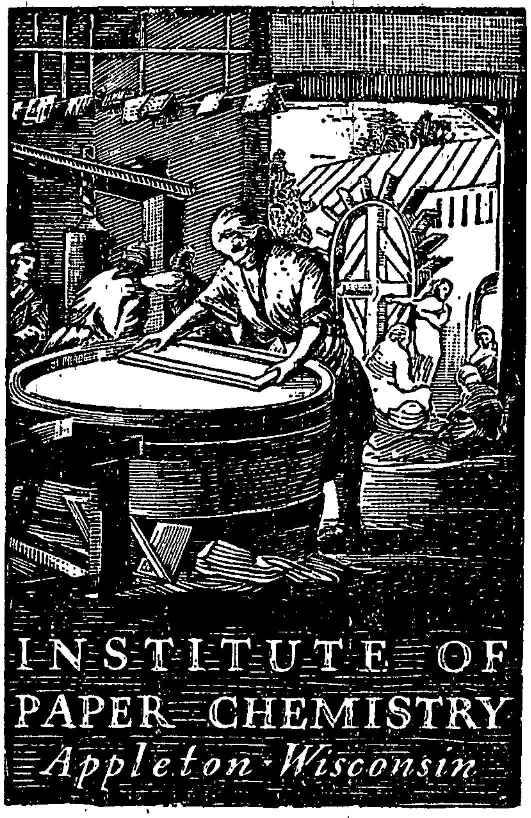

A REVIEW OF THE PHYSIOLOGY AND PSYCHOPHYSICS OF TACTILE SENSORY RESPONSE

Project 2817

Report One

A Progress Report

to

MEMBERS OF GROUP PROJECT 2817

January 5, 1970

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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A REVIEW OF THE PHYSIOLOGY AND PSYCHOPHYSICS OF TACTILE SENSORY RESPONSE

SUMMARY

The following review of the literature dealing with the mediation of tactile stimuli has been prepared as part of a research study of the feasibility of developing an objective measurement for softness in tissue products. Three different aspects are involved.

(1) A review of the physiology of the neuron and the neural receptors pertaining to the tactual sense.

(2) A review of psychophysical studies of the forms of human response to tactile sensations.

(3) A brief review of information theory as it applies to sensory perception.

A study of the fine structure of the peripheral nervous system (that is, the neural structure directly sensing mechanical stimulation) may, in itself, have little direct application to the feasibility of the development of a physical test for softness. However, some knowledge of the nature of the nervous system as a system of transduction and signal integration can lead to a distinction of the percepts that contribute to the sensation of softness. In this regard it is necessary to be aware of the histology of the neural endings that respond to touch sensations in terms of mode of response, sensitivity, and requirements for excitation.

Studies of the relationships involved in an individual's subjective impression of the softness or surface texture of one material in contrast to another falls within the domain of psychophysics. The feasibility of the psychophysical approach lies in the correlation of salient physical properties of a stimulus continuum (for

instance some surface property of a tissue) to some subjective response (say the perception of softness).

Information theory provides a means of analyzing one's ability to perceive and respond to sensory stimulation by considering the neural system as a system of communication. The ability of a single channel of the nervous system to transmit information is limited. It is this ability that determines the extent to which one can divide a sensory continuum (such as softness) into subjectively discriminable regions.

HISTOLOGY OF THE PERIPHERAL NERVOUS SYSTEM RELATING TO TACTILE SENSATION

PHYSIOLOGY OF THE NEURON

The Nerve Cell

The basic unit of the nervous system is the neuron. The neuron is a specialized cell consisting essentially of a cell body from which extend fibers (fiber processes) of two types: dendrites and the axon. The dendrites, of which there are several for each neuron, conduct pulses, termed afferent pulses, initiated by external stimuli toward the cell body. A neuron has only one axon possessing either of two types of endings: one providing a functional connection to muscle fibers or glands, this type of ending is called a terminal bouton, and the other serving to connect the neuron to the dendrites of another neural cell, such an ending being termed a terminal arborization. The axon conducts pulses away from the cell body (efferent pulses). The dendrites are usually short, while axons have been known to have lengths of several feet.

Rushton (1) mentions the nodes of Ranvier located along the nerve fibers at intervals of about one millimeter. These serve to boost the nerve signal in order to maintain its quality and, in that sense, they may be considered analogous to booster stations along long distance telephone transmission lines.

The whole neuronal structure is supported by a network of nonconducting (glial) cells called, collectively, neuroglia.

Dendrites are frequently covered with sheathings of various types. Such dendrites are referred to as having myelinated endings while those not sheathed are called nonmyelinated. The nerve endings themselves are of several types. These endings appear to play a very important role in regard to the specialization of nerve functions. For this reason they are a topic unto themselves and, as they pertain to the mediation of tactile sensations, they will be discussed later.

Conduction of a Pulse Along the Axon

Although the nervous system is often compared to systems of electrical networks and electrical stimulation is frequently used in the study of neural responses, the conduction of a pulse along the axon is electrochemical rather than electrical in nature. The electrochemical mechanism of pulse conduction has been described by Baker (2).

The axon consists of a tubelike membrane filled with a fluid called axoplasm. The axoplasm contains a high concentration of positively-charged potassium ions while the outside fluid bathing the axon contains a high concentration of positively-charged sodium ions. In an unstimulated condition the axon is said to be in a state of polarization. In this polarized condition the membrane of the axon is highly permeable to potassium ions and only slightly permeable to sodium ions, resulting in a leakage of the potassium ions through the membrane until an equilibrium state is attained. In the equilibrium state a potential difference of approximately -60 mv. exists across the membrane (inside to outside).

An electrical charge applied to the membrane depolarizes it causing a sudden increase in its permeability to sodium ions. The sodium ions migrate rapidly into the interior of the axon and thereby produce a reversal of the potential difference across the membrane from the interior to the exterior to a level of +50 mv. This condition is the first phase of what is called the action potential; occurring locally, it induces a current flow and triggers the depolarization of an adjacent region.

In this manner, a pulse or signal moves along the axon at a velocity in the order of 100 meters per second. Corso (3) notes that the process of local depolarization occurs within an interval of about one millisecond.

Requisites for Neural Stimulation

Corso (3) lists the factors necessary for the electrical stimulation of a nerve. These factors, which are based upon the electrical threshold properties of the nerve (i.e., the minimum degree of stimulation that will trigger a neural response), are a current of sufficient strength and the application of a sufficient current for a sufficient temporal duration. Two terms frequently used in discussing the requisites for electrical stimulation are: rheobase and chronaxie. The rheobase of a nerve is defined as the weakest current that will stimulate a nerve fiber if applied for an adequate period of time. Chronaxie is the shortest time of application required for a 2X rheobase current strength to stimulate a nerve fiber.

Other properties related to the threshold sensitivity of a neuron are: summation and the period of temporal summation. Summation refers to a process whereby subliminal stimuli (i.e., stimuli of individual intensities each less than the threshold level) combine or summate to initiate a neural pulse. The period of temporal summation is the period of time, starting from the application of the first subliminal pulse, during which summation can occur; it is of the order of 0.5 msec. These properties define the basic thresholds of a neuron and control its excitability cycle.

Excitability Cycle of a Neuron

The excitability cycle of a neuron refers to its response to a suprathreshold stimulus in terms of its sensitivity to further stimulation. According to Corso (3), the excitability cycle of a neuron occurs in four phases:

1. Absolute refractory period. This occurs immediately after excitation. During this period of about 0.5 msec. the neuron will respond to no other stimuli.
2. Relative refractory period. During this period, following the absolute refractory period, the nerve will respond only to relatively intense stimuli.
3. Supernormal period. The third phase is a period of hypersensitivity during which the neuron can be excited by stimuli of intensity below the normal threshold.
4. Subnormal period. This is the last phase as the neuron returns to its normal resting state. During this period, it will respond only to stimuli of greater intensity than the normal threshold.

The excitability cycles of neurons range from 80 msec. for large diameter fibers to one second for small fibers. The absolute refractory period limits the maximum firing frequency of a nerve to about 1000 impulses per second.

The Synapse

The functional connection between the terminal endings (terminal arborization) of the axon of one neuron to the dendrites of another is called the synapse. The transmission of a signal between neurons, depending upon the manner in which it is transmitted and received, usually involves some sort of decision-making or integrating behavior. Corso (3) notes, for instance, the importance of the synaptic transmission processes to the integration of body activities such as reciprocal innervation where the relaxation of muscle is necessary for the successful contraction of an antagonistic muscle (e.g., the biceps and the triceps).

Eccles (4) describes the anatomy of the synaptic juncture and the processes involved in the transmission of a signal across the synapse. The synaptic juncture consists of the synaptic knobs of the axon terminals uniformly separated from the dendrites or the body of the receiving cell by about 20 nm. (synaptic cleft). The mechanism of signal transmission is the diffusion of molecules of a chemical transmitter substance released from packets (vesicles) within the synaptic knob across the synaptic cleft into the receiving cell.

According to the hypothesis of excitatory and inhibitory synapses there are two types of synapse differing in the transmitter substances released from the synaptic knob to the postsynaptic neuron. One of the substances, the excitatory substance, facilitates the firing of the postsynaptic neuron through summation with similar excitatory signals from other neurons also functioning with the same postsynaptic neuron. The other substance inhibits the firing of the postsynaptic neuron even though it may be receiving excitatory signals from other neurons. It is these signal transmission mechanisms that give rise to decision-making and integrative network behavior of the nervous system.

NERVE ENDINGS IN THE TACTILE SYSTEM

Thus far, the nervous system has been discussed as a mechanism of signal transmission. The mechanisms that provide transduction of external stimuli are dependent upon the nerve endings. There are several that appear to be associated with the mediation of tactile sensations.

Principal Types of Nerve Fiber Endings

Corso (3) defines two principal types of nerve fiber endings that are found in the skin: nonencapsulated endings and encapsulated endings. The nonencapsulated endings are generally free nerve fibers while the encapsulated endings are encased in some form of pod or capsule. The simplest endings are nonencapsulated, nonmyelinated, terminal arborizations (free nerve endings) found in the dermal and epidermal layers of the skin and around hair follicles. Cauna (5) similarly states that the receptor organs are of two basic kinds: free nerve endings and corpuscular receptors.

Several kinds of free endings have been identified in the corium or derma (the deeper sensitive layer of skin beneath the outer layers or epidermis) of the human skin and studied by means of electron microscopy by Cauna and others. In areas possessing a thick epidermis and high dermal papillae (dermal ridges such as are found on the fingerpads), it has been observed that most endings project into the papillae. In areas where the epidermis is thin, the fiber endings tend to be horizontal and plexiform (complicated, interwoven, like a network).

Corso describes the nerve endings associated with tactile hairs as forming basketlike skeins around the hair follicles and the encapsulated nerve fibers as having nonmyelinated endings surrounded by special capsules of connective tissue.

The corpuscular receptors, as described by Cauna, are characterized by their nonnervous components and are located relatively deep in the tissue where they are less exposed to temperature changes and painful stimuli. From their location and the arrangement for the transmission of dynamic stimuli provided by the interposing tissue, he concludes that the corpuscle may be a relatively specific end organ for mechanical stimulation.

Three types of corpuscular receptor organs are commonly described in the literature; they are: Meissner's corpuscles, Merkel's touch corpuscles, and Pacinian corpuscles. Each appears to contribute in some specialized manner to the sensation or mediation of touch. Merkel's touch corpuscles are found in nearly all areas of the human skin and, while the general skin contains tactile hair, the hairless (glabrous) skin of the hands and feet contain Meissner's corpuscles in addition to the Merkel's corpuscles. The Pacinian corpuscles are located in the deeper tissues of the body.

Cauna's microscopy work (5) shows that the Merkel's corpuscle consists of a specialized basal epidermal cell and a disk-shaped nerve terminal. In the glabrous skin they are found in the papillary ridges where they are sheltered from thermal and painful stimuli but are sensitive to mechanical stimulation through the leverage of the overlying epidermis.

The Meissner's corpuscles are also found associated with the papillary ridges. They consist of stacks of laminar cells interleaved with nerve endings. Each corpuscle is supplied by two to six nerve fibers. The corpuscle itself is surrounded by an elastic capsule attached to the epidermis and the corium (the underlying vascular layer of the skin).

The Pacinian corpuscle is the largest of the sensory nerve endings. Quilliam (79) reports it to be typically one millimeter long and 0.5 millimeter wide. It was first identified in the dermis of the fingertips of man. It is an ovoid lamellated capsule consisting of zones of alternating fluid-filled spaces and cellular lamellae.

DETECTION OF TACTILE STIMULI

The first requirement for stimulus detection is that the stimulus intensity in the vicinity of a particular responsive nerve end organ exceed the minimum or threshold level of intensity that will cause the nerve to generate a pulse; e.g., "to fire." In regard to tactile stimulation, several mechanisms of stimulation are conceivable. Sources of stimulation can be tissue deformation, rate of movement of the tissue, or change in rate of movement (acceleration) of the tissue. It is also conceivable that sensitivities to these sources of stimulation can vary in terms of source and degree depending upon the properties of the end organ and the innervated tissue.

Threshold Sensitivity

Corso (3) quotes the work of von Frey as described by Woodworth (6) and the work of Hensel and Boman (7) concerning the absolute thresholds of sensitivity to mechanical stimuli. von Frey, by mechanical stimulation using a calibrated set of hairs as test probes, determined absolute thresholds for various parts of the body. These thresholds ranged from 2 g./mm.^{2} for the tip of the tongue and 3 g./mm.^{2} for the tip of the finger to 250 g./mm.^{2} for the thick parts of the sole of the foot. Hensel and Boman stimulated the exposed radial nerve between the thumb and forefinger with a one millimeter diameter rod and obtained a threshold of 0.15 to 0.6 g.

Dynamic Sensitivity

Mountcastle, Talbot, and Kornhuber (8) studied the response of nerve fibers located in the dermal ridges of the glabrous skin of a monkey's hand. This study was carried out by directly measuring the electrical responses of the exposed nerves of an anesthetized animal through oscillographic records. Three types of nerve endings were noted: (a) Meissner's corpuscles, (b) Merkel's disks, and (c) free nerve endings. Two classes of innervations appeared in their work: movement detectors (rapidly adapting fibers) and stimulus rate and intensity detecting fibers (slowly adapting fibers). (The measure of adaptation is the decline in the response with time to a sustained stimulus.) Receptor fields 0.9 to 2.0 mm. in diameter extending across 3 to 5 dermal ridges were found on the plams and finger pads. These fields were usually ovoid in shape with the long axis parallel to the ridges. A linear relation between the number of impulses per response vs. skin indentation was obtained for constant frequency and duration of stimulus application. A linear relation was also found between the force of the stimulus probe and the skin indentation. Prager (9) has concluded from his work on the mechanical response of living tissue to deformation that soft tissues deform easily under negligible load to a certain level of strain where their response becomes stiffer.

Loewenstein and Mendelson (10) and Mendelson and Loewenstein (11) studied the pulse generation resulting from direct mechanical stimulation of a Pacinian corpuscle before and after removal of its lamellating covering. They found that the duration of the generated electrical potential of the decapsulated nerve lasted more than 70 sec. when a sustained stimulus was applied whereas the duration of the generated potential of the encapsulated nerve decayed to zero in 6 sec. under the same stimulus. From these experiments, they identified two components of adaptation: a mechanical component and an electrochemical component. The pod of the Pacinian corpuscle apparently acts as a mechanical filter for slow or very low frequency stimuli and the electrochemical behavior of the nerve prevents repetitive firing under conditions of constant stimulation.

Zigler (12) measured adaptation times for weights applied to various parts of the body and concluded that adaptation time increases as a direct function of stimulus intensity.

The work of the above experimenters is described by Corso (3).

Verrillo (13, 14) compared absolute vibrotactile threshold measurements on the hand and areas devoid of Pacinian corpuscles and argued that the Pacinian corpuscle is the neural transducer of vibratory stimuli.

Verrillo (15) also found an upward shift in the absolute threshold for vibratory stimuli for hairy skin over glabrous (hairless) skin. He measured the absolute thresholds for vibratory frequencies ranging from 25 c.p.s. to 450 c.p.s. The threshold as a function of frequency, he found, was unchanged at the lower frequencies (up to 90 c.p.s. for hairy skin and to 50 c.p.s. for glabrous skin) followed by a decrease to a minimum in the middle frequencies whereupon the threshold increased with frequency uniformly to the highest frequency tested. The minimum threshold occurred at 220 c.p.s. for hairy skin and 250 c.p.s. for glabrous skin. The differences in the functional relationships between threshold and frequency for hairy and glabrous skin and the threshold insensitivity at the lower frequencies, Verrillo felt, were suggestive of two systems of tactile enervation.

In a summarization of histological investigations of encapsulated endings Kenshalo and Nafe (16) concluded that encapsulated endings do not occur in hairy skin; they exist only in specialized skin areas such as the palmar surfaces of the fingers and the palms of the hand. Contrary to the idea of specificity of nerve endings to mechanical stimulation, it was their feeling that qualitative differences in cutaneous sensations were derived from the properties of the surrounding tissue.

In 1941, Nafe and Wagoner (17, 18) according to Kenshalo and Nafe recorded the motion of a mechanical stimulus in producing tactile sensations. They were unable to relate the static aspects of the stimulus to the point of cessation of the stimulus. It was concluded that the relevant aspect of the stimulus was its dynamic component and that the cessation of the response was the result of cessation of the dynamic component rather than failure of the receptor. They tested this conclusion by simultaneously measuring the stimulus displacement and the neural discharge as functions of time for stimuli applied to the tongue of a rat. They found that the neural discharges were associated with the movement of the stimulus.

Lindblom (19) based his work on the results of earlier workers who concluded that touch receptors responded only during the actual movement of the skin. He determined rate sensitivities for the firing of neural receptors in response to skin displacement in terms of critical slope (the minimum rate of displacement that would produce a neural response). For the glabrous skin of a monkey, he determined critical slopes ranging from 0.08 to 3.5 mm./sec. The displacement thresholds observed in these tests varied from less than 10 μm. to nearly 200 μm. increasing exponentially as the displacement velocities were decreased toward the critical slope. A rate sensitivity was also observed as a frequency modulation of the neural output with displacement rate; as the displacement rate was increased the firing rate of the neuron increased to a level of saturation where further increases in displacement rate resulted in no further increases in firing rate. From this, Lindblom postulated the existence of a "continuum of touch receptors" all having a high rate sensitivity but differing in degree of response to static deformation. On the other hand, in glabrous regions where the nerve ending under test was likely to be encapsulated by a Pacinian corpuscle, a single displacement was found to produce usually no more than a single neural impulse on stimulus application followed by a single impulse when the stimulus was removed. This led to the conclusion that the glabrous skin contains at least two receptor systems.

Iggo (20) describes a "touch corpuscle" dome having a localized high sensitivity to mechanical stimulation and being uniformly sensitive over its central region to normal displacement but insensitive to lateral stretching. These have been found in the hairy skin of cats, rabbits, and monkeys. Each unit contains 30 to 50 receptor elements resembling Merkel's disks and apparently functioning as slowly adapting mechanoreceptors. They respond to a small mechanical displacement with a persistent discharge of impulses of varying frequency depending upon the amplitude and the rate of deformation and corresponding to dynamic and static phases of the displacement.

Capacity of a Neuron to Transmit Information

Information theory would seem to be useful in describing the operating characteristics of the nervous system. Its application to sensory perception and response by the individual is reviewed later in this report. Information theory has also been applied to the study of the physiological units of the nervous system — references to such work can be found in Volume III of the Proceedings of the International Union of Physiological Sciences, XXII International Congress, Leiden, 1962.* Much of the application of information theory is beyond the scope of this project; however, reference to the work of Mountcastle, Talbot, and Kornhuber (8) does seem pertinent. They evaluated the capacity of a single, afferent neuron for the transmission of information and found it to be three bits corresponding to capability for the resolution of a stimulus continuum into eight discriminable categories. This result is interesting due to its similarity to the capacity of human beings to recognize categories along a stimulus continuum.

When the just discriminable increments of neural stimuli were calculated as fractions of stimulus intensity ($\Delta S/S$) and plotted against stimulus intensity, S, a hyperbolic function was obtained. The calculation of the just discriminable increments as fractions of stimulus intensity (they are termed Weber functions) was first used in the early studies of psychophysics and served as the basis of an early psychophysical law (Fechner's Law) for the subjective perception of stimulus intensity. The hyperbolic relationship between the Weber functions and stimulus intensity obtained by Mountcastle, et al., they note, resembles the Weber function relationship determined for human performance in responding to mechanical stimulation.

*Gerard, R. W., and Duyff, J. W. (Eds.) Information processing in the nervous system. New York, Excerpta Medica Foundation, 1962.

HISTOLOGICAL MODEL FOR TACTILE PERCEPTION

There appears to be some disagreement among the physiologists regarding the mechanoreceptive aspects of the nervous system. This is to be expected when one considers its complexity and the experimental difficulties encountered in its study. For instance, the conclusions of Kenshalo and Nafe (16) that the specificity of nerve endings do not give rise to qualitative difference in cutaneous sensation do not seem compatible with Verrillo's (13-15) suggestion of the possibility of two systems of tactile innervation. Nevertheless, there is sufficient evidence to present, for the purposes of this project, a plausible basis of what must be considered to describe the histology of the tissue, say of a finger pad, as a receptor for tactile sensations.

It would seem from the structure of the nerve cell itself, the mechanics of signal transmission along the axon, and some experimental work, for example, of Lindblom (19) that the firing of a nerve in response to stimulation is frequency modulated rather than amplitude modulated. In other words, an increase in stimulus intensity does not result in an increase in the intensity of the neural impulse; more likely, the change in stimulus intensity would be seen as a change in the frequency of neural impulses.

The tendency for a nerve cell to adapt to a stimulus of sustained intensity indicates that movement rather than static displacement is important to the neural response. The mechanical properties of the tissue surrounding a given nerve along with the properties of the nerve fiber and its ending, in the case of an encapsulated nerve, modify the transmission of stimuli to the nerve receptor thus giving it specificity. The dermal ridges of the finger pads would appear to act as amplifiers of small mechanical displacements particularly those displacements involved in sliding the fingers along a surface.

The percepts contributing to a cutaneous sensation would come about then as the result of variable frequency firings of specific nerve cells depending upon the vibrations and displacement rates produced by the stimuli. This would require the existence of the so-called "continuum of touch receptors" suggested by Lindblom of sufficient quantity to cover the range of tactile stimuli that the human finger encounters and responds to.

PSYCHOPHYSICS OF TACTILE SENSATION

The apprehension of a tactile sensation involves the integration of nerve signals obtained in response to specific stimulation such as particular contact with the surface of an object. The study of the relationships between the perceived constructs and the physical attributes of the external source is termed psychophysics. An essential need in this project is to determine what physical properties of a surface are involved in its subjective characterization in terms that can be related to the concept of the softness of a tissue.

The problem is easily defined: Correlate physical properties with subjective properties. The surface of a piece of paper and the subjective impressions received by touch are not so easily defined. There is no base line or standard from which the development of a correlation can proceed; this requires a procedure whereby the physical attributes of materials having differing degrees of subjective softness are compared. To follow this procedure efficiently, one should be aware of the ranges of sensitivity of the neural system and the degree to which an individual can make subjective comparisons.

SCALES OF MEASUREMENT

Any measurement must be made in reference to some sort of scale. Stevens (21) lists four scales of measurement that may be applied in psychophysical investigations. They are the nominal, ordinal, interval, and ratio scales. The simplest of the scales, the nominal scale, is based upon the determination of equalities on a one to one substitution basis as is done in the numbering of football players. The ordinal scale is used in the determination of greater or less as is done in ranking items according to some quality, for instance, in the estimation of hardness from the mineral hardness scale (Moh's scale). The interval scale is based on the determination of equal intervals; an example is the Centigrade temperature scale. With the ratio scale, the equality of ratios is determined as is done in the measurement of distances on the basis of some unit length.

Stevens (22) discusses the permissible methods of averaging data derived with the preceding scales. The mode and the median are proper for the nominal and ordinal scales, while the average of data based upon an interval scale is validly represented by the arithmetic mean. Either the geometric mean or the harmonic mean serve for the ratio scale.

Corso (23) notes a conflict with this viewpoint; the opposition stating that Stevens' position is too limiting and wasteful of data and that as long as the data have a normal distribution and the assumptions of independence and homogeneity of errors are met the data are unaffected by scale properties.

DIMENSIONAL CLASSES OF STIMULI

Stevens (24) describes a dimensional class of stimuli characterized by the nonuniformity of a person's sensitivity to uniform increments of stimulus intensity which he calls "prothetic." This class is based on the systematic bias that results from the influence of stimulus intensity on the sensitivity to stimulus differences or change. For example, in a room illuminated by a single candle, the addition of a second candle produces a perceptible change in the light level, whereas the addition of a candle flame to the light of the sun produces no perceptible change in intensity. White (25) also discusses the dimensional classes of continua. He defines the prothetic class as those dimensions along which stimulus change appears to take place by addition or subtraction of stimuli. Examples of this class are brightness, loudness, and area. Changes which involve the substitution of one stimulus for another are classed as metathetic. Examples of the metathetic class of continua are: hue, pitch, locus on the skin, and locus in space.

METHODOLOGY OF PSYCHOPHYSICAL STUDIES

Corso (23) presents an analysis of three basic methods of dealing with the so-called organismic sensitivity, that is the sensitivity of an organism to stimuli. The three methods are:

(1) The Method of Limits.

(2) The Method of Constant Stimulus Differences.

(3) The Method of Average Error.

The method of limits is frequently used in the determination of the absolute threshold for various modes of stimuli. It involves simply the presentation of stimuli in increments of equal physical magnitude in ascending and descending series above and below some subjective limit. It is based upon the fundamental notion that a psychophysical study contains quantitative variables in three continua: a physical continuum, a subjective continuum, and a judgment continuum. It is assumed that a perfect linear correlation exists between the subjective and judgment continua. The method is applied to the determination of the absolute threshold using the operational definition of the absolute threshold as the stimulus that is judged to have been perceived in 50% of a set of trials.

The just noticeable difference (JND) or difference limen (DL) is determined by the method of constant differences. The difference limen is calculated as the stimulus difference reported correctly in 75% of the trials which is halfway between perfect guessing (50%) and perfect discrimination (100%). This method involves the presentation of a standard or unvarying stimulus in comparison with a variable stimulus that is varied symmetrically above and below the magnitude of the standard.

The method of average error is concerned with the equivalence of stimuli. The observer is presented with two stimuli, one standard, the other variable and greater or less than the standard. The task of the observer is to adjust the variable stimulus until it equals the standard according to some given attribute. A number of counterbalanced trials are run to give symmetry to the experimental design and minimize biasing errors.

PSYCHOPHYSICAL SCALING

Psychophysical scaling is the process of assigning scale values to subjective response. The purpose of a psychophysical scale is to provide a means of correlating sensory magnitude with stimulus intensity.

Corso (23) gives two approaches to the generation of psychophysical scales, the indirect or variability approach and the direct or quantitative judgment approach. The indirect approach utilizes a scale whose units are based upon just noticeable differences or some calculation of the judgment variability for each stimulus. This method has been found to be influenced by the method of measurement, giving different subjective scales for stimuli of the same physical dimensions. The direct approach is invariant to the method of measurement and, for this reason, is the approach generally used.

The development of the direct approach is attributed primarily to the work of Stevens (26). Corso discusses two methods for quantitative judgments using this approach:

(1) The Ratio Method of Fractionation. This method is dependent upon the observer's ability to perceive and indicate the magnitude of a sense ratio. A sense ratio is defined as the ratio between two subjective magnitudes on a given continuum (i.e., Light A is twice as bright as Light B).

(2) The Method of Direct Estimation. The observer assigns a value to a presented stimulus, usually on the basis of some arbitrary value previously assigned by the experimenter to a particular given stimulus.

In both of these methods, the psychophysical scale is derived from the quantitative judgments of the observer.

In addition to the preceding methods of scale development, Stevens (27) describes the category scale constructed by having the observer partition stimuli into a designated number of sequential categories.

PSYCHOPHYSICAL LAWS

The application of scaling techniques has led to the development of generalized relations between the physical and subjective magnitudes of stimuli. Such relationships have been designated as psychophysical laws.

Weber's Law and Fechner's Law

Weber's Law was formulated in the mid-nineteenth century by the German physiologist, Ernst Weber. Weber's Law states that the increase in stimulus intensity required to produce a just noticeable difference divided by the stimulus intensity is constant ($\Delta S/S = K$).

In 1850, Fechner assumed that Weber's Law was valid in differential form and could be integrated to derive Fechner's Law [Luce and Edwards (28)]. Fechner's Law states that the psychological magnitude of a stimulus (R) is a logarithmic function of its physical magnitude (S); viz., ($R = K \log S$). This law has never been fully validated [Ekman (29)] and has been disputed by Luce and Edwards (28) and Stevens (30).

The Power Law

More recent in the development of psychophysical relationships has been the formulation of the power law by Stevens (26) [see also Stevens and Galanter (31)]. The power law states that the psychological magnitude of a stimulus is an exponential function of its physical magnitude ($R = KS^n$).

Although the power law has been widely applied and is considered a valid law by many, it has been criticized by Pradhan and Hoffman (32). They note that Sidman (33) and Estes (34) have pointed out discrepancies between relationships determined from individual test data and the data obtained by averaging the test results for a group of individuals. These discrepancies, they felt, demonstrated that relationships determined by data from a group do not necessarily specify the forms of relationships for individuals. On the premise that if the power law is valid, it is valid for sets of stimuli having different means and ranges for individual as well as group-averaged data, Pradhan and Hoffman conducted a series of experiments in which subjective magnitude estimates of weights attached to the finger were determined. They found a linear relationship for group-averaged data on a log-log plot of subjective (R) versus physical (S) magnitude. The data for individuals were significantly nonlinear when plotted in the same manner. It was their conclusion that the power function relationship exists primarily as an artifact of group-averaging. This conclusion finds some support in the earlier work of Jones and Marcus (35) who fitted curves of the form $R = KS^n$ to subjective magnitude estimations by individuals in the sensory modes of taste, weight, and smell. An analysis of variance on the exponents indicated significant primary effects of subjects and modalities and interaction between modality and subject.

Pradhan and Hoffman offer four alternate explanations for the individual differences in psychophysical curves:

(1) Individual differences in perception of magnitude.

(2) Individual differences in use of numbers.

(3) Individual differences in both the perception of magnitude and use of numbers.

(4) Individual inability to estimate perceived magnitude on a ratio scale.

Ekman, Hosman, and Lindstrom (36) used the method of ratio estimation to investigate preference as a function of roughness and smoothness. They used stimuli consisting of paperboard, writing paper, and five grits of sandpaper. They concluded from their log-log plots of ratio-estimated roughness, smoothness, and preference data that the psychophysical relationships were described reasonably well by power functions for both individual and group-averaged data with the qualification that there is considerable variation in the slopes of lines fitting individual data. They presented the following two alternatives for the variations between individuals:

(1) The differences reflect variation in regard to sensitivity and are thus "perceptibly real."

(2) The differences reflect differences in the subjects' ability to handle numbers.

While there is some question regarding its applicability to individual data, the power law does appear to hold for group-averaged data. Despite the demonstrated criticisms of Pradhan and Hoffman, it can be argued that individual responses to a given stimulus are so varied that no general form of relationship can truly represent them collectively. Ekman (29) has commented (in 1961) that no convincing exception has been found to the power law. To this extent the power law exponents determined for various modes of stimulation by several workers appear to be in reasonable agreement. A tabulation of power function exponents, determined on a ratio scale of subjective magnitudes, from other published work by Stevens, Mack, and Stevens (37) is shown in Table I.

TABLE I

POWER FUNCTION EXPONENTS FOR VARIOUS CONTINUA TABULATED BY STEVENS, MACK, AND STEVENS (53)

Continuum	Power Function Exponent	Reference
Electric shock (60 cycle)	3.5	Stevens, Carton, and Shickman (38)
Brightness (white light)	0.33	Stevens, and Galanter (31)
Loudness (white noise)	0.6	Stevens (39)
Loudness (1000-cycle tone)	0.6	Stevens (40, 41)
Vibration (60 cycle)	0.95	Stevens (42)
Heaviness of lifted weights	1.45	Stevens and Galanter (31)
Pressure on palm of hand	1.1	Stevens and Mack (43)
Force on handgrip	1.7	Stevens, Mack, and Stevens (37)

In addition, Stevens (27) lists exponents for various prothetic continua based upon average values of subjective magnitude estimations by ten or more observers. These exponents are shown in Table II.

The power function according to Stevens (42) implies that equal sensation ratios correspond to equal stimulus ratios and is a psychophysical law although departures from it do occur. Deviations from linearity in log-log coordinate plots he ascribes to two different circumstances: (1) effects of fatigue, masking (influence of other stimuli), or disease and (2) the function may be the normal response for some continua. In either case, it appears that the departure from log-log linearity is accompanied by an elevated threshold and may be made into linear forms by the modification of the power function to: $R = k\,(S-S_o)^n$ where S_o approximately equals the threshold value.

TABLE II

POWER FUNCTION EXPONENTS FROM GROUP-AVERAGED SUBJECTIVE MAGNITUDE ESTIMATION FOR VARIOUS PROTHETIC CONTINUA, STEVENS (60)

Continuum	Exponent	Conditions
Loudness	0.6	Binaural
Loudness	0.55	Monaural
Brightness	0.33	5° Target — dark-adapted eye
Brightness	0.5	Point source — dark-adapted eye
Lightness	1.2	Reflectance of gray papers
Smell	0.55	Coffee odor
Smell	0.6	Heptane
Taste	0.8	Saccharine
Taste	1.3	Sucrose
Taste	1.3	Salt
Temperature	1.0	Cold on arm
Temperature	1.6	Warm on arm
Vibration	0.95	60 c.p.s. — on finger
Vibration	0.6	250 c.p.s. — on finger
Duration	1.1	White noise
Repetition rate	1.0	Light, sound, touch, and shocks
Finger span	1.3	Thickness of wood blocks
Pressure on palm	1.1	Static force on skin
Heaviness	1.45	Lifted weights
Force of handgrip	1.7	Hand dynamometer
Vocal effort	1.1	Sound pressure of vocalization
Electric shock	3.5	60 c.p.s. through fingers

CROSS-MODAL MATCHING

Cross-modal matching is a technique of magnitude estimation whereby the magnitude of a given stimulus in one sensory mode is matched by the subject's adjustment of a variable stimulus in another sensory mode. Cross-modal matches can also be made for the ratio of one pair of stimuli in a given mode by ratio adjustment of a pair of stimuli in another mode.

This technique can serve as a check on the validity of the power function for the representation of subjective magnitude estimations in each of two different modes. Stevens, *et al*. (37) and Stevens (27) have shown that the power function exponent determined by cross-modal matching is equal to the ratio of the subjective magnitude exponents for each mode.

Stevens (27) lists predicted and experimental exponents for cross-modality matches of the force applied to a handgrip *vs*. nine other continua based upon his work and the work of Stevens, *et al*. (37). These exponents are listed in Table III.

TABLE III

POWER FUNCTION EXPONENTS FOR CROSS-MODALITY COMPARISONS
OF FORCE OF HANDGRIP AND VARIOUS OTHER CONTINUA

Continuum	Predicted Exponent	Experimentally Obtained Exponent
Electric shock (60 cycle)	2.06	2.13
Temperature (warm)	0.94	0.96
Temperature (cold)	0.59	0.60
Heaviness of lifted weights	0.85	0.79
Pressure on palm of hand	0.65	0.67
Vibration (60 cycle)	0.56	0.56
Loudness (white noise)	0.35	0.41
Loudness (1000 c.p.s. tone)	0.35	0.35
Brightness (white light)	0.20	0.21

Stevens (44) also made cross-modal comparisons of loudness to vibration in which a low frequency noise was matched by a 60-c.p.s. vibration applied to the fingers. The experimental cross-modal exponent for vibration amplitude as a function of noise loudness was 0.6 (10 observers) and the predicted exponent from subjective magnitude estimations was 0.63. Experimental verification of predicted exponents was also obtained for cross-modal magnitude estimates of vibration amplitude applied to the finger tip vs. loudness (white noise), of electrical shock vs. loudness, and of electrical shock vs. vibration.

COMPARISON OF SCALING METHODS

Stevens and Mack (43) determined relationships between the subjective and physical magnitudes of a force on a handgrip utilizing three direct scaling methods and the method of category production. The scaling methods were:

(1) Ratio Production. The subject was asked to exert what he felt to be half and twice the magnitudes of given light, moderate, and heavy forces.

(2) Magnitude Production. The subject was asked to exert forces equal to given numbers based on a reference force of 10 arbitrary unit magnitude.

(3) Magnitude Estimation. The subject was required to assign numbers to given levels of force relative to a standard force of 10 arbitrary unit magnitude.

Data from the three scaling methods were plotted in log-log coordinates and could be fitted reasonably by straight lines. Average slopes for all the subjects tested were: 1.0 for data generated by the ratio method, 2.0 for data generated by the magnitude production method, and 1.6 to 1.7 for data generated by the method of magnitude estimation. Data for individual subjects also appeared linear in log-log coordinates; however, substantial variations in slopes were obtained.

Results from the category production method proved to be nonlinear when plotted against the results obtained from the ratio scale determined by the magnitude production method. Such a nonlinear relationship is noted by Stevens and Mack, as apparently characteristic of all prothetic continua. They refer to Stevens and Galanter (31) for a further discussion of this characteristic.

Stevens (27) states that the just noticeable difference scale, the category scale, and the apparent magnitude scale are linearly related on metathetic continua and nonlinearly on prothetic continua. On prothetic continua, the magnitude scale is a power function, the just noticeable difference scale tends to be logarithmic, while the category scale lies between the two curve forms. The nonlinear relation between the category scale and the magnitude scale for prothetic continua was also noted by Stevens (42) in an earlier publication. He termed this nonlinearity an invariant feature of prothetic continua.

The partitioning of a continuum into subjectively equal intervals as is done in applying the category scale is systematically biased by the nonuniformity of a person's sensitivity to differences as shown by Weber's Law [Stevens (24)]. From this reasoning, Stevens (24) concluded that the category scale is always nonlinearly related to the ratio scale for prothetic continua (curves toward the ratio scale axis).

Subjective Similarity

Ekman, *et al.* (46) studied the subjective similarity in two continua using gray cards of varying degrees of darkness and areas of circles. Subjects were asked to estimate the degree of similarity between two stimuli of a given continuum on a scale of zero to ten with zero denoting no similarity and ten denoting identity. The ratio scale of stimulus intensity determined by a ratio estimation method was compared to similarity estimates obtained from a relationship derived by Eisler and Ekman (47):

$$s_{ij} = \frac{R_i}{(R_i + R_j)/2} \qquad R_i \leq R_j ;$$

where R_i, R_j are the ratio scale values. Good agreement was obtained between the experimental and calculated similarities for both continua.

Ekman, et at. (46) account for the systematic deviation of the category scale from the ratio scale for prothetic continua with the assumption that in defining categories for a given range of stimuli the subject attempts to make successive intervals equally similar. This means that successive pairs of ratio-estimated values (subjective values) defining the interval of a category are equally similar, so that:

$$s_{12} = s_{23} = \ldots\ldots\ldots\ldots s_{(n-1)n}.$$

From the similarity equation, it can be seen that these category intervals correspond to equal successive ratios on the ratio scale:

$$R_1/R_2 = R_2/R_3 = \ldots\ldots\ldots R_{(n-1)}/R_n.$$

Since R is the subjective intensity of a stimulus, the value ΔR may be defined as a just noticeable increase in subjective intensity. (The values R and ΔR should not be confused with the components of the Weber function, $\Delta S/S$, where ΔS and S are stimulus intensities.) Assuming the similarity of a ratio scale value, R_i, of a stimulus to the ratio scale value of a stimulus increased a just noticeable amount, $(R_i + \Delta R)$, to be constant, it can be shown from the similarity equation that ΔR will increase with R. Ekman (48) has observed that this increase in ΔR with R is usually the case.

VIBROTACTILE SENSATIONS

Jones and Dawson (49) studied the static and dynamic components of a mechanical stimulus applied to the skin of human subjects. They varied stimulus area, force, order of reference variable, and presentation according to an experimental design. Their results supported the findings of electrophysiological studies on the individual nerves of frogs and rats that the dynamic results of tactile stimulation are of major importance to tactile discrimination.

Controlling Parameters in Vibrotactile Stimulation

The effect of contact pressure was shown by Verrillo (50), in agreement with the findings of Babkin, *et al.* (51), to result in a decrease in the threshold for vibrotactile stimuli applied to the finger. Contactor configuration was found to have no effect on threshold when the area of displacement was held constant, leading Verrillo to conclude that the area of displacement is a controlling parameter in vibrotactile stimulation. With contactor area as a parameter, Verrillo then plotted absolute threshold *vs*. the frequency of vibrotactile stimulation and obtained a family of U-shaped curves with a minimum threshold occurring at 250 c.p.s.

When frequency was used as a parameter in plots of vibrotactile threshold *vs*. the logarithm of contactor area, a series of parallel straight lines was obtained for areas greater than 0.02 $cm.^2$ and frequencies greater than 40 c.p.s. The fact that no changes in vibrotactile threshold occurred at lesser areas or lower frequencies suggested (to Verrillo) the possibility of two types of neural receptors, one sensitive to differences in frequency and stimulated area and the other insensitive to these differences. The family of lines for greater areas and higher frequencies had a slope of -3 db. per doubling of the contactor area indicating that the vibrotactile sensitivity is directly proportional to the stimulated area. Verrillo notes that the slope of -3 db. per doubling of the stimulated area is the same slope obtained by other workers for the threshold:area relationship for a patch of light falling on the retina, and the threshold:energy band width relationship for tones and noise at constant loudness.

Adaptation

When a stimulus is sustained at some given level, a decrease with time is generally observed in the output of the activated nerve fibers. The decrease is usually a decrease in the rate of discharge (firing rate) of the neuron and it is accompanied by a decrease in the magnitude of the sensory response. This is known as adaptation. Corso (23) defines adaptation as "the process by which the sensitivity of a sensory system is modified due to the continuous presentation of a stimulus at a constant level of intensity."

Hahn (52) studied the changes in threshold and the ability to match successive stimuli applied to a pair of contralateral fingers (similar fingers, opposite hands). Sixty c.p.s., 200 μm. (peak to peak) amplitude, adapting stimuli were applied to one of the fingers for durations of from 10 to 1500 sec. This was followed by a stimulus application of continuously increasing intensity to the contralateral finger to determine either the absolute threshold or an intensity subjectively equal to the adapting intensity. The absolute threshold was found to be more greatly affected (increased) by the adapting stimulus than the subjective magnitude matching ability. The ability to make subjective magnitude matches was also found to recover to the unadapted level more quickly than did the absolute threshold.

Discrimination Between Stimuli Applied at Two Points

In a study of pressure-sensitivity and two-point discrimination of the female breasts, Weinstein (53) found a greater pressure sensitivity on the left side of two homologous areas while the side having the poorer pressure sensitivity showed better two-point discrimination. He notes that this result is similar to the finding of Axelrod (54), in a study of the tactual sensitivities of blind and sighted children, that a finger with poorer two-point discrimination had superior pressure sensitivity.

Masking and Funneling

Masking refers to the suppression of a stimulus applied at some locus by the simultaneous or nearly simultaneous application of a stimulus of greater subjective intensity elsewhere on the body.

In a study of simultaneous two-point stimulation of the skin, Sherrick (55) refers to the hypothesis of von Békésy (56) called funneling. von Békésy defines funneling as a functional characteristic whereby a single suprathreshold stimulus produces an area of excitation surrounded by a refractory (insensitive) annulus such that, when two stimuli are presented, the areas may overlap and summate algebraically to produce a pattern of excitation. This funneling effect can account for sensitivity to stimuli that are in themselves very weak.

Sherrick performed four experiments dealing with masking effects. In the first, he demonstrated the masking effect for two simultaneous, single pulse, suprathreshold stimuli applied to different fingers by increasing the intensity of one until the awareness of the weaker stimulus disappeared. Masking was found to occur at intensity ratios of 2:1 to 8:1 depending upon the areas chosen for stimulation.

In the second experiment, the temporal aspects of masking were determined by setting various time intervals between the masker and the test signal. The masking effect diminished rapidly for time intervals greater than 40 msec.

The masking effect produced with simultaneous vibratory stimuli was studied in his third experiment. Masking frequencies of 50, 100, and 400 c.p.s. were used while the test signal frequencies were varied from 25 to 700 c.p.s. The masking effect was found to be greatest in the vicinity of 200 c.p.s., which is near the region of maximum vibrotactile sensitivity [shown previously by Verrillo (50)]. Sherrick explains the greater masking effect as resulting from the variation in growth of perceived intensities at different frequencies. He verified this by having subjects match the "loudness" of vibrotactile stimuli at various frequencies to a 100 c.p.s., 25 db. standard. Seventeen decibels were required at 30 c.p.s. and 600 c.p.s. to match the standard while 23 to 25 db. were required in the frequencies between 70 and 300 c.p.s.

Sherrick's fourth experiment compared the masking effects of a steady vs. a pulsed (on 0.35 sec., off 0.65 sec.) 150 c.p.s. masking stimulus as functions of masking signal intensity. The pulsed masker was found to increase in its masking effect at a greater rate than the steady masker with increasing signal intensity. This was attributed to adaptation of the steady masker as well as a deterioration of the von Békésy funneling effect.

Judgments of Successiveness

Hirsh and Sherrick (57) studied judgments of successiveness and simultaneity for two-point stimulation in three sense modalities: visual, auditory, and tactual. They found that in the tactual modality for 100 c.p.s., 1 msec. duration pulses applied to the fingertips, a 20-msec. interval was sufficient to judge successiveness between two stimuli. This temporal interval also appeared to hold for judgments of successiveness in the other two sense modalities and in cross-modality judgments.

JUDGMENTS OF ROUGHNESS AND SMOOTHNESS

Investigations of the ability to make subjective judgments of roughness and smoothness on individual and group-averaged bases have been made by Stevens and Harris (58) and Ekman, et al. (36).

Ekman, et al. compared subjective estimates of smoothness, roughness, and preference to the coefficients of friction determined for five grits of sandpaper, a specimen of paperboard, and a specimen of writing paper. They found that the measured coefficients of friction and the grits of the sandpaper were not proportional. Ten subjects made judgments by the three criteria with ratio estimates using free numbers (i.e., the comparative roughness of two specimens could be judged 3 to 1, 300 to 100, 1 to 0.33, etc.). Judgments of roughness and smoothness appeared to follow the power law and tended to be inversely related. The preference judgment variable was in direct proportion to the smoothness judgment. These conclusions held for individual data and the averaged data for the whole group (group-averaged); however, substantial variations were found in the power function exponents for individual data.

In the experiments conducted by Stevens and Harris, 12 grits of emery cloth were judged for roughness and smoothness by 20 subjects using two techniques of magnitude estimation and one of cross-modality matching. The grit values were used as the physical characterization of the properties of roughness and smoothness. In the first magnitude estimation technique, numerical ratings were given on the basis of a value of ten assigned to one of the intermediate samples; in the second technique, no value was assigned. The cross-modal matching was made by adjustment of the intensity of a 500 to 5000 c.p.s. noise band. Geometric means were used as the group-averaged magnitude estimations.

The mean values of roughness and smoothness estimates obtained in an assigned value experiment were found to have approximately linear relationships on a log-log plot vs. grit values with slopes of +1.4 and -1.4, respectively. An adaptation condition was noted whereby the standard (Value 10) presented a second time in the run was given a mean value of 6.43 on the roughness judgment and 13.03 on the smoothness judgment. The mean values of roughness and smoothness obtained with no assigned value fell closer to straight lines on the log-log plot with slopes of ± 1.5.

Previous work has shown that the power function exponent for subjective loudness (magnitude estimation) physically characterized by sound pressure measurements in decibels is 0.6 [Stevens (39)]. The predicted slope (log-log plot) for a cross-modal match subjective loudness vs. subjective roughness and smoothness is ± 2.5. This was experimentally verified when a slope of ± 2.6 was obtained. It is interesting to note that when the authors plotted sound pressure in decibels (a logarithmic function) as a function of grit (log scale) straight lines were obtained in accordance with the power law with the ± 2.6 slope described above.

Some inversion was noted in these experiments. Two particular samples that were consistently inverted were examined under a microscope. The particle sizes of the samples were found to concur in regard to grit values; however, the finer particles (higher grit) appeared to be less deeply imbedded in the adhesive matrix apparently producing a greater sensation of roughness than the more deeply imbedded coarser particles. Stevens and Harris concluded that the particle size, in this case, was not the only physical variable affecting the perception of roughness or smoothness.

PERCEPTION OF WARMTH AND COLD

Sensations of warmth and cold are not tactile sensations in the sense that they define the geometric properties of a surface or an object. Nevertheless, it is certainly conceivable that the sensations of warmth or cold, resulting from heat transfer between the skin and a surface, can be an important variable in the tactile judgment of a surface. For this reason a very limited review pertaining to the perception of warmth and cold is included in this report.

Kenshalo and Nafe (16) have reviewed the physiology of the receptor mechanisms proposed for the mediation of thermal sensations. Murray (59) has discussed the biophysics of nerve membranes in relation to thermal stimuli and Hensel (60) has described classes of neural receptor units responsive to thermal stimuli.

Two types of proposed receptor mechanisms are summarized by Kensalo and Nafe. The first assumes the existence of specialized nerve endings that respond to thermal stimuli. The second mechanism is based on the assumption that the skin is innervated only with endings that respond to mechanical stimulation. Sensations of warmth and cold, according to the assumption of the second mechanism, are obtained from the stimulation by movement of innervated smooth muscles of the cutaneous vascular system. It is well known that smooth muscles are responsive to temperature changes: they tend to relax when warmed and contract when cooled. The muscular contraction and expansion would provide the stimulation for the sensations of cold and warmth and the differences in the sensing processes (expansion for warmth and contraction for cold) would explain the subjective differences in sensitivity to warming and cooling of the skin.

Stevens and Stevens (61) studied the subjective magnitude of warmth and cold as functions of the temperature of aluminum cylinders applied to the inside forearm of 12 subjects. They found the subjective magnitude to be a power function of the stimulus intensity above or below a level they termed physiological zero. For warmth, physiological zero was found to be 305.7°K and for cold it was 304.2°K. The exponent for warmth was 1.6 and for cold an exponent of 1.0 was obtained resulting in two subjective magnitude equations, one for warmth and one for cold:

$$R_{warm} = k(T_w - 305.7)^{1.6}$$

$$R_{cold} = k(304.2 - T_c)^{1.0}$$

Cross-modal matches with a hand dynamometer having a subjective exponent of 1.7 (37) produced exponents of 0.96 and 0.60 for warmth and cold, respectively, in good agreement with the predicted exponents of 0.94 and 0.59.

Stevens and Stevens held their findings to be consistent with the view that the sensations of warmth and cold involve two different receptor mechanisms. They further suggested that the uneven distribution of warm and cold "spots" on the body are indicative that the operating characteristics for warmth and cold may vary from one part of the body to another.

TACTILE PERCEPTION

Gibson (62) in a discussion of man's sensibility to the spatial order and the geometry of things refers to Katz (63) who, in 1925, showed that the perception of a solid substance by touch required relative motion between the skin and the surface, lateral motion being more effective than perpendicular motion.

Gibson suggests that active touch consists of two components, one _extero-specific_, and the other, _propriospecific_. In the process of sensing external stimuli, one, through some sort of "feedback" system, senses not only the fact of an object in contact with the skin (exterospecific) but also an awareness that he is engaged in the act of touching leading to movements that tend to isolate and enhance specific stimuli (propriospecific). It is the latter component that is necessary for purposeful control of the touching action. The activity of "tactile scanning" in analogy to ocular scanning is a positive and purposeful activity necessary to obtain neural stimulation and seek stimuli that will characterize a surface or an object.

One would expect from the physiological evidence that movement is necessary for the stimulation of the neurons associated with the tactual sense. The psychophysical studies with vibratory stimuli further indicate an optimal rate of movement for maximum sensitivity. The propriospecific component of tactile scanning appears to be a definite action whereby _specific_ stimuli are perceived. The fact that the scanning involves motion and the stimuli obtained result from specific events (e.g., the stimulation from each bristle when the fingers are passed across a brush) leads to a question of whether one's perception is based upon the rate of stimulation with time, with distance, or with both distance and time.

The results of a study conducted by Wapner, _et al_. (_64_) suggest that scanning may be a temporal or time-oriented process. Wapner, _et al_. studied the effects of speed of movement on the perception of extent; i.e., distances traversed. They used a motor-driven carriage to move a blindfolded subject's finger over surfaces of variable lengths at two different speeds. They varied the distances traversed until a point of equality of perceived distances was obtained. It was determined that a distance must be made relatively long at a given speed to be subjectively equal to a distance traversed at a slower speed.

APPLICATION OF INFORMATION THEORY TO PSYCHOPHYSICS

INFORMATION TRANSMISSION IN THE NEURAL SYSTEM

There is a considerable difference between one's ability to discriminate between two stimuli of different magnitude on a given continuum and one's ability to make absolute discriminations along a continuum. The ability to discern just noticeable differences is limited by the sensitivity of the neural system much as the resolving power of an optical system limits its ability to discern two points in close proximity. By similar analogy, the depth of field of an optical system may be compared to the ability to make absolute discriminations — how many things can be distinguished along the range of a continuum.

An understanding of absolute discrimination is particularly important in a subjective evaluation where individuals are asked to assign numerical values to their sensory responses. For example, for any given stimulus level, there will be an uncertainty about the proper numerical value to be assigned to the response. The value may be precisely assigned but it will vary in repeated subjective evaluations. All of the values for a given stimulus will fall within a range having particular numerical limits. Only when the ranges of their subjective responses do not overlap are two stimuli absolutely discriminable. Within the limits of the range, however, one may be able to discriminate between two different stimuli if they are evaluated at the same time or in a manner permitting direct comparisons. Such direct comparisons may permit the ranking of two stimuli with respect to intensity even though they may not be absolutely discriminable. Thus, one's ability to make a heavier-than or lighter-than comparison is better than the ability to assign an absolutely discriminable value to a single weight.

The number of stimuli that can be distinguished along a single dimension (e.g., discrimination by taste of the "saltiness" of salt solutions of various concentrations) is limited by the patterns of signals that can be transmitted by the neuron and recognized by the brain. Physiological studies have shown that, while a receptor may be very sensitive to stimulation, the number of discrete responses to a range of stimulus intensities are few. This is a clue that one's ability to make absolute discriminations in one dimension may be rather narrow.

Consider the example of discrimination by taste of salt solutions of various concentrations. Although an individual may know that he is about to taste a salt solution, he is completely uncertain of its concentration prior to the act of tasting. The degree to which he can discern its concentration by the intensity of his gustatory (taste) response is equal to the degree that his uncertainty is decreased by the act of tasting. The amount of information obtained by his gustatory response equals the amount by which the subject's uncertainty is reduced.

INFORMATION THEORY

The amount of information transmitted in a system determined by a scale of uncertainty is the province of Information Theory.

Corso (65) devotes a chapter to information theory as it applies to sensory behavior. Quastler (66) presents the mathematical development of information theory for practical application with examples relating to communications and psychology. Other articles pertaining to information transmission in the nervous system are contained in a collection of papers edited by Rosenblith (67) from a 1959 symposium on principles of sensory communication.

The mathematical developments in information theory that provided the way for its application to systems is fairly recent, beginning with a paper by Shannon (68) in 1948 followed by a book by Shannon and Weaver (69) in 1949. Shannon argued that the importance of a message was its ability to change the state of uncertainty of its receiver. From this it was determined that the amount of information in a communication regarding some ensemble of possibilities is equal to the amount by which the uncertainty is reduced.

THE UNIT OF INFORMATION

The minimum condition for the transmission of information exists when there is a choice of two alternatives such as exists in the flipping of a coin. The maximum uncertainty for the condition of two alternatives occurs when the alternatives have equal probabilities. The condition of two equally probable alternatives is used to define the unit of information, termed a bit (contracted from the words "binary digit").

This corresponds to a binary system where the number of units of information transmitted in the choice of a particular outcome from an ensemble of equally probable outcomes for some event is equal to the minimum number of binary choices that will always produce the correct choice.

Two raised to the power of the number of binary units of information is equal to the number of elements in the ensemble. For example, an ensemble of eight equally probable elements numbered from one to eight is characterized by three bits of information — this is readily apparent from the fact that any element can be identified by three binary questions (Is it greater than four? No. Is it greater than two? Yes. Is it greater than three? No. It is three.).

THE UNCERTAINTY EQUATION AND SHANNON'S FORMULA

Expressed mathematically, the relationship between the number of equally distributed elements (n) in an ensemble and the number of binary questions (H) necessary to locate a single element is:

$$n = 2^H$$

This may be expressed logarithmically as:

$$H = \log_2 n$$

It has been shown by definition that the uncertainty (U) equals the information transmitted which, in turn, equals the number of binary questions (H) required for the ensemble, so that:

$$U = \log_2 n$$

Since the elements are equally distributed, the probability of a single element (p_i) equals 1/n and:

$$U = -\log_2 (p_i).$$

This is the uncertainty equation as it is derived by Corso; Tribus (70) demonstrates Shannon's proof which is more rigorous.

The information carried in a message, defined as the decrease in the uncertainty of the system, may be represented by:

$$I = U_1 - U_2 = -K \ln p_1/p_2.$$

Both Tribus and Corso (Tribus in the more rigorous manner) show how the uncertainty equation is extended to the condition where the elements of an ensemble of possible outcomes of an event have different probabilities. The resulting derivation is Shannon's Formula expressing the average information per element:

$$S = -K \sum_i p_i \log p_i .$$

It is apparent from this formula that the average information is equal to the sum of the weighted average uncertainties of the elements (i.e., $-p_i \ln p_i$) divided by the sum of the weights which is unity.

CALCULATION OF INFORMATION TRANSMISSION AND CHANNEL CAPACITY

Corso describes a method of computing the information transmission in a stimulus-response situation through the application of Shannon's formula to the absolute probability of each possible outcome of an ensemble. The computation requires a statistically sufficient number of test replications to obtain a distribution of responses (outcomes). The <u>absolute probability</u> of each response is determined by dividing the frequency of each response by the total number of responses. The products of the absolute probabilities and their logarithms are summed according to Shannon's formula to obtain the average uncertainty of all the responses which is equivalent to the information transmission.

As the number of possible responses is increased, the information transmission will increase to a maximum level. Further increases in the number of possible responses will have no effect in increasing the information transmission because the system has reached its maximum number of output responses. The system has reached its capacity; this leads to the definition of channel capacity. The <u>channel capacity</u> of a system is defined as the maximum amount of information that the system can transmit.

Referring to the earlier example of an experiment where the subject must identify salt solutions of various concentrations by taste, the experimenter may increase the number of solutions (possible responses) in a series of tests from two to ten and determine the information transmission for each set of possible responses. It is quite likely, on the basis of previous work (71), that as the number of solutions increases above three, there will be very little increase in the information transmitted obtaining a maximum transmission of about 1.7 bits.

CHANNEL CAPACITIES FOR VARIOUS PERCEPTUAL CONTINUA

Channel capacities determined for a number of psychophysical continua are cited by Corso (65); these are listed in Table IV.

Results of channel capacity studies such as those listed in Table IV led Corso to conclude that "man's ability to make absolute judgments is limited; the capacity for making unidimensional judgments is relatively small; and the differences in capacity among sensory attributes vary by a factor of about two-and-a-half to one."

The explanation of how, in the light of his limited channel capacity, man is able to recognize and discriminate among relatively large numbers of physical entities apparently lies in their characterization in more than one dimension. Most judgments are evidently made on a multidimensional rather than a unidimensional basis. Corso refers to the work of Eriksen and Hake (76) in which they studied the information transmission for stimulus judgments in three dimensions — the size, hue, and brightness of squares of paper. The information transmission obtained for simultaneous variations in all three dimensions was 4.11 bits, corresponding to 17.3 absolutely discriminable stimuli, while the information transmission for unidimensional variations was 3.08 bits for hue, 2.34 bits for brightness, and 2.84 bits for size.

It is noted for this and other work cited by Corso that, although the information transmission for multidimensional judgments is greater than the capacity in either dimension alone, it is less than would be obtained from the summation of the capacities of each of the component dimensions.

TABLE IV

CHANNEL CAPACITIES DETERMINED FOR VARIOUS CONTINUA

Continua	Information Transmission, bits	Absolutely Discriminable Stimuli	Reference
Positions of a pointer along a line	3.2	9.2	Hake and Garner (72)
Tones (100 to 8000 c.p.s.)	2.3	4.9	Pollack (73)
Loudness (1000 c.p.s., 15 to 110 db.)	2.1	4.3	Garner (74)
Color hues at constant intensity	3.6	12.2	Chapanis and Halsey (75)
Size (squares of paper)	2.84	7.2	Eriksen and Hake (76)
Brightness (squares of paper)	2.34	5.1	Eriksen and Hake (76)
Taste (salt and sucrose)	1.7	3.25	Beebe-Center, Rogers, and O'Connell (71)
Odor (amyl acetate, *n*-heptanal, *n*-heptane, phenylethyl alcohol)	1.9	3.7	Engen and Pfaffmann (77)
Cutaneous vibration — frequency	2.8	7.0	Geldard (78)
Cutaneous vibration — intensity	1.6	3.0	Geldard (78)
Duration of cutaneous stimulation	2.3	4.9	Geldard (78)

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THE INSTITUTE OF PAPER CHEMISTRY

L. E. Leporte

L. E. Leporte
Research Fellow
Division of Materials
Engineering & Processes