an experimental, self-contained, completely hands-free telephone was developed. All normal telephone functions are controlled by the user's voice. In addition, the unit performs repertory dialing functions and includes facilities for voice control of appliances such as a reading lamp or a television set.

Telephones and the Disabled

Background

The telephone plays a most important part in rehabilitation medicine, according to Dr. Howard A. Rusk, one of the leaders in the field of rehabilitation. He once remarked that even with the most skillful surgery, the most effective medication, the best post-operative care, the finest physical and occupational therapy, and the most advanced orthotic and prosthetic devices, rehabilitation cannot be a success unless the patient's needs for communication are met.

Because of restricted mobility, a disabled person has a greater need for telephone communication than the rest of us. If he can use a telephone, he can maintain contact with his friends, conduct a business or practice a profession, summon assistance in emergencies, and, in many cases, release another member of the household from full-time custodial duties.

Bell Offerings for the Handicapped

For many years, the Bell System has offered telephone equipment to aid people with many categories of disability, including hearing impairment and deafness, impaired vision and blindness, weak speech and total loss of voice. Many simple arrangements are available to make telephoning easier for people with minor motion handicaps, and numerous one-of-a-kind installations have been made on a specially engineered basis for individuals who are virtually immobile.

Special engineering is time-consuming, however, and the higher cost of a special installation is often a burden to a handicapped individual with limited financial resources. Thus there has been for some time a need for a simple, standard, inexpensive arrangement for controlling the telephone which is not dependent on motion of the fingers, toes, limbs, head or neck.

Control Without Body Motion

Breath Control

One possibility which has been exploited with considerable success in Great Britain is breath control. The British POSSUM (Patient Operated Selector Mechanism) provides not only control of the telephone but control of environmental variables and control of work operations such as typewriting. Control is accomplished by sucking and puffing on a small air tube in accordance with a prearranged code. A glowing layman's description of the POSSUM appeared not long ago as the feature article in a U.S. mass-circulation magazine (1).

Voice Control

Perhaps the most attractive approach is voice control. Certainly it is the designer's ultimate dream and the user's hope, but the technical problems are so formidable that a practical and economical device based on speech recognition principles may not become a reality for many years.

Meanwhile, Clifford J. Hoffman of Bell Telephone Laboratories has proposed a radical simplification of voice control techniques, in which recognition is by means of time-induced orthogonality (2). With the simplified technique, the user exercises control merely by synchronizing his vocal utterances with an active feedback, which may be either audible or visual. To put it another way, he generates control codes by dropping his words into specific time slots which are defined by a machine-to-man feedback. The recognition problem with time separation of speech utterances is so simple that in the most elementary control scheme only an energy threshold detector is required.

From the user's point of view, this kind of voice control is obviously more awkward, more artificial, and appreciably slower than control based on straightforward speech recognition. The advantages, however, are impressive. First, cost is reduced by several orders of magnitude, and so are space and complexity. Second, there is complete insensitivity to the speaker variations which are one of the major bugaboos of speech recognition. Third, and most convincing, voice control by time-induced orthogonality is feasible today, with today's state of the art.

The Basic System

Visual Feedback

Time-induced orthogonality provides a form of binary control in which, for each time slot, acoustic energy in excess of a preset energy threshold represents a "1" decision and a sub-threshold signal (or silence) represents a "0". In its simplest embodiment, the voice-control apparatus consists of suitable speech input equipment and a visual feedback display of ten digits arranged in a circle. Each digit has associated with it a light, and the lights are illuminated sequentially, each for a time T, as shown in Figure 1.

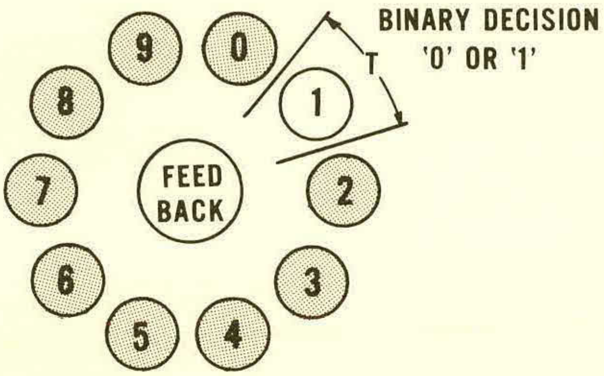

FIGURE 1. Binary control scheme.

The numerals are lighted sequentially with period T. A number can be selected by applying an above-threshold acoustic signal while it is illuminated. The feedback lamp in the center indicates successful selection.

The display runs continuously and any desired digit may be selected during the interval when its associated light is on, i.e., during its time slot. Successful selection takes place if at any time during this interval T the acoustic input exceeds the threshold value. Success is indicated or fed back to the user in two ways, by a momentary flash of the feedback signal light at the center of the circular display and by a momentary pause in the apparent rotation of the display.

Audio Feedback

Another possibility is the use of audio feedback rather than visual feedback. Instead of watching a series of lights being illuminated sequentially, the user listens to a series of spoken digits on a recording. He selects a specific digit by putting a voice signal into a chosen time slot, just as in the case of visual feedback, but successful selection is indicated by an audible signal. This might be, for example, audible repetition of the digit selected.

Audio feedback has two obvious advantages. First, the user's visual attention is not required; his eyes are free for other tasks, such as looking at a number in the telephone directory while dialing it. He could also use such a dial if he were blind as well as motion handicapped.

Second, it is conceivable that the equipment for audio feedback could be installed at the central office, which would reduce somewhat the cost to the customer. Still further cost reduction might be accomplished by arranging for use of the equipment on a shared or common basis among a number of handicapped customers. It is not likely, however, that concentrations of disabled individuals warranting shared equipment would occur very frequently outside of hospitals or rehabilitation centers. Thus equipment sharing would seem to have its principal application behind the PBX's in such institutions.

The major disadvantage of the audio feedback approach is that the recording with the spoken digits could not be allowed to operate continuously. In continuous operation it would have an annoying and distracting effect which the continuously-running visual feedback does not. This means that some form of supplementary mechanical control, either a touch switch or breath switch or the like, is necessary to activate the feedback prior to dialing and to disconnect it after completion of dialing. Likewise, it would have to be activated prior to entering any control code and deactivated immediately afterward.

Control Codes

For practical applications of a voice-controlled telephone, two kinds of inputs must be processed, control codes and telephone numbers. Control codes are of fixed length, but telephone numbers are not. They are random digit sequences varying in length from two digits for a dial intercom or small dial PBX up to as many as twelve or fourteen digits.

The straightforward way to deal with this problem is to assign one control code for access to the dialing mode. Escape from this mode must be provided following the last digit of the telephone number, and the simplest escape route is via an eleventh position on the feedback display. An above-threshold acoustic input in the eleventh time slot signals the apparatus to discontinue processing variable-length telephone numbers and to resume responding only to fixed-length control codes.

In addition to its control function, a control code guards the voice-control system against false operation by conversation or environmental noise, i.e., it minimizes what is commonly referred to as "talk-off". The longer the code, the greater the talk-off protection.

Experimental Units

General

A small number of experimental voice-controlled telephones employing visual feedback principles have been built by Messrs. V. J. Biancomano and G. S. Soloway of Bell Telephone Laboratories and have been used in a limited and informal field experiment.

For maximum flexibility, these units generate dial pulses, rather than TOUCH-TONE signals, so they can be used in any locality. They are equipped with a jack for connection of an external control switch such as a touch or proximity switch, microswitch, foot switch, breath switch or any other suitable normally-open single-pole switch.

Visual Feedback Display

The circular display on the experimental units, as shown in Figure 2, has twelve positions, designated "1" through "0" and "S" and "D". Twelve positions make a layout similar to a clock face, which was felt to be advantageous, and two time slots in addition to the ten for the digits were needed to accomplish all the desired control functions. "S" stands for "STORE" or "STOP", depending on context, and "D" stands for "DIAL". "DIAL" is used to obtain dial tone, preparatory to outpulsing. "STORE" is used to write a new number into the repertory, and "STOP" has several uses.

A light-emitting diode (LED) is associated with each of the twelve clock positions. The LED's are illuminated one at a time in a continuously-running sequential display, but the 90° points on the "clock" face (corresponding to 3, 6, 9 and 12 o'clock) are dimly lit at all times. This facilitates operation in total darkness. LED's consume much less power than conventional incandescent lamps, are inexpensive, and have a service life which far exceeds the life of the equipment.

Timing Considerations

Human factors studies indicated that the rotational rate of the display should not be greater than about one revolution every six seconds, and it was assumed that most users would want considerably slower speeds when first introduced to the equipment. A rotational rate control was provided, so that the display speed could be increased as the user became familiar with the dialing procedure. The optimum speed setting was viewed as that which yielded the best compromise between dialing speed and dialing error rate.

FIGURE 2.

Even at maximum rotational speed, interdigital dialing time would be six seconds when dialing double digits, whereas maximum allowable interdigital dialing time in modern central offices can be as little as 4.5 seconds. For this reason, the number dialed is inserted in an electronic store, after which it is released on command and outpulsed to the central office at a standard rate.

Typically, a handicapped person can dial a random 7-digit number, plus the necessary control codes, in 35 to 45 seconds with this arrangement, and expend negligible effort in doing so. Considering that he might not be able to dial manually at all, or that he could dial manually only very slowly and with extreme difficulty, the extra time involved does not appear to be a very serious penalty. After all, non-handicapped individuals frequently take as much as 15 to 20 seconds to dial a 7-digit number with a rotary dial.

The overall dialing process will be slower if the control code is longer, and talk-off protection will be less if the control code is shorter. Thus optimum length of the control code is a compromise between the desire for speedy and uncomplicated operation and the need to minimize talk-off. For the experimental units, a three-digit code was selected as a reasonable compromise, and talk-off protection was enhanced by employing codes with a structure such as 2-5-8 rather than adjacent number codes such as 2-3-4. Because numbers at the 90°, 180° and 270° locations on the dial seemed easiest to remember, the 3-6-9 code was chosen for controlling incoming and outgoing telephone calls and providing access to the repertory store locations.

Greater Utilization of Electronics

The electronic store, once having been provided for the number being dialed, was available for other possible uses. It was arranged to function also as a last-number repertory, so that the complete dialing procedure would not have to be repeated to redial a number after encountering a busy signal.

With the one store location already provided, it was a simple matter to add more locations. Four additional store locations were accordingly provided for conventional repertory dialing purposes, on the assumption that four repertory numbers would be adequate for most users. Numbers are inserted in the repertory by voice command, using control code "S" (for "STORE"), and can be changed at will.

The logic circuitry for recognizing control codes was also put to other uses. In addition to the 3-6-9 code chosen for telephone control, two 3-digit codes were assigned for controlling auxiliary apparatus. This was done to provide an opportunity for evaluating the feasibility and utility of an auxiliary control function. By employing codes with the same structure as 3-6-9, e.g., 2-5-8 or 1-4-7, the same degree of talk-off protection was obtained.

Other Features

Because the user of an electronic device generally wants to know at a glance whether it is on or off, an ON light was provided on the experimental voice-controlled telephone. The light is turned on by the 3-6-9 code which activates the system, and it stays on until this same code is used a second time to turn the system off. The rotating light display is unaffected; it operates continuously, whether or not the ON light is lighted.

In addition to its visual feedback function, the rotating light display also enables the user to monitor outpulsing and verify the number being dialed. As each digit is outpulsed, the LED's are momentarily lighted in sequence at the outpulsing rate of 0.1 second per dial break, beginning with No. 1 for the first pulse, No. 2 for the second, No. 3 for the third, etc. For example, dialing a 5 causes LED's 1 through 5 to be lighted momentarily and in sequence; dialing a 3 causes LED's 1 through 3 to be lighted momentarily and in sequence, and so on.

While the voice-control system is powered by commercial a-c, a rechargeable battery has been provided to assure service continuity during power failures. The battery will give about three hours of emergency service. The cells are continuously on charge during normal operation, and recharge time from completely discharged to fully charged condition is about 28 hours.

Allowance has been made for complete flexibility of telephone instruments. The experimental voice dialer is equipped with a jack into which a regular handset, a headset or a Speakerphone can be plugged.

As the system was developed, the easiest number to dial is "operator." This could be very helpful under emergency conditions.

Informal Field Experiment

Aims

It was apparent that the only reliable way to find out whether the experimental voice-controlled telephones would do what they were intended to do would be to let disabled people use them. This would provide operating experience, an opportunity to observe - and perhaps remedy on the spot - any conditions which were bothersome to the users, and a chance to obtain and assess user reactions. A very small and very informal field experiment with these objectives was accordingly undertaken.

Trial Subjects

The trial subjects were volunteers recommended by Dr. Richard A. Sullivan, Director of the Kessler Rehabilitation Institute from a roster of outpatients and former patients. Other subjects were volunteers recommended by Prof. Muriel Zimmerman of New York University's Institute of Rehabilitation Medicine or by Mr. A. Maurer of New Jersey Bell. The subjects included eleven males and six females, ranging in age from 12 to 45 years. They had been disabled by traumatic quadriplegia, poliomyelitis, multiple sclerosis, muscular dystrophy, arthrogryposis, and, in one instance, by an undetermined muscle disease. These individuals represented a wide range of dialing capabilities, from one person who could use a TOUCH-TONE dial with relative ease, to those who could dial only with the greatest difficulty or not at all.

Trial Locations

Trial installations were made in the following locations:

Hospitals and convalescent centers	2
Rehabilitation centers	2
Offices	2
Homes	11

Installation Details

The subjects took full advantage of the flexibility offered by the experimental equipment. Five used headsets, one used a Speakerphone, and the rest used handsets held in a suitable position by some kind of adjustable arm. All subjects but one used voice control, the exception being a man who used the Speakerphone with a pushbutton control.

User Reactions

A preliminary evaluation of the subjects' comments indicates that the voice-controlled telephone was well regarded and was rated all the way from very convenient to almost indispensable. Nevertheless, it was clear that to debug the system completely would involve a small amount of additional development work.

Preliminary findings are as follows:

1. None of the users had trouble placing calls.
2. Nearly all users, at one time or another, had been distracted while dialing and had had to stop and begin again at the beginning.
3. Not everyone fully mastered the technique of re-using the last number called. Those who did master it reported liking this feature and using it frequently.
4. Practically everyone used and liked the repertory feature. They were satisfied with the capacity of four numbers. Understandably, the number most frequently stored was "411" (Directory Assistance).
5. Use of the 3-6-9 code for answering incoming calls was felt by most respondents to be acceptable but a bit unwieldy.
6. All subjects had asked to have the speed of the rotating LED display adjusted. Several had it set at maximum and two preferred minimum. The rest were spread out between these extremes.
7. All subjects, without exception, reported having been cut off by talk-off. Frequency of cutoff appeared to be correlated with display speed.
8. Slurred speech or speech affected by the action of mechanical respirators caused dialing errors.
9. The auxiliary controls were very highly regarded by everyone, even by those who were the least enthusiastic about or had the least need for voice dialing.
10. The procedure for answering an incoming

call that has been picked up first on another extension was found to be inconvenient. (This situation can be easily remedied by minor circuit changes).

11. As the equipment is presently wired, the user cannot immediately answer an incoming call if, when the bell starts ringing, he happens to be in the midst of dialing and storing a telephone number. He must first stop and void what has been stored before he can answer.

12. Users who were accustomed to manual service or DOP (dial operator privilege) and liked it were nevertheless strongly in favor of the voice-operated dial. They reported that it gave them an added feeling of independence and a greater sense of privacy.

13. Users reported that they had no objection to leaving the rotating light display on all night. Although a switch had been provided for turning the display off at night, it was seldom used.

14. When used with an external control switch instead of voice control, talk-off was precluded and operation of the system closely approached the ideal.

Conclusions

A voice-controlled telephone along the lines of the experimental model described herein would fill a real need for many people with severe motion handicaps. For those able to use it, a unit with external switch control would be even more valuable.

All the extra features provided were found to be sufficiently useful so that their inclusion in the experimental models was fully justified. The auxiliary control function was particularly well liked.

Talk-off protection requires further study.

References

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