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After reviewing the history of communication through the skin, this paper considers recent research into the problem of cutaneous stimulation induced both mechanically and electrically. The general demands of a cutaneous communication system are discussed, and four primary dimensions of cutaneous stimulation are summarized (locus, intensity, duration, and frequency). The problems of pattern discrimination, masking and confusion, tracking, and adaptation are presented. The use of a cutaneous communication channel for coding and information processing is explored. Problems relating to cutaneous reception are considered from an anatomical and theoretical view, and include an evaluation of structures of the hand in terms of muscles, muscle spindle, motor unit, motor points, and the pacinian corpuscle. Current views are summarized revealing favor toward a pattern theory of central neural decoding. A 129-item reference list is included. (DP)

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PROBLEMS IN CUTANEOUS COMMUNICATION FROM PSYCHOPHYSICS TO INFORMATION PROCESSING*

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INTRODUCTION

The possibilities of making use of the skin as a sensory communication channel have captured the imagination of investigators from time to time even before the early basic works of von Frey and Kiesow (1899). Geldard (1957), in describing a successful attempt in tactile literacy using machanical vibrations, brought into perspective the overall problem when he said that "even the 'applied' problems in this area are themselves 'basic' because so little is really known about the skin as a sense channel....The discussion of the background of (the problem) fails to recognize that this is an area with a substantial literature and a long history of failures and disappointments."

In commenting on the transmission systems for skin sensation Wall (1962) emphasized that we are dealing with more than just an engineering problem when he said, "Physiologists have come to realize that you cannot properly study a system such as the sensory system by adhering to the traditional methods of investigation employed in physics, chemistry, and mathematics." Or says Sheridan (1962), "Using a cane to acquire information is similar to sounding the depth of the ocean or looking for oil under the earth's surface."

What are the demands of the communication system in terms of information to be conveyed? What are the discrimination capabilities and limitations of the skin? Can the skin function in transmitting information accurately, and under what conditions? Is it possible that cutaneous signals can be coded to give both context and content to a language? Is this form of communication practical for complex information processing?

The literature related to these questions is diffuse and

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quite extensive. Just the psychophysical studies of cutaneous stimulation for example, run into many hundreds of publications. Relevant studies of these questions are found in different types of journals, conference notations, and in technical reports that often find restricted circulation. This paper reviews a number of these efforts, but we have not sought to present an overall survey of the literature. Rather, we have searched the experimental and theoretical writings for converging (and diverging) views about the adequacy of stimuli, dimensions of sensitivity, and anatomical structures. Coding and information processing, a vast domain unto themselves, are brought into the picture briefly to help identify basic problem areas for expanded research.

It is hoped that this report will be useful to those becoming interested in the problems of this "neglected sense," possibly serving as a guide in helping them to avoid revisiting some of the blind alleys of futile problems.

GENERAL DEMANDS OF A CUTANEOUS COMMUNICATION SYSTEM

The practical need for a tactile communication system has whetted the imagination of those who are involved in a variety of roles, with suggestions ranging from vibratory barographs for frogmen to covert codes for use in secret transmissions, from supplementing communication with astronauts in outer space to the need for a primary channel of communication for the deaf-blind. To be effective a system must be able to convey a minimum of seven classes of information: 1) Through "amounts" one can present quantitative information, and 2) through "coordinates" one can give relational information. In landing an aircraft, for example, 3) "directions" and 4) "rates" can be transmitted through the skin. The attention-demanding qualities of vibration or an electrical nudge give these stimuli some uniqueness in 5) "warning" or in 6) "vigilance" problems, but the primary demand for a cutaneous communication system is in 7) "language."

Communication systems for the sensory handicapped have centered around problems of travel, obstacle detection and orientation utilizing the cane and other mobility instruments, active and passive energy radiating systems, and a host of reading and auditory devices. For the most part such communication has been conceived of as an engineering problem, without sufficient regard for the sensory characteristics of the human.

In 1960 fourteen investigators conferred at Fort Knox (Hawkes, 1960) and opened up the basic problem areas of "asking the skin what language it could compass," how it compared with vision and hearing, and what unique qualities the cutaneous stimulus might possess. Audition is the temporal sense, and vision holds superiority spatially. Could it be that the skin is unique in combining the temporal and the spatial, even though inferior in both? Henneman (1952) has made the point that the choice between the eyes and ears as sense channels for the presentation of information rests upon the specific demands of the situation. There are relative virtues and defects in both seeing and hearing.

In some message-processing situations two senses are better than one, and there are some in which either sense will do. Gregg (1960) has made the point that engineering the language instead of the machines has proved to be an effective way of overcoming the difficulties in some communication systems. One may, then, postulate that by its very nature the skin is not handicapped with a lot of excess verbiage as is the written and spoken word. Perhaps the skin has possibilities for coding even superior to those of other channels because of its "simplicity." In other respects it is most complicated. Whereas vision is often thought of as a synthetic sense, and hearing and olfaction are said to be analytical senses (Jones and Woskow, 1964), it is most difficult to classify the skin senses.

THE SKIN AS A CHANNEL OF COMMUNICATION

The skin as a sensory channel may have one completely unique aspect; it is rarely ever "busy." In spite of the fact that there is a wide range of individual differences in skin sensitivity, for all practical purposes there is no such thing as complete "skin deafness" - certainly not to electrical stimulation! Whether or not the skin has advantages or disadvanges in handling irrelevant information is not known. It is known, however, that as the amount of irrelevant visual information is increased, performance decreases in a linear manner, and that the types of errors made in using simultaneous auditory and visual signals indicate that subjects respond primarily on the basis of the visual stimuli, ignoring the auditory stimuli (Lordahl, 1961). There is support for the hypothesis that there is some temporal process in the central nervous system that limits and orders the perceptual events of the major sense modalities. The upper perceptual rates of visual, auditory, and vibratory senses are approximately the same (White and Cheatham, 1959). Possibly as we learn more about sense comparisons and channel loadings the cutaneous senses may be important in helping process supplementary information, and particularly important where redundancy is desired (Hawkes, Meighan, and Alluisi, 1964).

In terms of a communication system involving sensory inputs, cognitive processing, and response, most research to date has dealt with cutaneous and proprioceptive stimulation. Major attention has been given to stimulus dimensions which we shall detail later. Important also are the problems of stimulus variables and stimulus presentations which have been observed more as by-products than as planned studies, and much the same can be said for response studies in terms of work, task, tracking, and motor behavior.

In terms of stimulus variables research has centered around studies of acuity, compatability, errors, masking, apparent movement, and patterning. A small amount of work has been done on adaptation, but little is known about such problems as aftereffects, coherence, contrast, distractions, expectancy, the gamma and tau effects, interference, and intermittence. Only indirectly do we have data on stimulus lag, channel load, message storage, and even the types of stimulus variables.

Stimulus presentations to the skin have had little research on the discreteness or irregularity of stimuli, whether they should be long or short, or how they should be presented for maximum clarity. Only a little work has been done on redundancy, on qualitative and quantitative information, or on the problems of sequential presentations. Spacing and timing of signals have been studied only incidentally.

There have been studies of learning and of tracking which we shall mention later, but little is found in the literature related to work as a part of the cutaneous communication system or of the task variables. Even such an attention-getting thought as "warnings are best presented via the skin" has little evidence to support the idea. Should warnings, for example, come as "break in," or be "drawn out"? Not much is known about the nature of feedback in a cutaneous communication system, about problems related to decision making, processing procedures, and activation variables.

To date there has been no overall description of how psychophysical, neurophysiological, and anatomical problems may be related in the reception of sensory inputs. Little or no consideration has been given to the problems of cutaneous communication in terms of systems thinking.

In contrast to vision and audition which have laws and languages all their own, even cutaneous thresholds are measured in borrowed terms, and currently laboratories for skin communication can be counted on the finger pads of two observers. One medical economist has estimated that more money is spent each year on cosmetics than on cutaneous research since the beginning of time.

HISTORY OF THE PROBLEM

The Benedictine abbot Johannes Trithemius of Trittenheim, 1462 to

1519, was the first to invent a sort of wireless telegraphy for communication through the skin, which he called "Steganographia" (Gnudi and Webster, 1950). Some five centuries later the Medical World News of September 13, 1963, reported Soviet physicians finding a young woman in the Ural Mountain area who apparently possessed "sight" in her fingertips, and this report has led to some recent interest among several psychologists. Tactile experience in personality development and cultural patterning has long interested social scientists who have viewed the skin as "the envelope which contains the human organism and provides its earliest and most elemental mode of communication" (Frank, 1957). And there is another history of the problem born and bred in the laboratory and in the clinic.

Among the first practical efforts to take advantage of the literacy of the human integument was that of Louis Braille in 1826. The blind have been reading through their fingertips with varying degrees of success for over a century, but the mastery of this language requires long practice, as pointed out by Smith (1929). Even when thoroughly mastered, braille is still slow. Proficient readers are limited to a speed less than one-fourth that of visual readers. Its efficiency is also reduced by such factors as excess perspiration and cold fingers. The maximum speed of braille reading is considerably less than the cognitive processing time required, and this has caused some difficulties in use of the system.

To a large extent research on braille reading has centered around the practical aspects of training. Typical are the studies of Funchess (1934) on the effects of practice and the work of Fertsch (1946) on the analysis of braille reading. It was not until recently that Foulke (1965) conducted the first study on the transfer of braille reading ability to normally unused fingers. Such work, which uncovered a number of theoretical as well as practical problems, may well mark the beginning of more important studies in this area of complex perceptual skill.

During the 1930's Gault and his associates (1936) spent a decade attempting, without success, to utilize the skin for purposes of communication. In essence these investigators tried to bypass the ear by transducing speech sounds into mechanical vibrations and applying them directly to the skin. By 1950 Project "Felix" (Weiner, Wiesner, David, and Levine) of the Research Laboratory of Electronics of MIT had made attempts to translate speech into electrical and into vibratory stimulations for transmission through the skin, but again failure of the skin to make appropriate discriminations led to discontinuance of the project. Guelke and Huyssen (1959) devised a tactual speech analyzer which presents vibratory stimuli to the fingers. Saslow (1962) and Bliss and Kotovsky (1962) described experiments of using air jets for tactile communication. Bliss (1962) presented a kinesthetic-tactile display device for communication. Hirsch, Shafer, and Eitan (1964) have come up with an apparatus for transmitting vibrations to the fingers, involving a system not basically unlike others, which has not yet proved operational.

In 1932 isolated researches in the field of cutaneous sensitivity were begun in the Virginia laboratory; by 1948 they had developed into an extensive program which expanded in 1962 to Princeton. The program carried the central theme of discovering what discriminations the skin is capable of making, still placing some emphasis on the utilization of cutaneous signals in communication.

Geldard (1962), in commenting on almost two decades of work, says:

> "The present outlook is not for some new *experimentum crucie* the results of which may be expected to revolutionize communication theory and practice. Except for von Bekesy's carefully thought out vibratory program at Harvard, Wolf Keidel's research at Erlangen, Uttal's electrical experiments at IBM, and the current projects of some of our own alumni, there is not nearly the attention being directed to this set of problems that it needs and deserves....We have found ourselves forced back at every turn to the exploration of basic problems. There has been found little 'on the shelf' in the way of fundamental data that could be used. Moreover, many things in the older literature of cutaneous communication we have found to be misconceived, commonly subject to error of interpretation, and to have been evolved from faulty techniques of measurement. It became apparent long ago that we should have to discover for ourselves what the 'language of the skin' was if we were going to code cutaneous signals successfully."

The reader may find the following specialized reviews useful in obtaining some of the detail of the more recent history of the problem: Geldard (1940), Hill, Flanary, Kornetsky, and Wikler (1952), Keidel (1956), Rosler (1957), and von Bekesy (1960). For a look at the problem as a whole see Geldard in <u>Science</u> (1960).

CUTANEOUS AND PROPRIOCEPTIVE STIMULATION

The stimuli which have been used in the development of cutaneous communication systems have included the pressure patterns used in braille, mechanical vibration (pressure in motion), alternating electrical currents, square wave electrical pulses, and more recently air jets.

TYPES OF STIMULATION

A major advantage of nonelectrical stimulation is that the resulting perceptions are usually painless, often in contrast to the sensations induced electrically. In terms of disadvantages the equipment for inducing mechanical vibrations and air jet stimulations is bulky and inconvenient for operational purposes, and braille has the disadvantage of being slow. Vibration, in the main, spreads out and is more difficult to localize precisely.

Work with air jet stimulation is recent and limited in scope. Saslow (1962) and Bliss and Kotovsky (1962) describe the sensation as being comparable to stimulation by a stylus with a diameter of the same order of magnitude as that of the diameter of the air jet at the skin surface. At low values of pressure, sensation appears to be due to cooling off of the skin surface, becoming stronger with increased stimulation. For purposes of information transfer a modulated air jet of frequency 1 to 2 cps is superior to an unpulsating jet providing an information transfer rate of 2 bits/sec with experienced observers. In an experiment using a 3-by-3 air jet matrix transfer, rates of approximately 5 bits/sec can be obtained. A subject can correctly identify any three jets activated on his finger tip. Ability to identify the point of stimulation of the jet is related to locus, and when several jets are stimulated simultaneously confusion is experienced. It is reported that the sensation does not adapt out, and that experiences of apparent motion can be induced.

The work of Gibson (1963) and of Gilmer (1961, 1964) has amplified how square wave stimulation may be used in communication, and there is some indirect evidence that electropulses stimulate both the cutaneous and proprioceptive systems.

Hawkes (1961a, 1961b) has laid emphasis on the use of the Stevens (1956) magnitude estimation technique in utilizing cutaneous electrical stimulation. Vernon (1953) studied the interaction involved in the simultaneous electrical and mechanical vibratory stimulation of the skin, opening up some important theoretical questions. Sherrick (1960, 1964) and Hawkes (1960) have related some common psychophysical functions as applied to the skin and opened up questions of the adequacy of stimulation. Hahn (1960), in commenting on the unfinished chapter, has outlined some problem areas related to anatomy, impedance of the skin, adaptation, equal loudness functions, intensity changes, onsets, summation, and other spatial and temporal problems facing the researcher as he sloshes around in the apperceptive mass in facing the gigantic task of coding.

DIMENSIONS OF STIMULATION

There are four primary dimensions common to the several cutaneous stimuli, namely, locus, intensity, duration, and frequency; and there are several derived dimensions and stimulus variables which have been found important in perception. We shall summarize some of what is known about cutaneous and proprioceptive stimulation under four headings.

Locus

One of the most critical aspects in receiving cutaneous signals concerns the place where the stimulus is applied to the skin surface; yet there have been no systematic investigations of locus. It is known that pressure "spots" are highly sensitive to a small vibrating needle and feel like vibration when appropriately stimulated with alternating current, but one question concerns exactness of location. It is also known that spot distribution varies widely in both hairy and smooth tissue. Geldard (1940) has found that the amplitude threshold for vibration sensitivity between 64 and 1024 cps is constant with a small contactor and that the spots are the same. Von Bekesy (1959) found vibration-sensitive and pressure-sensitive spots did not coincide, but were separated by a distance of 0.5 mm from one another. (More will be said later about this problem in relation to studies of frequency-intensity functions and the size of stimulus contactors.)

With appropriate stimulation tactile sensations can be felt anywhere when presented individually, but for an efficient communication system interstimulus interval is a critical variable. No one really knows how many loci can be distinguished simultaneously. By 1962 twelve vibrators spaced over the body had been so identified (Geldard, 1962). The past failure to explore the entire body for vibratory locus is a technical one because of the difficulty in getting very small power-laden transducers. Only recently has such a transducer been developed (Geldard and Sherrick, 1964) which bids fair to open up ways of getting at many locus and interaction problems.

Electrical currents are limited for use in the problem of multistimulation because of stimulus summation. For example, Gilmer (1964) found that even using concentric electrodes on the palm of the hand, summation becomes an unpleasant problem when more than four areas are stimulated at the same time. Several investigators have shown that problems of masking, confusion, and attentional shifts arises with multiple stimulations.

Two-point limen data, whether obtained by esthesiometer, electrically, by mechanical vibration, or by air jets, raise more questions than they answer about the nonuniformity of skin sensitivity. Geldard (1960), in discussing the question of how many places on the skin can be utilized, says the problem is not settled by extrapolation of the results of two-point esthesiometer measurements. Unlike static pressure, mechanical vibration applied to the skin does not stay "within bounds" unless special steps are taken to prevent its spread (von Bekesy, 1959). The two-point limen for vibration is greater than the static one for any given region. Bishop (1944) found that electrically induced the two-point limen is related to the strength of the stimulus. Weaker stimulation, or pulses of only one or two shocks per second, made it necessary that the points be placed farther apart in order to be discriminated. Temporal summation was also found to be a factor which cannot be ignored.

Uttal (1960), in dealing with a series of experiments on spatial interaction, set up an array of stimulating electrodes on the surface of the forearm. It was found that the Weber circle for electrical stimulation was, in fact, a long thin ellipse. The two-point threshold was much smaller when the electrodes were stimulated laterally on the arm than when the test was made with longitudinally separated electrodes. He interpreted these findings as being related to the longitudinal nature of the nerve supply to the arm. Wall (1962), in discussing neurological decoding mechanisms, makes the point that an electric shock stimulus can never be made to resemble any common sensation. An electric stimulus applied to the skin produces a very unusual time and space pattern of nerve impulses and does not really resemble any other sensation. This may be borne out by some paradoxical findings on the experience of apparent movement in the skin, and by some of the phantoms of apparent location found in electrical stimulation. For example, Bliss and Kotovsky (1962) found that apparent movement could be induced by air jets in a similar manner with the use of mechanical vibration (Sumby, 1955), namely, by using an onset delay for vibrators around 0.10 sec, with or without overlap. Gibson (1963), on the other hand, reported apparent movement with electric pulses of a varying nature related to stimulus onsets, distance, duration, and their interaction, contrary to Sumby's results and not in line with one of Korte's laws of visual phi. These laws cannot be readily transposed from apparent visual movement to apparent vibrotactile movement (Geldard and Sherrick, 1964). Foulke (1962) has found that when alternating currents are applied to the skin the distance between the electrodes, in relation to intensity, determines the degree of acuity of separation. Schmid (1961) has found that masking is a problem to be dealt with in any two-point limen study with electrical stimulation.

If proprioception is involved in communication, as it may well be with strong stimulation, the problem of "where to stimulate for what" becomes important. It may well be that when anatomical relationships become better known we may be forced to revisit the problem of locus as a first-order dimension, particularly when the channel capacity for information transmission is reexamined.

Intensity

In some respects electricity elicits sensations similar to those produced by mechanical deformation of the skin, but the growth of "loudness" which accompanies the increase of stimulus intensity is more rapid for electrical stimulation. Stevens (1959a, 1959b) and Jones (1960) show the relationship to be approximated by a power function with electricity of 3.5, of vibration 0.95, and of touch around 1.0. The unit change of stimulus intensity caused by electrical current produces a greater change in apparent loudness than does the unit change in the amplitude of the vibrator.

In studies of the intensity difference-limen (DL) of vibratory stimuli Rosler (1957) found that when the duration of a stimulus pair is shortened, there is apparent asymmetry in the perception of an intensity change, depending on the direction of the change. In the case of a stronger second stimulus the DL of the double stimuli increases little; it increases more for a weaker second stimulus. A weak second stimulus may be completely inhibited. He concludes that this is of importance for the tactile perception of speech when the spectrum energy is not distributed over several areas.

The average observer, under laboratory conditions and with the use of a careful psychophysical procedure, can detect about 15 steps of vibratory intensity. However, Geldard (1960) states that on an absolute recognition basis, for use in an operational system, it would be unsafe to include more than three steps widely spaced over this range. "Intensity is," says he, "the least exploitable of all the first-order dimensions." Howell (1958) has shown, from an analysis of errors in a vibratory communication system located on the chest which coded locus, intensity, and duration, that nearly all the mistakes were made along the intensity dimension. Hawkes (1961), using alternating current as the stimulus, found information transmission was around 1.3 bits at three intensity levels with accuracy less than 100 percent, and that at comparable frequencies the Weber fraction for intensity is smaller for alternating electrical cutaneous stimulation than for mechanical vibration. There are similar data indicating that some three levels of square wave electrical intensity, widely separated, can be detected.

Vernon (1950) has found a linear relationship between threshold intensity and stimulating frequency. Most experimenters report that it is difficult to obtain reliable relationships between intensity and pain. Hahn (1960), in making a comparison with vision and hearing, points out that most hues shift as stimulus intensities vary, and stimulus intensity is also known to affect pitch. The same phenomenon occurs with either electrical or vibratory stimulation of the skin. Sherrick (1960) noticed that raising intensity lowered the perceived rate of vibration, and von Bekesy (1960) has provided the clue with the observation that the effect is influenced by changes in the area of skin stimulated. Uttal (1960) in his studies of psychophysical-neurophysiological comparison concluded that temporal factors seem to be unimportant in the coding of sensory intensities, but that a count of the number of impulses, either spatially distinct and temporally synchronized or sequential events on single lines, is correlated with fluctuations in sensory intensity.

Duration

As a dimension in cutaneous sensitivity, stimulus duration received little attention until the practical considerations of efficiency in communications became apparent. When durations of mechanical vibration are less than 0.1 sec they may be misjudged (Howell, 1958), and when square wave electrical pulses have a duration width less than 0.5 msec, spiking occurs and hence pain can be induced readily on any tissue. For mechanically induced vibration a durational continuum between 0.1 sec and 2.0 sec allows the average observer to make about 25 distinctions, the steps being of the order of 0.05 sec at the low end and 0.15 sec at the high end of the range. Absolute identifications with 100 percent accuracy yield four or five considerably more widely dispersed levels. A range between 0.5 and 10.0 msec has proved appropriate for square wave stimulation. Presumably when the duration of the stimulus is increased beyond a critical value, only the pain receptive system continues to integrate the current, and thus the pain threshold continues to decrease and approach the touch (pulse) threshold.

Hahn (1958), in analyzing strength-duration functions, found that change of frequency has a negligible effect on electrical vibratory threshold, but there is a pronounced effect of pulse duraation on threshold. In studies of response to alternating current Hawkes and his associates (Hawkes, 1962) found that for signaling purposes it is important to consider the dependence of discrimination on both intensity and duration. A maximum transmission of information was found with combinations of four stridence levels and four durations, with a channel capacity of about 2.97 bits for experienced observers.

Frequency

Recent frequency discrimination studies for mechanical vibration have invalidated previous measures, helped change neural coding theory, and complicated communication systems buildings. The complexity of these problems has been magnified when stimulation is induced electrically.

Goff (1959) assembled a band of equal loudness mechanical vibration stimuli which differed in frequency. She found that at very low frequencies, below 70 cps, vibration judgments of the rate were good, but ability to make accurate discriminations faded rapidly as the frequency was raised. In the region of best speech sounds, says Geldard (1960), the skin does very badly indeed in making discriminations, and this finally explains why the "hearing through the skin programs" have yielded such disappointing results. Cutaneous (or proprioceptive) vibratory pitch induced mechanically is frought with uncertainty in judgments. Studies of the "feelings" related to electrical stimulation show the problem to be even more complicated. Changing frequency can induce varying sensations, ranging from clear-cut perceptions of vibration through tingle, warmth, cold, psychological heat, and many qualities of pain (von Frey, 1915; Crook, 1932; Gilmer, 1937; Vernon, 1950; Hahn, 1960; Hawkes, 1961). Geldard (1960) concludes that frequency would have to be handled gingerly in a communication system, especially if intensity were simultaneously manipulated as a variable. For example, if the amplitude of a 40 cps mechanical vibration applied to the finger tip is increased, the perception of pitch undergoes a marked downward shift. Decrease the amplitude and the pitch goes up noticeably. Von Bekesy (1960) has recorded shifts of the order of three octaves.

Changing the frequency of alternating current affects the amount of current necessary to reach absolute threshold, but the relationships involved are not simple. Important are locus, frequency-intensity-duration functions, and the various aspects of inhibition. Some of these problems are no less complicated when the stimuli are induced mechanically. It has been shown by von Bekesy (1959) that inhibitory effects along the surface of the skin can be easily demonstrated. Through stroboscopic observation he has observed traveling waves along the skin moving away from the edge of the vibrator. The wave length is long for small vibratory frequencies and short for high frequencies. On the surface of the upper arm, for example, stimulation at 50 cps induces a wave length of the order of 2 cm. From such experiments he concludes that sensations are localized at the place of maximum vibration amplitude and the locus where the stimulus is first presented. Air jets of different frequencies can produce a sensation to "the pulsating end-points of a bar" when at least one of the air jets is below 20 cps. Two air jets of different frequencies can produce both apparent location and apparent motion effects. The sensation of pulsation is not apparent when air jet frequency goes above 20 cps (Bliss and Kotovsky, 1962).

One complexity of cutaneous interaction was measured by Vernon (1953) in his study of the effect of imposing simultaneous subliminal alternating electric stimuli upon mechanical vibratory thresholds. When the two forces were presented in an in-phase condition the mechanical vibratory thresholds were greatly lowered as compared to normal mechanical vibration thresholds. When the two forces were presented in an out-of-phase condition the resulting mechanical vibratory thresholds were essentially the same as normal mechanical vibration thresholds. When presented at a common locus the interaction of mechanical and electrical vibrations could induce beats of 1 to 3 per sec rate. One critical requirement for inducing clear, stable beats was to work in a frequency range of 280 to 300 cps.

From several independent sources comes data to support the conclusion that the skin as a medium for vibratory forces, as in all mechanical systems, has a natural resonance period at certain loci. This period of maximum sensitivity is in the region of 250 cycles (Knudsen, 1928; Gilmer, 1935; Geldard, 1940; Sherrick, 1953; Verrillo, 1963). It can be changed, however, by the size and shape of the contactor. Gilmer (1935), working on the finger tip, found that the peak of greatest sensitivity was shifted to 900 cps with a concical shaped vibrating contactor which made the skin taut, and stretching the skin had a similar effect. But why do small pressure-sensitive spots show a flat frequency response to vibration as Geldard (1940) discovered? The problem remains intriguing. Verrillo (1963) determined thresholds as a function of frequency, contactor configuration, and contactor area. He found that absolute threshold seems to be independent of frequency when very small contactors are used and is independent of area at low frequencies. For higher values of these parameters it strongly depends on both.

There seems to be somewhat general agreement that the lower frequency limit for "vibration" is around 15 to 20 cps, whether induced by mechanical vibrations, electrically, or by air jets. No one knows what the upper frequency limits are (Hahn, 1960).

DISCRIMINATION AND RELATED PROBLEMS

Whether communication involves the "simplicity" of alphanumeric coding utilizing unitary dimensional properties or some multi-dimensional schema involving phonemes, perceptual patterning is important.

Pattern Discrimination

Little is known about even the variety of experiences that can be evoked by changing stimulus parameters of square wave pulses. Reports of "bouncing balls," "kaleidoscopic shapes," and a host of other descriptions have been given by both sophisticated and naive observers (Gilmer, 1964). Practically nothing is known about the results of more complex stimulations, such as those induced mechanically and described by Geldard (1960). He placed a ring of vibrators around the body, energized them successively with an 0.1 sec temporal separation and reported novel experiences in most of his subjects: "...a prepossessing experience with the observer at the center of it!" We may look forward to some interesting results from experiments now under way in the Princeton Laboratory of Cutaneous Communication where observers are learning to discriminate complex patterns of mechanical vibration displayed by an electronically programmed signalling system (Geldard and Sherrick, 1964, 1965). Interesting, also, may be results from the Stanford Research Institute Laboratory involving a system designed to program an array of 96 air jet tactile stimulators in a variety of rapid spatial-temporal patterns. Perhaps J. J. Gibson (1963) may get something to add to his stimulating position that sensations are not the cause of perceptions.

The work of Howell (1958) has shown that the coding of patterns is quite feasible. Foulke (1965) has under way a program of electrocutaneous communication related to the braille code. He is presenting patterns of electrical stimuli to the subject comparable to the pattern of dots that occur in the braille cell. Vibratory patterns induced kinesthetically from the cane have been found by Sheridan (1962) to differ depending on the objects and materials probed. The work of Bice (1961) on pattern recognition, simultaneous vs. sequential vibratory discrimination, movement, and localization has led to the position that the skin is capable of better time discrimination than previously believed. Massa (1961) has found that short term visual memory for spatial patterns is partially eidetic. Observers in the tactile field have indicated similar ideas.

Some effort has been devoted to the problems of spatial stimulation with electric pulses in the Carnegie Institute of Technology laboratories (Gilmer, 1961; Gibson, 1963; Alexander, 1963; Milligan, 1964). It has been found that the type, size, shape, and spacing of electrodes, the locus of stimulation, and pattern perception are related to problems of summation.

Milligan (1964) varied electrode location within 16 regions of the palmer brevis area of the hand and found no significant pulse threshold differences from one region to another for both single and multiple pulse stimulation. When tissue area exposed to stimulation was changed by varying electrode area peak current, values for touch threshold increased as electrode area increased up to 37 mm^2. Threshold values above this area size remained constant. Plots of current density threshold as a function of electrode area indicate spatial summation was involved. Is summation a problem which is peripheral, central, or both? The question is as yet unanswered. It is encouraging, however, that under certain conditions subjects are able to report reliably on the acuity of discriminating one stimulus pattern from another. The palms of the hands have been found to have certain advantages as a place to work, as we shall indicate later in the section dealing with anatomical structure.

Masking and Confusion

Sherrick (1964) and Alluisi, Morgan, and Hawkes (1965) gave an experimental emphasis to the problems of multiple stimulation of the skin, problems that have been experienced in one way or another by others as by-products, or in a few instances problems generated by interest in the nervous system per se. For cutaneous communication masking and confusion are to be avoided. We shall begin this section with a brief review by Sherrick, filled in with observations pointed up by others, particularly those utilizing electrical currents as stimuli.

Von Bekesy (1959), in dealing with the similarities between hearing and skin sensations, reported a series of experiments that included manipulations of intensity and phase relations between vibrotactile stimuli. He has suggested that a functional characteristic of the nervous system, called "funnelling," explains some of the effects produced by multiple simultaneous stimulation of all sensory surfaces. When two stimuli are presented the areas of excitation and refractoriness may overlap and summate algebraically to produce a resultant pattern of excitation that will vary according to a degree of temporal and spatial overlap, and according to the intensities of the two stimuli. Uttal (1959) demonstrated a masking effect with the multiple stimulation of the fingers by electric pulses which was related to the test finger, the masking finger, and the intensity of the masking pulse. Schmid (1961) found a relation to time between onset of the masker and the test signal. These findings and others are somewhat analogous to data in audition which were reviewed by Raab (1963). Sherrick and his associates found masking, or threshold shift as some have called it, to be a function of the sensation level of the masker, the temporal order of its pulses, and the body locus of the test signal. Control of the time of onset and relative intensities of the two stimuli is important. Important, also, are the discriminations of electrical onset (Geldard and Sherrick, 1964). Transient suprathreshold stimuli presented simultaneously with and contralateral to test signals will mask such signals more effectively than do steady stimuli.

One may think of the skin as being a multiple receptor, possessing as it were "several eyes and ears." But what of confusion? Sheridan (1962) found that even the tactile-kinesthetic information from a cane can be confusing as environmental discriminations are impaired by the elasticity of the cane itself. Bliss (1962) noted that even the ability of subjects to localize pairs of fingers which are moved simultaneously in an up-direction is confusing, and that the error rate involving kinesthetic-tactile recognition of patterns was 10.5 percent, compared to 0.25 percent for vision. This same author, in a paper published in the IRE Transactions (1962), states: "It is suggested that the key to a high information transmission rate is the development of a complex tactile display in which many stimulators and many sensation dimensions are used. Very little research has previously been done with tactile displays having more than ten stimulators, probably because of engineering difficulty." Saslow (1962) reports that there are increased interaction effects and subsequent confusion in interpretation when several air jets stimulate simultaneously as compared with sequentially.

From the Virginia Cutaneous Project, 1948 through 1962, has come the conclusion that the use of spatial arrays of mechanical vibratory stimuli, delivered simultaneously, requires that the vibrators be placed sufficiently far apart for identification, and that intensity variation be confined to a small range to minimize the effects of masking. Cohn (1952) says we must think in terms of overlap in the primary sensory areas of the brain. Vernon and Wessman (1956) found that the electrical stimuli to two independent, concentric electrode circuits on one finger interacted to produce summation or cancellation depending upon the stimulus phase relationships. Summation at one electrode increases the loudness at that electrode and masks the sensation produced at the other electrode. Gilmer (1964) found that increasing the time between sequential electrical stimulations of a pattern with five loci decreases confusion. Using a reference point likewise increases identification of both place and sequence of areas stimulated.

How much vibratory tactual stimulation can the body endure? Certainly with electrical stimulation a few simultaneous shocks, each just below threshold current, can become most unpleasant and confusing. Nadel (1962), in a literature review and a study of the effects of shaking the body up with vibration, concludes that the susceptibility of the human to various vibration stresses is in the low frequency spectra. The most critical area in regard to injury is the thorax-abdomen system. Certainly the administration of cutaneous vibratory stimuli is different from shaking the whole body in its physiological effects. No one really knows what many vibrators operating simultaneously would do. Bender, Green, and Fink (1954) have reviewed the literature in clinical neurology on the use of double tactile stimuli in diagnosis of central nervous system damage. In reviewing the effects of multiple simultaneous tactile stimulation, Geldard (1962) concludes: "Like psychology, this area has a long past and a short history. Its importance for nearly all psychophysical studies, and for many applied areas in communications, is as yet incalculable."

Tracking

A much studied task in engineering psychology has been tracking, because it has so many practical implications. Tracking has received only an introductory amount of attention from cutaneous researchers interested in the possibilities of compensatory and pursuit behavior. It has been found under certain conditions that vibratory tracking is just as efficient as a visual analogue, and under other conditions it is inferior. A bidimensional vibratory display which works both in the "right-left" and "up-down" directions has been devised. But what happens when the observer crosses his legs and is asked to identify the direction of the vibratory stimulus? "The old problem of crossed fingers is still there," says Hahn. Howell and Briggs (1959) studied tracking error as a function of input frequency for three display modes in a positional, a quickened, and a super-quickened control system, and found poor showing at high frequencies as compared to a visual display. Learning and compatability relative to the problem were possibly involved in the results.

Adaptation

Hawkes (1961), for the most part, summed up what we know about adaptation thusly: "Present data on adaptation to mechanical cutaneous vibration indicate little more than that a vibrating stick held by the hands results in a feeling of pressury numbness after an hour or so of continuous stimulation. Further, accomodation does not occur under some circumstances. Almost nothing is known of the course of the adaptation-recovery cycle."

Hahn (1960) has made the point that there is some evidence that a phenomenon which occurs in visual adaptation is also found in the cutaneous senses. If one measures the course of light adaptation by fatiguing one area of the retina, and then makes brightness matches with a comparison light falling on an unfatigued area, it takes no more than 3 minutes for complete adaptation to occur. He points out that Hawkes (1961), using the instantaneous threshold method of measurement, found that adaptation to a level of alternating current twice threshold required from 3 to 6 minutes. Von Bekesy (1960), using the matching method, found adaptation to be complete in about a quarter of a minute. With the same method, he found that adaptation to mechanical vibration is much slower, the sensation level dropping about 10 dB in 2-1/2 minutes. Of a different sort, extended monitoring of vibratory signals was studied by Gilmer (1958) in a situation involving an uncomplicated communications system. When the stimuli were presented at a rate of 15 per minute subjects could function in a stable fashion for 3-1/2 hours without deterioration of performance.

CODING AND INFORMATION PROCESSING

Gregg (1960) emphasizes that the structure and properties of a cutaneous communication channel depends first of all on the purpose that the channel is to serve. Certain design problems disappear and others emerge as one envisions different uses for the system. Using the skin as an auxiliary channel scarcely raises the problem of an appropriate code. Such development problems as reliability of the device, comfort and convenience in use, and cost of production are of concern. A completely new artificial language is a different matter, involving, in addition to the sensory input problems, such research areas as language structure, channel loading, and a vast array of cognitive considerations. One may even give thought to the fact that here, for the first time, we have the chance of actually engineering a language from the beginning, compatible with human abilities and limitations.

We have a storehouse of information about rate of reception of auditory and visual signals and how we interpret a particular code, but we know little about cutaneous codings beyond the long history of the use of braille.

Hawkes (1962) notes that cutaneous and auditory signaling may be evaluated in terms of reception, training time, and performance. Geldard (1957) points to the fact that cutaneous communication using vibratory stimuli compares favorably now to Morse code in these respects. The work by Staack (1962) on braille code revisions, and that undertaken at Louisville by Foulke (1965) with his "electrically stimulated braille," indicates potential superiority to present means of communication for the blind. Several investigators have shown that simple alphanumeric coding can be built into an operational system. Perhaps it is fortunate that no one is now doing so since it would only be repeating history. Think where we might be today if Morse code had been better planned from the start.

Coded symbol sets, such as used in business shorthand, could reduce the number of input signals required for rapid communication, but possibly not enough. The system of Notehand developed by Seymour (1949) offers another illustration. Alluisi (1960), in a supplement to some adventures in tactile literacy, shows how signals could be used to represent phonemes. Such a system may well help maximize compatibility. Myers (1960) has shown that subjects can be trained to discriminate phonemes. Alluisi (1960) says some combinational literate-linguistic form might offer a possible solution to the problem of selecting an appropriate response alphabet not unlike the Japanese "Kana" system.

Engineering signal inputs and the complex information processing of a cutaneous language raises a number of questions, according to Gregg (1960, 1961). What is the nature of cutaneous imagery, the contents of the image cell? What combinations of levels and dimensions of the cutaneous stimuli provide unique sense "sample points" over variations in rate and intensity? How many distinct symbols based on the cutaneous stimuli can be derived, and what is the duration of each? What are the possibilities for simultaneous stimulation over dual cutaneous channels? When we make analyses based on information theory concepts it seems that much more information is provided the organism than it could ever possibly use. Cutaneous inputs may well be able to provide even a primary language structure. Teichner and Sadler (1962), in their studies of visual symbol identification structure, represent some of the things that need to be studied in the tactile area. In the area of vigilance, using auditory and visual signals, the literature is confusing (Buckner, Harabedian, and McGrath, 1960). In the tactile area there is also confusion, but Loeb and Hawkes (1961) concluded from their work that moderately intense electrical cutaneous stimuli can be reliably monitored even against a background of masking noise.

ANATOMICAL AND THEORETICAL CONSIDERATIONS

Whether ignored, wished away, studied with futility, or speculated on, many of the problems of the mechanisms of cutaneous reception are still with us. There is a development of thinking, however, away from one-to-one correspondence between sensation and receptor toward varying considerations of impulse patterns. Nerves, structural units, and pathways may be important, as well as some new theorizing about the general nature of perception. It may be that anatomical considerations will become even more important to our overall problem of communication as more attention is given to efficiency in information processing and to operational use. In this section we shall give reference to the long history of receptor controversy, descri e certain anatomical structures that appear with varying degrees of evidence to function in receiving mechanical and electrical stimuli, and present some converging views on theory.

Story of a Controversy

There has been no lack of theory and arguments about the receptors of cutaneous sensations since the doctrine of specific nerve energies was propounded by Muller around 1842. The von Frey theory of 1885 and the writings of Bevr, Bethe, and von Uexkull in 1899 made the story sound reasonable and fairly simple. Sherring began to ask some shaking questions around 1900.

The first extensive review of the problems of cutaneous end organs was published by Dallenback (1927). He emphasized how the original views of von Frey had become oversimplified and distorted over the years, particularly by the authors of textbooks. Nafe (1934) introduced some new ways of thinking about cutaneous reception that opened up the field to some different types of research. The Geldard (1940) review was devoted primarily to mechanical vibration facts and pointed to the necessity of getting more of them before letting theory run rampant. Gilmer and Haythorne (1941) described the history of direct excision experiments in looking for possible cutaneous receptors. Bishop (1946) reviewed the neural mechanisms of the cutaneous senses. An overall picture of the receptive capacities of the skin was summarized by Kenshalo and Nafe (1960) and Melzack and Wall (1962) pulled together some current thinking on the nature of cutaneous sensory mechanisms in a paper on facts and theory.

Certainly, in terms of the possibilities for receptors in the skin, we may agree with Weddel (1955) who says there has been some suffering from a "crisis of abundance." There is less controversy in the literature (Barker, 1962; Basmajian, 1962) about the receptor mechanisms related to proprioception generated by small muscle spindle movements, as well as those resulting from the more gross stimulations. There is agreement, with some skeptics, that free nerve fibers may be related to pain and possibly to ache, and that A_1- and A_2-fibers function in passive and contractual muscle movement, with B- and C-fibers less specialized. Little is being said positively these days about most of the once-heralded encapsulated end organs, save that the Pacinian corpuscle may function in deep pressure sensitivity.

On the qualitative side, the failure to find a narrow one-to-one relationship between receptor specialization and perception has not obviated the law of the adequate stimulus. On fiber size the evidence permits only a loose association of function with fiber diameter. On nerve routes there is evidence that central somesthetic pathways are specialized for the transmission of particular kinds of information. But there is no evidence that would allow us, even at central levels, to assume that each pathway carries information about a single physical dimension, or gives rise to only one psychological sensory dimension. Melzack and Wall (1962) propose that receptors are specialized physiologically for the transduction of particular kinds and ranges of stimuli into patterns of nerve impulses, rather than modality-specific information. Temporal and spatial patterns of impulses cutaneously aroused may be filtered out presynaptically by the properties of terminal arborizations. Central cells can detect characteristics of impulse patterns by means of their properties of differential threshold, temporal and spatial summation, and adaptation as a result of special connections of afferent systems. It is essential for central cell detection that there be more than one nerve impulse in a single fiber, or more than one fiber carrying single nerve impulses. Uttal (1960) states that impulse patterns are carried intact toward the cortex and decoded there into parameters of sensation in a manner described for taste perception by Pfaffman (1959).

There is no evidence for discrete thalamic or cortical "centers" for any dimension of somesthetic experience. Pattern theory, still discussed in a fog of vagueness, fails to provide an adequate account of cutaneous and proprioceptive experiences.

Some Converging Views

Hahn (1958), in using square wave electrical stimulation of the skin, found a chronaxie with a value typical of that obtained from A-fibers. Uttal (1959), reporting on an experiment involving the effects of ischemia on threshold for single electrical pulses applied to the forearm, also concluded that A-fibers were involved in electrical cutaneous sensory stimulation when the sensation was a painless pulse.

Hawkes (1961), in an experiment and a review, concluded that the dependence of sensitivity to pressure or to mechanical vibration on skin temperature is a peripheral effect, and that electrical current applied to the intact skin apparently affects nerves directly without requiring transduction by a chemical or other process at the receptor. It is generally accepted that no nerves exist which are specialized for maximal response to electrical energy applied to the skin, yet all such nerves may be sensitive to electrical stimulation. The painful experience of "sting," which can be readily elicited under a number of conditions of electrical stimulation of hairy regions of the body, may well involve C-fibers, with painless experiences stimulating A-fibers, Pacinian corpuscles, or various mechanisms associated with muscles. "Ache" has been posed as a result of strong muscular contraction, while "nerve pain" results from excessive stimulation of main nerve trunks.

Verrillo (1963) has discussed some indirect evidence which indicates that there are at least two receptor systems involved in the vibrotactile sensation; one is dependent on frequency and on the area of the contactor, and one is independent of both of these parameters. Winkelmann (1960) says there are two networks of nerve fibers of the skin possibly related to differential sensitivity: a superficial network having small diameter fibers with either light or no myelin, and a deep layer containing large diameter, heavily myelinated fibers. Several investigators have demonstrated the sensitivity of the Pacinian corpuscle to vibrating stimuli (Scott, 1951; Gray and Matthews, 1951; Hunt and McIntyre, 1960; Hunt, 1961). Weitz (1939), investigating the effect of local anesthesia on vibratory sensitivity of the skin, found that with the return of the painful sensation of "prick" there was little change in the vibratory thresholds; with the return of "contact" there was little change in the vibratory thresholds; with the return of "contact" there was a sharp drop in these thresholds, which came back to normal with the return of "pressure."

Electrical Stimulation and Underlying Structures

There are two aspects of electrical stimulation favorable to experimentation. First, electricity can readily induce both painful and painless experiences; second, it can "get down deep" easily. A confusing aspect resulting from electrical stimulation centers around all of the weird patterns of experience that can be induced. Kenshalo (1963), by the process of iontophoresis, drove adrenalin into the skin with electric current and reported an array of sensations which originated in the deeper structures.

The square wave electropulse has particular advantage in providing a painless touch experience which, on the palm of the hand, can be controlled in several ways. It is useful not only in seeking out painless pulse sensitive "spots" for study, but it is also a most adequate stimulus for identifying motor points and nerve trunks. The palm is a convenient place to work, and possibly has certain advantages for communication uses. It also has many deep lying structuctures not found in such abundance on hairy regions of the body, and it is relatively free of the small surface fibers. One can stimulate the palm electrically for long periods of time without inducing noticeable neurovascular changes. For example, electrical stimulation of the arms, legs, back, and other hairy regions of the body for extended periods of time creates redness, sometimes soreness. The palmar side of the hand, and particularly the finger pads, have been used more for cutaneous study than any other region of the body, save for studies of cutaneous pain. The anatomical literature has both gross and minute descriptions of these areas that may well be involved in the reception of mechanical vibration, sinusoidal alternating currents, and square wave electrical pulses.

Pacinian corpuscles, concentrations of muscle tissues, large sensory fibers, and well-organized motor units are found beneath those general areas sensitive to painless pulse stimulation. Concentrations of some or most of these structures are lacking in some areas that do not give good pulses. Electropulse stimulation can penetrate certain regions of the palm where some of these mechanisms are found in abundance. We can even speculate that we are dealing with both cutaneous perception and proprioception in the mediation of good pulses, and that in those regions giving a wide separation in the pain-to-touch ratio there are a few free nerve endings to pick up pain, allowing the electrical stimulations to get to other tissues first, both cutaneous and muscular. Or, we can conclude readily (maybe hastily) that the Pacinian corpuscle as a receptor of deep sensibility is our primary mechanism. If one wishes to look for psychophysical-neuromuscular comparisons, or at least for representations of "parallelism," we have one enticing example. A number of sophisticated observers report that the subjective feelings of a good painless pulse on the palm, and on other muscular regions, to be an estimated size of approximately 4 mm to 6 mm in diameter. Without drawing an unwarranted conclusion we do wish to note that Buchthal and his associates (1957) found that the spike potentials from each motor unit on the human biceps were located in approximately a circular region where the fibers were confined to a diameter of approximately 5 mm. This area of 5 mm includes many overlapping motor units. The potentials could be traced in their spread out to a distance of some 20 mm.

A primary receptor which may be involved is the Pacinian corpuscle, but what of those pulse sensitive regions that have no such corpuscles? Gairns (1955) reports finding no Pacinian corpuscles in the hard palate, yet Gibson (1963) has found this region gives sensations of good painless pulses. Gairns does, however, report that the hard palate contains closely knit and well-localized nerve terminations, and muscle bundles are also present.

Do pressure-vibration sensitive spots also respond as good pulse spots? There is some negative evidence on this. For example, Gilmer (1935) tatooed a 1-square-inch area slightly above his left wrist on the dorsal surface. This region was carefully explored for temperature, pain, and pressure-vibration spots, and sensitivity records have been kept over a period of three decades. Aperiodically this region has been tested for sensitivity. He has found that two cold spots have remained in the same location for these thirty years, as have several very sensitive pressure-vibration spots. This region, however, responds only by giving painful sensations to electrical pulse stimulations except under very carefully controlled conditions involving use of large electrodes. The pressure-vibration spots do, however, respond to alternating currents above 20 cycles as feeling like mechanical vibration.

To draw conclusions from indirect evidence relating anatomical structures, psychophysical function, and stimulation loci borders on speculation. We do conclude, however, that the palm of the hand offers a good place to work with electrical stimulation. Here regions can be found that give good pulses with large separation between pain and touch, relatively stable thresholds, and where stimulation can be presented over long periods of time without undue fatigue or irritation. Hahn (1960) has discussed some of the psychophysical gaps that need to be filled in before we can write anything very definitive about receptors or about electroanatomy. Some things are known about certain anatomical structures, however, that should not be ignored while we await more sophisticated aid from biophysics.

STRUCTURES OF THE HAND

In terms of gross anatomy the tissue of the palm of the hand is well described in anatomy texts, but one must turn for the most part to the professional journals for descriptions of the structures and functions of the cutaneous and proprioceptive mechanisms that may be related to the perception of electropulses. We shall summarize here descriptions pertinent only to this problem.

Muscles

The *abductor pollicis*, near the base of the thumb, is a thin, flat muscle placed just beneath the skin. Running laterally and downward, it is inserted by a thin, flat tendon into the radial side of the base of the first phalanx of the thumb and the capsule of the metacarpophalangeal articulation. Beneath is the *opponens pollicis*, a small, triangular muscle which passes downward and laterally, becoming inserted into the bone of the thumb. Arising from the lower border of the transverse carpal ligament is the *flexor pollicis*, which has both a superficial and deep portion. Beneath is the most deeply seated of this group of muscles, the *adductor pollicis*. This latter muscle is supplied by the ulnar nerve. Grenlich and Pyle (1959) report that bilateral asymmetry in nerve supply is frequently found, and that only one out of every four flexor pollicis muscles are exclusively supplied by the ulnar nerve, while in almost all of the remainder both ulnar and median nerves shared in the supply. The opponens pollicis was supplied exclusively by the median nerve in two-thirds of the cases only, the other one-third having a double supply.

On the opposite side of the hand is the *palmaris brevis*, a thick quadrilateral muscle found just beneath the skin. The flesh fibers of this muscle are inserted into the skin of the ulnar border of the palm. Nearer and deeper are the *adductor digiti quinti* and the *flexor digiti*, and beneath these the *opponens digiti*, a triangular muscle group found quite deep. All the muscles of this group are supplied, for the most part, through the ulnar nerve. Intermingled with the above groups are the intermediate muscles around the base of the fingers. They are supplied by a mixture of the median and ulnar nerves.

The Muscle Spindle

The muscle spindle has been known to react to various stimuli and to produce afferent nerve currents, since the early works of von Haller around 1750 (Bastholm, 1950). It appears, however, that in the history of the study of muscles in general more attention has been given experimentally and theoretically to problems of muscular contraction, as heat regulatory organs, problems related to physical work, and other motor things, than to proprioception and the various aspects of perception associated with muscles. Perusal of professional journals indicates that slightly more attention has been given to the sensory aspects of small muscle groups in the past decade than was given in a previous century. We find detailed descriptions of the sensory aspects of muscular action given by Morgan (1943), Katz (1950), Bourne (1960), Basmajian (1962), and Barker (1962).

The muscle spindle is well supplied with nerves. Terminals of large myelinated A-fibers are arranged spirally around the muscle fibers of the spindle, and endings associated with smaller myelinated fibers end in spraylike arborizations upon the muscle fibers. Both are stimulated when the muscle stretches, while Golgi tendon organs record muscle contraction. Pacinian corpuscles associated with muscles are generally larger than cutaneous encapsulated end organs. They have been regarded as organs of deep pressure sensitivity and have been generally described as being activated by deformation of the tissue in which they are located. Muscles and tendons are supplied with a variety of receptors ranging from free nerve endings to encapsulated organs. Afferent fibers are concentrated at the "nuclear bag" region of the spindle, and are so arranged that they can easily be mechanically distorted. Free nerve endings are found in abundance in the blood vessels serving muscles.

Kinesthetic nerve fibers do not include any pain fibers comparable to cutaneous C-fibers. They are known to be thicker and more myelinated, and to show faster conditions than do average cutaneous fibers. They parallel in these respects the cutaneous A-fibers. When a spindle potential is generated by stretching there are changes in membrane potential. In studies of the phasic and tonic components of spindle discharge the phasic sensitivity of a spindle is high whether a vibrator is applied to a sensitive spot on the skin, or on the tendon.

The Motor Unit

The functional unit of the motor system is neither the entire muscle nor the individual muscle fiber itself, but rather what has been called the *motor unit*. It has been described in detail by Buchthal, Guld, and Rosenfalk (1957), Ruch, Patton, Woodbury, and Towe (1961), and Basmajian (1962, 1963). Just before and just after entering the muscle, the axon from each ventral horn cell (motoneuron) branches many times, thus innervating a number of muscle fibers. The motor unit consists of a single motoneuron, its axon, and the group of muscle fibers. The motor unit consists of a single motoneuron, its axon, and the group of muscle fibers innervated by this single axon, operating in squad fashion.

Since motor units are the smallest functional units of muscle, the weakest possible natural movement is the twitch of a single motor unit. As more force is required more units are recruited, discharge is increased, and finally the motor unit twitches summate to form a tetanus. There is evidence that neuromuscular transmission is mediated by acetylcholine. This may be of some relevance to our problem. All fibers in a motor unit do not contract at the same time; some are delayed several milliseconds. The larger the motor unit electrical potential registered, the larger the motor units producing it. Motor units in the hands are known to give larger potentials than, for example, in such places as the facial muscles. Paintal (1961) has presented evidence that electrical stimulation of muscles activate receptors either by local contraction (mechanical stimulation) or by some other change. He states that muscular contraction can stimulate both pressure and pain endings, though these as yet have not been well defined.

Motor Points

Motor points, not to be confused with motor units, are important to us because of the disturbing problem of gross muscular twitching found under certain conditions of stimulation. Motor points are usually situated over the place at which the motor nerve enters the muscle (Kovacs, 1949; Scott, 1962). This is frequently at the junction of the upper and middle one-third of the fleshy belly of the muscle, although there are exceptions. The exact position of motor points varies from individual to individual. Although not regarded as anatomical structures per se they can be charted easily as points of maximal irritability and muscular movement. They have been described in the literature almost exclusively in terms of their use in electrotherapy and can be found by exploring the skin surface over muscles with make-and-break shocks. Motor points do not respond to current which flows steadily. They are frequently found where the nerve is nearest to the skin. Milligan (1964) has studied motor points and muscle twitch thresholds and found them unrelated to good pulse sensitivity. Stimulation of motor points can easily be avoided, and should be avoided in any operational system.

The Pacinian Corpuscle

Of particular interest to our problem as a possible major sense receptor for electropulse stimulation is the Pacinian corpuscle. Writers have for a long time suggested that this organ may be related to "deep sensibility" (Geldard, 1953; Hunt 1961). It is the most familiar receptor in and around muscles and very receptive to vibratory stimuli. The palms of the hands, in regions of the muscles, are exceptionally well supplied with these end organs.

Gray and Malcolm (1950) demonstrated that isolated Pacinian corpuscles were responsive to both "on" and "off" displacements. When the corpuscle is deformed by a mechanical stimulus it returns to normal shape after the withdrawal of the stimulator. Gray and Sato (1953) found that mechanical movement apparently distorts the receptor membrane of the corpuscle and causes a change in permeability. The movement may be transmitted to the axon as a stretch or through compression and decompression. The corpuscle might be thought of as a partly damped oscillating system.

By 1960 much work had been done on the Pacinian corpuscle as a biological transducer. This work has been summarized by Lowenstein (1960). His investigations, and those of others, led to the conclusions that the Pacinian is "truly a giant among receptors" and that "more than 99.9 percent of the mass of the corpuscle could be dissected away without impairing the transducer function." When stimulated mechanically, it produced generator currents which, if the outgoing nerve fiber was left intact, triggered the firing of nerve impulses in the normal manner. The nerve ending was found to be the transducer site. The Pacinian corpuscle and the muscle spindle have three characteristics in common: the absence of myelin sheath, presence of large number of mitochrondria associated with metabolic activity, and the presence of many small, round structures of unknown function that resemble certain structures found in motor nerve endings. Lowenstein applied mechanical stimulation to a tiny patch of membrane (0.03 mm in diameter) and measured the resulting generator currents at varying distances from the stimulated site. He found that the current decreases exponentially with the distance. The experiment showed that excitation in the receptor membrane is confined to the mechanically distorted region. When two spots on the membrane were simultaneously stimulated the generator current summed. As stimulus strength was increased, deforming progressively more of the receptor membrane, the excitation spread over a correspondingly greater area. Spatial summation may be involved, as it is well known that the receptors occur in groups. A weight (or other stimuli) applied to the skin surface may excite many Pacinian corpuscles. It is known that the rate of adaptation differs widely in receptors. In some, like the muscle spindle, adaptation takes minutes. In the Pacinian corpuscle, however, adaptation to zero frequency is complete within a few milliseconds (Mendelsohn and Lowenstein, 1964). That the receptors are not uniformly distributed may be related to the fact that the skin is not uniformly sensitive to pressure, mechanical vibration, alternating currents, electropulses, or to other stimuli.

Toward a Pattern Theory

Converging views on the mechanisms involved when mechanical and electrical stimuli are applied to the surface of the skin center around the proposition that both cutaneous and proprioceptive systems are functioning and there are no specific receptors as such. Some mechanisms are attuned to react with patterns inducing pain, while other mechanisms are most responsive in giving touch sensations. Aside from the uncomfortable experience of ache related to excessive stimulation of muscle tissue, those shock sensations related to the stimulation of nerve trunks, and the jerks caused by the stimulation of motor points, most pain seems cutaneous in origin. Excessive stimulation will cause pain anywhere and over any system. Mechanical vibration and air jets are normally not adequate stimuli for pain, while electrical currents are adequate stimuli for both touch and pain.

Within the cutaneous system pain is served primarily by the superficially located free nerve fibers, and touch is served by the larger diameter fibers. The appropriate package of the parameters of stimulation finds differential reception. Touch sensations may be experienced before pain because of a lower threshold and the abundance of favorable receptors in certain regions. Pain may be induced more readily in other areas because of the predominance of free nerve fibers. In these regions, however, pain may be bypassed through appropriate packages of stimulus dimensions when stimulated electrically.

The deeper receptors, including Pacinian corpuscles, motor units, and other mechanisms associated with muscles, are particularly adapted to giving painless sensations. The palm of the hand is well endowed with these structures stacked in depth. In those regions of the body where good touch is experienced without certain structures (such as the hard palate which has no Pacinian corpuscles) other structures serve instead.

Current views favor a pattern theory of central neural decoding, involving selective peripheral systems. Learning the basic facts of such decoding may be most important in engineering an efficient cutaneous communication system.

SUMMARY

Attempts at communication through the skin have a long past frought with repeated errors. This paper deals briefly with this history and with recent researches into the problem of the psychophysics of cutaneous stimulation induced both mechanically and electrically. Some attention in given to the problems of coding and infor-

mation processing. This selected review concludes with anatomical and theoretical considerations of cutaneous and proprioceptive mechanisms that may be involved in asking the skin "what language it can compass."

What are the demands of the communication system in terms of information to be conveyed? What are the discrimination capabilities and limitations of the skin? Why have so many attempts to talk through the skin been failures? What is new about the current researches that now gives practical promise of tactile literacy?

The general demands of a cutaneous communication system involve conveying a minimum of seven classes of information. The psychophysical problems center around stimulus variables, stimulus presentations, and the basic four primary dimensions of locus, intensity, duration, and frequency. Important also are several derived dimensions. The problems of pattern discrimination, masking, and confusion are presented. In terms of coding and information processing, modern attempts to communicate through the skin offer for the first time a chance of actually engineering a language from the beginning which is compatible with human abilities and limitations.

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