Taylor, M.M., Lederman, S.J., & Gibson, R.H. (1973). Tactual perception of texture. In Carterette, E., & Friedman, M. (Eds.), Handbook of perception Vol. III. New York: Academic Press.

Reprinted from:
HANDBOOK OF PERCEPTION, VOL. III

Chapter 12

TACTUAL PERCEPTION OF TEXTURE

*M. M. TAYLOR, S. J. LEDERMAN, AND R. H. GIBSON**

There is more to touch than meets the eye!

I. INTRODUCTION

Consider the richness of our tactual impressions—the exquisite smoothness of soapstone used in an Eskimo carving, the softness of a kitten's fur, the roughness of sandpaper, the warmth of a woolen blanket. Consider how a passionate kiss, a sharp slap, a gentle touch on the cheek can communicate a world of emotion. When we think of touch in this way the frequently made suggestions that vision is "more accurate than" (e.g., Cashdan, 1968; Lobb, 1965) or "dominates" (e.g., Rock & Victor, 1964) touch seems to miss the point. Suggestions of this kind derive from the notion that touch exists only to do what vision can do better. Touch is not simply an inferior form of vision, nor yet of hearing. Touch, as touch, has its own capabilities and limitations.

---

* DCIEM Research Paper No. 820.

Touch is old and intimate, and ill understood. Whether or not hearing evolved from a touch-like vibratory sense, the touch of which we are possessed is complex. A partial list of object properties readily determined by touch and not by vision or hearing might include temperature, hardness, roughness, elasticity, stickiness, slipperiness, rubberiness, the homogeneity of what lies under the surface, and so forth. Combinations of these properties are together perceived as texture, and texture, not form alone, is the prime province of touch. The perception of texture by touch is at least as complex as the perception of auditory qualities, and may well prove to be more so.

II. EXPERIMENTS RELATED TO TEXTURE PERCEPTION

A. Historical Direction of Touch Research

What does academic research tell us about touch as a means of determining the properties of the external world? Unfortunately, to date very little. With the two major exceptions of Katz (1925, 1930b) and Revesz (1950), most of the work before 15 years ago considered the sense of touch along with pressure, pain, and temperature under the more general rubric of cutaneous sensitivity. In most of these experiments, fine rigid hairs, the tips of hot or cold metal cylinders, mild electric shocks and sharp pins, to name a few of the popular stimulators, were used to prick, prod, poke, stroke, shock, or vibrate immobile (and sometimes heroic) observers. The tactile effects were brought about by an external agent applied, presumably, under the experimenter's control. The emphasis was upon the nature of the cutaneous sensations arising from the stimulation rather than on the observers' perceptions of the properties of the stimulus objects. Such forms of stimulation were used to determine two-point separation thresholds, and intensity thresholds for sensations such as pressure, pain, heat, cold, and chemical sensitivity over various parts of the outside and the inside (e.g., Boring, 1915) of the body. One major result of this work was finding that different spots on the body were differentially sensitive to the various stimuli. There exist warm- sensitive, cold-sensitive, pressure-sensitive spots, and so forth. Much of the work has been referenced by Boring (1942), and a more up-to-date annotated bibliography has been produced by Baker and Hall (1969). An interesting variant was the major study on tactual illusions conducted by Reiber (1903) which compared illusions produced tactually by patterns of skin stimulation with illusions produced visually, and found that in many cases the same illusions appeared.

More relevant to the consideration of texture perception are studies on the tactual vibration sense. The vibration sense has been compared to hearing (Katz, 1930b; von Békésy, 1959), which is a refreshing change from the usual comparison with vision. Moreover, the comparison with hearing can yield some insights into the functioning of the vibration sense through consideration of the more comprehensively studied hearing sense. Just as can hearing, the vibration sense can detect differences in frequency, or, more properly, in power spectrum, as well as in timing differences between two vibration sources. The capability of detecting timing differences apparently gives one the ability to externalize sources of vibration, as can be done routinely with sound sources. Katz (1930b), for example, claimed that if the two hands are placed on the edge of a table which is then tapped, the observer can usually tell where the table was tapped. Since the observers in Katz' study were deaf and blindfolded, the direction sensing was almost certainly performed by touch. In the same paper, Katz reported another experiment in which timed impulses were delivered to the two hands. His observers were able to discriminate intervals of as little as 140 μsec between pulses, a remarkably small interval. Although his methods were ingenious, his apparatus was crude, and the exact figure would probably not stand the test of more modern experimental verification.

Katz (1930b) further discussed several cases of deaf persons for whom the vibration sense had come to serve as a substitute for many of the functions of hearing. For example, he mentioned some who could understand speech by placing the hand on the speaker's body, and others who were able to appreciate music through vibrations felt in the chest or through the feet. Although for these people the vibration sense could serve as a form of surrogate hearing, the fact that it is not more widely used in this way suggests that the sonic world perceived through vibration must be far less rich than when it is processed through the normal hearing channels. However it has been suggested (e.g., Gibson, 1968) that a rich vibratory substitute for hearing might be provided by frequency division and time compression of the sound signal, to bring the auditory information down into a frequency range more suited to the vibratory sense without unduly slowing the sequence of auditory events.

The work on the vibration sense by Katz and von Békésy was, like the more psychophysical studies, based on stimuli applied to an observer who had no control over them. On the other hand, the perceptions studied, such as directionality, refer to external objects, not to skin sensations, and in this respect are more like studies of texture perception.

Some more recent studies have considered the experiences of an observer who brings about the contact under his own control. Most such experiments have used objects as stimuli, and have thus involved relatively large skin areas, in contrast to the small regions or points stimulated by the classical hairs, prods, and shocking coils. However, they have concentrated mainly on qualities of form such as size, shape, and orientation. Since these are primarily suited to vision, it is not surprising that many of the experiments compared the development and relative accuracy of visual and tactual form perception. Similarly neither is the general result surprising that the visual modality proves superior in these tasks (e.g., Cashdan, 1968; Lobb, 1965; Rock & Victor, 1964).

B. Active and Passive Touch

We have followed a train of thought which develops the expansion of the touching experience from brief punctate stimuli of well-specified kinds, through the involvement of larger skin areas for greater lengths of time, to the point where touching requires the active participation of the observer using his muscles and whatever features of his skin senses he cares to bring to bear. This increasing involvement of the observer seems to increase the "object nature" of the percept. We must pause here to give greater consideration to what seems a central feature of the touching process as it is used in everyday life.

There are two very different modes of "touching" in the cited experiments. In one situation, the immobile observer is stimulated by an external agent over which he has no control, while in the other he can actively explore the stimulus object as he chooses. Few writers before Gibson (1962), other than Katz (1925) and Revesz (1950), even distinguished the existence of these two modes. In spite of this history of neglect, Gibson observed very great differences in percept depending on whether a given stimulation was brought about by the observer or by the experimenter. The former leads to concentration on the properties of the object, while the latter gives rise to labile skin sensations. These skin sensations do not seem to exist if the object-perception occurs. Gibson refers to the classical technique as "passive touch": "being touched by a moving object," which he contrasts with "active (haptic) touch": "the touching of a stationary object." He provides several examples of the differences between active and passive touch. Active touch exhibits object-constancy, but passive touch does not. By active touch one feels stable corners and edges, solid surfaces, and so forth, while similar patterns of skin deformation caused by the experimenter give rise to rapidly changing sensations with no stable referent. An object felt actively with two fingers feels like one object, while felt passively it feels like two touches. With active touch, an increase in the amount of skin deformation with increased force is felt as object rigidity, whereas with passive touch it is felt as increasing pressure on the skin.

In a related experiment, Katori and Natori (1967) compared the reproductions of simple geometric forms seen by subjects with the reproductions they made after touching the form with various amounts of experimenter control. If the experimenter moved the original form under a finger held stationary, or if the subject moved a finger along the lines of the form in a continuous manner, the reproduction tended to be made with a single line. The active condition was more accurate than the passive. If, however, the touching was done freely by the subject, using as many fingers as he liked in any manner at all, then the reproductions tended to be done with several individual strokes, as was the case when the originals were seen. Free active touch appeared to provide percepts much more akin to those of vision than did the controlled active or the passive touch conditions.

It is possible that the extreme nature of the differences reported by J. J. Gibson between active and passive touch was due in part to the instructions given to his subjects. They were simply asked to describe what they felt, and if there were a bias toward the sort of descriptions given, this bias would be self-reinforcing. It would also be subject to the sort of unconscious experimenter biases noted by Rosenthal and Rosnow (1969). Judging from experiments as informal as Gibson's, we believe that both active and passive touch can lead to either skin-centered or object-centered perception, although the tendency is definitely to feel in the manner described by Gibson. All the same, the results of Katori and Natori (1967) also indicate real differences in perception between active and passive touch. We discuss the perceptual qualities of active and passive touch from a different point of view in Section III of this chapter.

C. Texture Perception

Texture is as much the essence of touching as form is of seeing. However, few studies have dealt with the nature of texture perception as such. Katz (1925) seems to have been one of the first to discuss the question in any detail; he considered the effects of different manners of touching and of different components of the touching process, such as hand rate and finger force. His classic monograph has yet to be translated into English, although highlights have been reviewed by Zigler (1926) and Krueger (1970).

Passive touch was used at about the same time in two other studies following the introspective tradition. Meenes and Zigler (1923) investigated the perceived roughness of objects, and Sullivan (1927) studied the perception of hardness and softness. Meenes and Zigler, in particular, provided some interesting results on the perception of cutaneous stimulation by surfaces of different roughness, on the value of relative motion between hand

and object, and on the effect of varying the force of the object against the skin. In addition, they suggested that there might be a physiological difference between processes responsible for "roughness" and those giving "smoothness." Sullivan discussed the differences in the perceptions of hardness and softness and the effects on these percepts of varying the object temperature. A strong perception of hardness required a cool object.

Binns (e.g., 1937) conducted a series of experiments in the textile industry. Using both trained and naive judges, he examined visual and tactual judgments of the fineness, softness, and value of wools. His finding was that experience improved visual judgments, but had little effect on tactual skill. Gliner (1967), on the other hand, determined discrimination thresholds for shape and texture using kindergarten and third-grade children, and found the older children to be better at texture discrimination. Texture discrimination seems to improve with age but not with training.

Using magnitude estimation techniques, Stevens and Harris (1962) found that perceived roughness and smoothness were power functions of the grit number of sandpaper; the two exponents were equal and opposite. They concluded that smoothness and roughness were opposite poles of the same continuum, in apparent disagreement with Meenes and Zigler (1923). Ekman, Hosman, and Lindstrom (1965) found perceived roughness to be a power function of the coefficient of friction between the fingers and various paper and sandpaper surfaces. They found great individual differences in the values of the exponent.

Yoshida (1968a,b) conducted an ambitious series of experiments designed to discover the principal dimensions of tactual impression. He used stimulus samples differing in size, shape, and texture. His factor analysis showed that 70% of the variance could be accounted for by three factors, which he designated (*1*) heaviness-coldness, (*2*) wetness-smoothness, and (*3*) hardness.

D. Roughness and the Vibration Sense

We have recently been interested in surface roughness as one important aspect of texture. The vibration sense is closely related, since roughness is perceived in a surface only when the interaction between skin and surface sets up a vibration in the skin. Passively sensed fingertip vibration is indistinguishable from the vibration induced by stroking a rough surface except that it occurs in the absence of relative motion between skin and surface, and without sideways deformation of the fingertip.

Surface roughness is explored by moving the fingers across the surface, and sensing the various interactions that then occur. This process is considered in more detail in Section III. One of the more prominent interactions is the varying skin deformation which sets up the physical vibration. Depending on the speed and force of hand movement and on the spacing and size of surface prominences, the vibration will vary in dominant frequency and in overall energy. Variations in the perception of roughness may depend on the overall energy of the vibration modulated by the sensitivity characteristic of the sensors (as loudness depends on the energy of the sound and on the spectral sensitivity of the ear) or it may depend on the vibratory frequency. Since this reflects on the studies performed and on their interpretation, a disagreement should be stated here. MMT and SJL feel that the primary component of the roughness percept is the vibratory energy transmitted to the fingertip at frequencies to which the finger is sensitive. Frequency has the effect of changing the quality of the roughness, but otherwise has no effect except insofar as the receptors are not equally sensitive to all frequencies. RHG feels that frequency is the primary contributor to the roughness sensation and that variations in frequency should be matched by concomitant variations in perceived roughness; overall energy also modulates the perceived roughness. With the data currently available, either view is tenable.

If vibratory frequency is important in the perception of roughness, studies of vibratory frequency discrimination are important, even those done using passive touch, since they should indicate the limits bounding the degree to which tactile vibration could serve as a cue to surface texture. One may presume that frequency sensitivity is at least as good in passive studies as in active, since in the active condition many information sources are competing for the observer's attention whereas in the passive situation the frequency to be discriminated can be given his whole attention.

Goff (1967) studied vibratory frequency discrimination at the fingertip, using bands of vibrotactile stimuli matched beforehand in apparent intensity. The frequency JND (just noticeable difference) ratio $\Delta f/f$ was about 0.2 for frequencies below about 100 Hz at 35 dB SL (Sensation Level). Above 100 Hz, the value of the JND rose sharply, until it was nearly doubled at 200 Hz, showing a markedly reduced sensitivity to frequency differences. At a lower vibratory intensity, 20 dB SL, the JND was larger. If judgments of roughness depend on sensory factors which determine vibratory frequency discrimination, then when frequencies produced by rapid hand motions (coupled with finely spaced surface crests) are in a region showing poor frequency discrimination, the related roughness judgments might show a sharp increase in variability or might display a shift in the shape of the function relating roughness to surface character.

In an experiment to determine the ability to recognize letters presented by a moving band of small air jets striking the palm, accuracies of above 50% were found after about 900 trials for strings of letters moving at 30 five-letter groups per minute (Rogers, 1970). These rates were obtained with three relatively inexperienced subjects, and they held true only for high stimulator frequencies of 160 Hz; when the pulse repetition rates were reduced to 20 or 40 Hz, reading rates fell by one-third. This reduction seems at first puzzling, when one considers recent neurophysiological evidence that there are at least two separate touch receptor systems in the hairless skin of man (cf. Lindblom, 1970); there is a low (below 40 Hz) frequency system with small receptive fields and relatively low sensitivity, and a high frequency (peaking around 250 Hz) system with wide receptive fields. On this basis, one might expect that the lower frequency pulses would stimulate the system with the small receptive fields, thus giving higher acuity and better ability to read the letters. But there are at least two possible reasons why this reasoning might be false. One is that as in the retinal periphery, the large high-frequency receptive fields might be suited to perception of moving stimuli, and thus be well adapted to the determination of the letter patterns being pulsed at high rates while moving across the skin. The second argument is that the letters moved appreciably between pulses at the 40 Hz pulse rate, thus giving an impression akin to stroboscopic lighting. Writing is notoriously hard to read if it moves in a stroboscopic manner, and a similar effect might be occurring with the letters. In any event, the vibration sensitivity of the fingertip is shown by this experiment to be more complex than might have been supposed from simple frequency discrimination studies (e.g., Goff, 1967).

Vibrotactile stimulation studies lead naturally to a consideration of Braille reading rates as a possible index of the information carrying capacity of the vibration sense. Braille patterns consist of rectangular arrays of raised dots which characteristically represent one letter. Braille transmission rates therefore refer not to a single skin region, but to sets of independently stimulated regions, and should be more directly relevant to texture perception than are the frequency discrimination data. However, this seems not to be the case, since studies of Braille capacity (e.g., Nolan & Kederis, 1969) report upper limits for symbol transmission speed of the same order of magnitude as those found for visual reception of letters presented serially (Taenzer, 1970) and for auditory "spelled speech" (Metfessel, 1963). Using either modality, an appropriately trained observer can receive at a rate of about 10 characters/second. Just as Sperling, Budiansky, Spivak, and Johnson (1971) have shown that this is not a visual transmission channel limit, so it seems likely not to represent a tactual transmission channel limit. Rather, it probably is a limit in the more central processing to do with identification of letters as such.

Taenzer (1970) compared visual reading in a "moving window" study with a similar tactile study by Bliss and Linville (1966). Letters were displayed moving across an array of neon lights (Taenzer) or (Bliss and Linville) an array of tactual vibrators. In each condition comprehension was excellent at up to 50 words/minute, provided that the size of the window was sufficient to permit each point of the moving display to be available for at least 150 msec in its transit across the aperture. This result again suggests that the limit is not in the sensory channel but in the more central processing. It does, however, place a lower bound of about 25 bit/sec on the capacity of the vibration channel. Although this situation gives a lower bound which is probably an order of magnitude or more below the full capacity of the channel, it does show that the vibration channel has a respectable capacity, and is capable of playing its postulated role (see Section III) in the perception of texture.

E. Current Research on Roughness Perception

Lederman and Taylor (1972) controlled the finger force applied to the surface, and showed that the perceived roughness of metal plates with parallel grooves increased with groove width and with the fingertip force applied, but decreased slightly with increases in the width of the flat top (the "land") between the grooves. The slope of the magnitude estimation function also increased with increasing finger force, implying that roughness contrast is greater with greater finger force. In a subsequent experiment, the observer was free to use whatever force he wished, and the perceived roughness was found to be appropriate for the force chosen. Perceived roughness depends strongly on the width of the grooves in these plates, and weakly in the other direction on the width of the lands. It therefore does not depend directly on the frequency of the vibrations induced in the fingertips by the successive grooves. On the other hand, the vibration energy might well increase with increases in the applied fingertip force.

Continuing this series of experiments, Lederman (1973) found that rate of hand motion had a consistent effect on perceived roughness which was negligible relative to the groove width and finger force effects. As groove width was held constant while rate varied, the experiment provided additional support for the idea that vibratory frequency does not directly affect perceived roughness.

In another study, the coefficient of friction between skin and surface material was found to have no influence whatsoever on perceived roughness. The seeming contradiction between this result and that of Ekman, Hosman and Lindstrom (1965) may be explained by the distinction between apparent friction due to gross features of the surface, and friction due to the quality of the material. Ekman, Hosman, and Lindstrom (1965) probably measured the former, while Lederman (1973) measured the latter. This problem is discussed further in Lederman (1973).

R. H. Gibson (unpublished study) has found that observers who freely stroke a grooved surface rapidly press considerably harder than do those who stroke more slowly. Those subjects who press harder show lower slopes of the magnitude estimation function, in apparent contradiction with Lederman and Taylor's result. RHG suggests that the contradiction may be explained by the fact that vibrotactile frequency discrimination gets worse with increasing vibration frequency above 50 Hz, but is improved with greater stimulus intensity (Goff, 1967). Therefore, an observer moving his fingers rapidly over a rippled surface (thus producing higher frequencies) may, by pressing harder, improve his vibrotactile frequency discrimination. On the other hand, SJL and MMT suggest that possibly those of Gibson's subjects who were less sensitive to texture variation might have pressed harder to provide some compensation for their deficiency. They would then tend to move their hands faster, to prevent their fingers sticking on the surface, which tends to happen when large force and low speed are combined.

R. H. Gibson and M. Cinanni, in a study still in progress, used a signal detection procedure with category ratings to determine the ability to discriminate ruled tactile grids, and calculated the resulting vibration frequencies produced at the fingertip. Preliminary findings were that the implied frequency JND values fell close to those reported by Goff (1967) for passive fingertip vibration frequencies, suggesting that there may be a common mode of operation or vibrotactile frequency discrimination and for this aspect of texture discrimination.

Finally, R. H. Gibson and A. Sztepa (unpublished study) have found that the exponent of a perceived roughness function is not influenced by the temperature (within 10°C of room temperature) of the textured surface. With a warm hand on a warm textured surface, the whole function was the same as that found with stimuli and hands at normal room temperatures. However, when the stimuli and hands were cooled 10°C, the function was substantially lowered with no change in exponent. Cold textured surfaces feel smoother than neutral or warm ones. These parametric and rather psychophysical studies of roughness are a far cry from the studies of texture perception that need to be done. But they are a necessary prologue. It is remarkable how little is known about perception by touch after more than a century of experimental sensory psychology. The reason may lie partly in the extreme difficulty of stimulus construction, but hopefully, modern technology may put control of complex stimuli within our reach. We still disagree over a matter as fundamental as roughness. Perhaps more progress will be made when touch is viewed as a sense with its own qualities. The model sketched in Section III is intended as a framework for such a viewpoint.

III. TOWARD A CONCEPTUAL MODEL OF TEXTURE PERCEPTION

A. Introduction

Among the means by which perception achieves its goal of permitting one to act effectively is the construction in memory of a model of the world. The structure of the world attained through perception provides a basis for projecting the possibilities of future action. For one's current purposes some facts about the world are important, some irrelevant. A well-adapted perceiving mechanism must take this into account, and husband its resources by working only on the parts of the world that are probably relevant. The different senses give rise to one world, rather than several, because any action may cause changes in any of the world's varied aspects. There is not a "World of Colour" and a "World of Touch" as the titles of Katz' monographs would have it (Katz, 1925, 1930a); there is a World of Perception.

Usual perceptual experience does not come from the stimulation of single receptors, or from the simple stimulus patterns so much used by those of us who call ourselves psychophysicists. It comes from rich and complex patterns of stimulation of various senses, from coordinated variation in the outputs of logically independent receptors, from information deliberately sought and from information fortuitously acquired, from patterns of motion kinesthetically sensed combined with patterns of motion visually, auditorily, and tactually sensed. Information arising from a single receptor, unsupported by a relevant pattern of information from other receptors, is usually and properly discarded as noise. It leads to no perceptual experience. Only coordination among receptors in the retina permits us to sense the movement of shapes in the visual field. Only coordination among taste, smell, touch, vision, and kinesthesis permits us to savour a fine wine or reject a poor steak.

Although it is perhaps not obvious, the tactual perception of texture provides a prime example of the coordinated action of independent sensory systems. We shall contend not only that several disparate skin senses are involved, but also that the kinesthetic and proprioceptive systems which yield information about body motion and static bodily states, as well as hearing and vision, are deeply involved in the perception of texture obtained by touching a surface. The single "tactile" percept does not depend on the unaided operation of any one sensory system, but results from a widespread pattern of coordinated activities. We shall further contend that it is this "multimodal" nature of touching which gives touch the feeling of providing substance and reality to the perceived world.

We do not know of any experimental work relevant to this view of texture perception; we must therefore present the following "cybernetic" model unsupported except by its own plausibility and internal coherence.

B. The Sensations and Modes of Touching

Introspect, modern psychologist though you may be. Try a small experiment and feel the texture of a surface near you. What did you do? Probably you first moved your hand until your fingertips made a light contact with the surface. Most likely, you were guided by vision until you sensed tactually the fact that your fingertips had arrived at the surface. Next, using only a light force on the surface, you probably began a smooth and fairly slow back-and-forth motion over the surface, looking at your fingers and listening, perhaps without being aware of it, to the noises your fingers made on the surface. This initial motion taught you a lot about the surface, perhaps enough to satisfy you. But if you wanted to learn more about the object, you would have had to change how you were touching it. What you did next depended on what you had already learned and what you wanted to find out.

Touch can tell you about temperature, and thus about thermal conductivity. If you are feeling a bright silvery surface and it feels cold for a while after you start to touch it, you probably feel "metal" rather than "hard, cold." But if a visually identical surface feels cold and warms up rapidly under your touch, you feel "plastic." To tell the difference, you must let your finger rest on one spot long enough to let you judge the rate of temperature change. On the other hand, Katz (1930b) has shown that one can tell differences among a great variety of materials with a single tap lasting no more than 10 msec. Since the experiments were conducted with sound cues excluded, this ability probably depends, as Katz suggested, on the ability to sense the vibrations set up in the material by the tap. Another mode of touching is needed if you want to determine the substructure under a deformable surface. Experiencing "furry" or "leather," for example, depends on surfaces and on depths; you will probably use a variety of pressures, gliding rates and other manipulations to determine the quality of a leather coat.

What sensations are available to you as you glide your fingers over the surface? You can see where your hand is in relation to visual patterns on the surface, even if the object is itself moving. You can feel through kinesthesis how your hand moves and what forces you are applying to the object. The forces include the lateral force due to friction between fingertip and surface. As you press and move, your fingertip is grossly squashed inwards and sideways, and deep sensors can detect those deformations, which depend on the forces and on the resilience of the object. In addition to the gross deformations, your skin partially conforms to minor irregularities of the surface, and changes in these minor deformations of the skin as you move over the surface can be sensed as vibration. Sharper irregularities passing under the fingerprint patterns may snag the skin, causing sharp impulse sensations. Not only can you feel the vibrations and snags, but also you can often hear them and the resonances they induce in the object you are feeling. The sound may be an important constituent of the total percept, especially the resonance which may help in determining the mechanical qualities of the whole object. Another important sensation arises from the heat flow between the fingers and the object, from which you learn something about the temperature and the physical properties of the object.

There is also an additional important but often ignored "sensation." This is the feeling that you have the freedom to choose where on the surface you want to touch. This exploratory freedom permits you to generalize the sensations derived from one part of the surface to any other part that you might as well have sampled. If you have no reason to suppose that the untouched parts of the surface are characteristically different from the part that you actually touched, you can and probably will generalize, thereby attaining the perception of a complete object existing independently of yourself. If you do not have this freedom of choice as to where you can touch, you have no rational grounds for assuming the object to exist beyond the points actually touched or beyond the region within which you do have apparent freedom to explore. You may perceive a complete object, if you have other grounds to support generalization, but you will be more likely to refer the sensations to your own skin rather than to an external object. Gibson (1962) made this point very clearly, although without using the sampling rationale, when comparing the sensations induced by passive and active touching of the same object. He indicated for several different "sensory" experiences that, "In all cases the sensory impression can be aroused by an experimenter (bringing an object into contact with the observer's hand), but when the observer himself brings them about they seem to disappear." With the active participation of the observer, stable objects in the real world are perceived, but when the experimenter controls the touching process, the perception is of labile sensations referred to the skin. The difference may well be attributed to the observer's impression of freedom of choice about where to touch.

Although it does not lead to a "sensation," the purposive nature of the active touching process is important when the observer is free to choose what and how to touch. It permits the observer to use information gathered at an early stage to direct his search for further relevant information. What you feel in the early stages modifies the manner of later touching. Formally the touch process in the real world is a feedback process. This formal statement is fundamentally important to an understanding of touch.

C. A Model of Texture Perception

1. THE IDEA OF THE TRANSDUCER FUNCTION

A transducer is a device which changes energy in one form to energy in another form. A loudspeaker is a transducer which takes electrical energy as its input and changes it into sound and heat. We usually ignore the heat, but it is as much a part of the loudspeaker's output as is the sound. A transducer in general can be described as a black box with inputs and outputs, which are connected by a transducer function as in Fig. 1(a). The transducer function in the figure is labeled "X". X is more correctly called an "operator" than a "function," since it operates on the inputs to provide the outputs. The term "operator," however, is easily confused with the human operator of a machine, so that we will continue to use the term "transducer function" to describe the input–output relationships of the transducer.

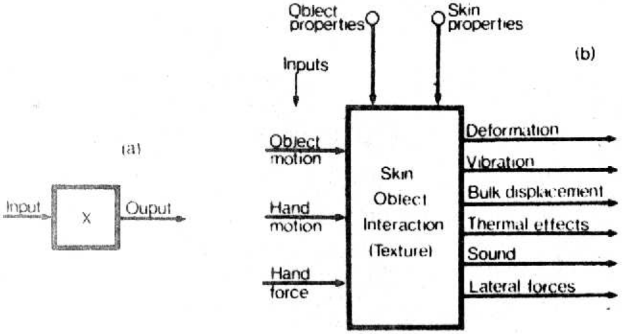

FIG. 1. Transducers. (a) A general block diagram of a transducer; the transducer operator (function) "X" transforms input energy into output energy, which may be of an entirely different form. (b) The transducer describing the interaction between the fingertip and an object being touched. The transducer function is determined by the properties of the object and of the skin, which may be thought of as controlling the transducer. The inputs are the relative motions of object and skin and the force between the hand and the object; the outputs are of several different kinds: skin deformation, variation in which leads to vibration, lateral (friction) and vertical (resistance) forces, bulk deformation of the fingertip, thermal effects, and sound.

Consider the interaction between an object surface and the skin as a transducer. The transducer has the large low bandwidth movements of the hand as input, while its outputs are the various vibrations, sounds, and heat flows which can be sensed [Fig. 1(b)]. The transducer function that relates the input to the output is determined by the surface texture coupled with the mechanical state of the skin. Providing that the skin state is known, it would not be far wrong to say that the transducer function *is* the texture. The *perception* of texture is the *analysis* of the transducer function. The function contains all the information which can be derived from the mobile contact between hand and surface.

Given the input to a transducer, the properties of the transducer function determine the output. Hence, if the input and the output are known, the tranducer function can, in principle, be found. However, with a transducer as complex as texture, defined by the skin–surface interaction, there are many different simple transducer functions, which correspond to the different components of texture, such as roughness, hardness, and so forth. No single type of input can tap all components of such a complex transducer function, no matter how precisely it and its corresponding output are known. No one manner of touching permits the simultaneous determination of thermal conductivity and surface roughness, for example. Only by varying the input over its entire useful range can the complete transducer function be determined. Only by using all different modes of touching can the full richness of the feel of an object be found.

Notice that the transducer function is determined by the properties of the skin as well as those of the object, and that unexpected properties of the skin will thus affect the perceived texture of the object. If your skin is dry, objects feel different. If they are unfamiliar, you may not even notice that your skin is dry. But if the object is familiar, the difference is immediately attributed to the skin condition, not to the object's texture. More formally stated, the transducer function is a joint function of object and skin properties. Only if one is known can the other be uniquely recovered by the analysis of the transducer function.

2. INFORMATION AND CONTROL FLOW

The simple transducer function of Fig. 1(b) represents only a small part of the texture perception system. As we pointed out above, feedback is an important characteristic of the total system, both in the small scale of controlling the motions and in the larger sense implied by the purposive nature of active touch.

At least three basic behavioral feedback loops are probably important (Fig. 2). The major one is an overall control loop (i) whose function is to carry out the policy decision to look for a certain feature of the texture, such

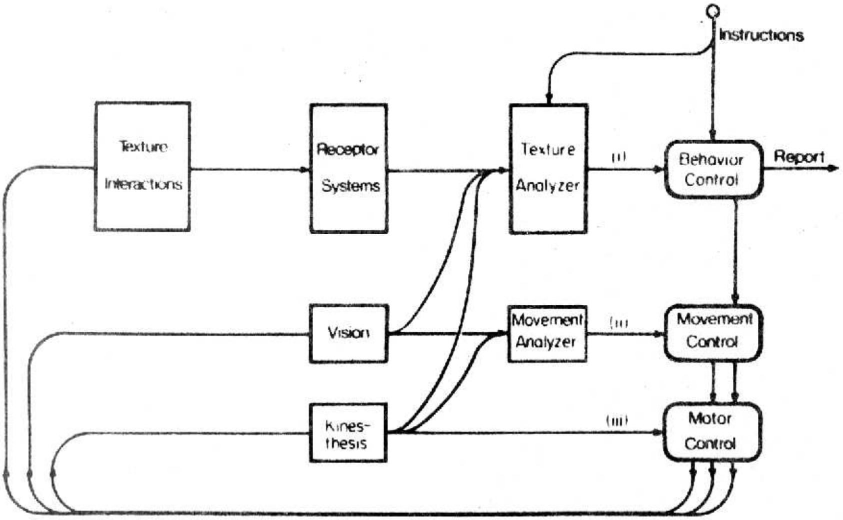

FIG. 2. The three feedback loops involved in the control and information flow. Control flows from the instructions to the Behavior Control element down to the Movement Control element and to the Motor Control element which controls the individual muscles. Information about the actual movements accomplished is fed back through kinesthesis to the Motor Control element. Information about the relative movement patterns of hand and object is fed via vision and kinesthesis to a Movement Analyzer which combines their information and feeds back to the Movement Control the results of its commands. The relative motions and forces between hand and object cause the various interactions which can be sensed, analyzed as texture, and so passed to the Behavior Control element to complete the major feedback loop. If the texture percept satisfies the requirements of the original instructions, a response is output.

as roughness or elasticity. The original intention to touch something, to investigate an aspect of texture such as roughness, is taken to be a command to the major loop control element, labeled Behavior Control. The function of this module is to select a touching strategy adequate for the job. In the case of roughness, the appropriate mode of touching involves a light sweeping motion of the fingertips back and forth over the surface. Probing for subsurface objects in an elastic medium, such as a pea under a foam mattress, requires an entirely different mode of touching.

The secondary loop (ii) has the function of executing the individual motions required to implement the desired touching mode. Its commands are produced by the element labeled Movement Control. This element breaks down the general command from the Behavior Control into a sequence of specific motion commands, which go to the control element of the innermost loop (iii) labeled Motor Control. This is the familiar kinesthetic control loop, which breaks down the individual movement commands into muscle commands and monitors the effects to ensure that the movement command is properly executed.

It is interesting to note that Leo and Vitelli (1971) found that "On the basis of literature review and the experience of our group. . . [a] hierarchical structure seems to be the best for control purposes: in this structure three levels are distinguished: dynamic control [our iii] . . . algorithmic control [our ii] . . . strategic control [our i] . . . ." Leo and Vitelli's system, developed for an entirely different purpose (the construction of a six-legged walking machine) seems to be almost identical to the one we propose for the control of touch activities.

At this point the fingers are moving across the surface, and all the interactions that form the transducer function of Fig. 1(b) are happening. We now consider the flow of information rather than control. The transducer outputs are available as inputs to the skin senses, to the ear, and to the kinesthetic sense. Analysis of the transducer function requires information about the transducer's input as well as its output. The relative motions between hand and object can be sensed visually and perhaps kinesthetically, the hand forces kinesthetically. All the sensory inputs from the transducer input and output are available to the large and largely unknown module labeled Texture Analyzer. This module also has as input the information from the Behavior Control module concerning the intent of the motion. It would be pointless for the Texture Analyzer to look for structures in depth if the Behavior Control wants roughness information. We cannot suggest any reasonable structure for the Texture Analyzer at this point, other than to suggest that the problems it faces are very like those facing other pattern recognition devices in the perceptual system and that its solutions to those problems are probably "ordinary" pattern recognition solutions.

As its output, the Texture Analyzer provides a "texture evaluation" (for lack of a better term). If this evaluation satisfies the requirements of the command to the Behavior Control module, then the touching process has been completed. But if the information so far gained is insufficient to satisfy the command, then the movement strategy must be continued or modified. Hence the informational link between the Texture Analyzer and the Behavior Control element completes the major strategic feedback loop. The entire pattern of control and information flow is shown in Fig. 3.

3. DISCUSSION OF THE MODEL

Apart from the interrelations postulated for the various control elements in the feedback loops, which depend more on a theory of motor control than on texture theory, the other paths of information and control flow in

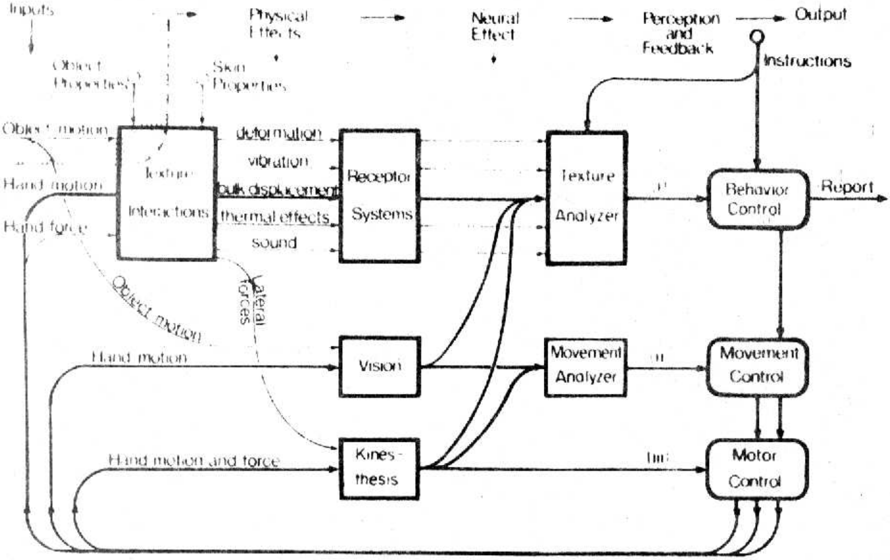

FIG. 3. The detailed structure of the model, including the various different physical effects produced by the skin–surface interaction transducer. The main feedback paths from Fig. 2 are shown with heavy lines. As in Fig. 2, information from efferent systems is ignored for the sake of simplicity.

Fig. 3 seem to be a necessary part of any model of texture perception. The benefits to be obtained from this attempt to systematize the patterns of information flow probably derive largely from the questions that arise from considerations of the importance of the different pathways. The model currently has as its main function the direction of experiments toward functional aspects of the touching process rather than toward the commonly studied psychophysical parameters. Parametric studies are clearly required in the definition of what happens when we touch, but, for the most part, they are not the studies that have been done as yet.

To determine the importance of the various pathways postulated among the different modules of the texture perception system, experiments should be performed in which the different pathways are blocked or provided with irrelevant information. If the logically independent sources of information about the transducer function, for example, are made to give incompatible results, the relative weightings applied to the channels in different circumstances might be derived. It is perhaps possible, for example, to mask the vibration channel by introducing an extraneous vibration into the hand or into the object being touched. As another example, the sounds of touching may be unimportant as a general rule or may perhaps be used to determine features different from those obtained from the vibration sense. The implications of this question can be tested by masking or falsifying the auditory channel. Sounds appropriate to touching some other object could be deliberately introduced along with vibration to mask the vibration channel, to determine whether the feel of the false object could be induced by its sound. So far as we know, there has been no formal research along these lines.

Another indicator of the relative importance of the different pathways is their capacity as information channels. Channel capacity depends on both the speed and the precision with which a channel responds. Again we know little about the capacities of the channels implicated in texture perception. The studies cited in Section II on discrimination of vibratory frequency and on Braille reading rates give a little information about the vibration channel, but the other tactual channel capacities remain unstudied.

The rate at which information can be obtained about the texture transducer function depends not only on the channel capacities of the output channels, but also on the precision with which the input is known. This means that the positions, rates, and forces of hand motion must be well specified by kinesthetic or visual information. The analysis of the transducer function can be only as precise as input and output allow. Timing precision is an important aspect of the stability of the percept, as, for example, in the discrimination of the difference between a rolling grain of sand and a fixed piece of grit on a surface. The required timing precision may possibly be more readily attained with fast hand motions, but these same fast motions induce faster sequences of sensory events in the output of the transducer function, thus more nearly overloading the output channels. The mating of hand motion to channel load for different surfaces and different purposes is one function of the feedback systems, expecially the Movement Control.

We are conducting a series of experiments interfering with the motor control aspect of the touching process. The attempt is to do for the control processes what the experiments suggested above would do for the information channels. In the Lederman and Taylor study (1972), the subject was not permitted to vary his touching force. In other experiments, touching speed has been controlled (e.g., R. H. Gibson, unpublished study; Lederman, 1973), and in yet others, the subject's hand has been directly moved by the experimenter. While these experiments do not change the information flow, they do have effects, not all yet fully analyzed, on the perception of roughness. Other components of texture have not yet been considered in these studies.

Studies using interference with the control flow to manipulate the texture percept attack the active–passive dichotomy in a way which clarifies the meanings of the two terms. Active and passive are not simply two opposed possibilities. Rather, they refer to two extremes of a continuum. At one end of the continuum, the observer has complete control over all aspects of how he touches. This is pure active touch. At the other end, the experimenter controls the whole touching procedure, and the observer is passive. But in between these two poles, there lies a wide range of possibilities. Any aspect of the touching process may be controlled by the experimenter, while the observer is free to do as he wishes with the other aspects. The experimenter may even limit the range of freedom that a subject is allowed to exercise over an aspect he otherwise controls, as, for example when the experimenter trains the observer to move his fingers across a surface at a given rate. Studies of the effects of such partial control show promise of being able to determine what is important about the control processes in active touch.

As experiments provide more information about the nature of the feedback systems involved in the control of touching behavior, and about the information processing performed by different elements, so the model may be revised or refined, and become a true model rather than the sketchy outline that we have here presented.

IV. GENERAL DISCUSSION AND CONCLUSION

Touch is the "reality sense." When one kicks a stone to refute the idea of a solipsist universe, he is appealing to a general impression that things touched are more "real" than things seen. Certainly in this day of full color holographic reproduction one cannot be assured that seen objects have any necessary reality to the other senses. One can pass one's hands through what seems to be a perfectly real object. Indeed, the same thing can be done with real images created in more old-fashioned ways, and very good stage illusions have been created in this way. But one would not be inclined to say that these images were real objects in the same sense that an invisible pane of glass on which one has just cracked one's head is real.

The "reality" of the touch sensation may possibly be related to the multimodal nature of touch. A thing seen and heard is more "real" than is the disembodied voice of a singer heard on a stereo system. A thing touched may be at once sensed as a vibrating object, a warm one, and a hard one. The touch may also be heard. Correlative information from three or four senses yields a much more stable perceptual experience than does information from a single sense unsupported by independent corroboration. Vision only yields a single pattern of information. Touch always gives two or three, possibly four independent proofs of the existence of the touched object.

A second, but related aspect of the "reality" of actively touched objects derives from the exploratory nature of active touch. By exploring freely, one obtains a succession of independent chunks of information about the object, such as could only in very unlikely circumstances have been produced by anything other than a real object. The same freedom of choice that permits generalization across the surface from the small sample of points actually touched also permits the inference that a real object does exist. The requisite data independence derived from the presumption that, being randomly selected, the place touched has no special qualities. Similarly improved appearances of reality occur for purely visual phenomena if free exploration is allowed on all sides of the object. The unreal visual effects, like holographic or classical images, lose their appearance of reality on being examined from all sides, and images on a screen have even less tolerance for changes of viewpoint. In spite of this, the reality of the object is usually given the final test by touch.

Returning from the wider problems of the touch sense to texture perception, we must observe that very little work has been done since the early introspective studies. What work has been reported has not been done within any coherent conceptual framework. The model presented in this chapter is a first attempt to provide such a framework. It suggests experiments of many different kinds, and although we do not yet know its predictive value, the quantitative results of relevant experiments might well make it useful.

References

Baker, C. H., & Hall, R. J. Cutaneous sensitivity: A review of some literature, problems and approaches. U.S. Army Human Engineering Laboratories, AMCMS problems and approaches. U.S. Army Human Engineering Laboratories, AM Code 5016.11.84400 Technical Memorandum 21–69, 1969.

Binns, H. Visual and tactual 'judgement' as illustrated in a practical experiment. *British Journal of Psychology*, 1937, **27**, 404.

Bliss, J. C. and Linville, J. G. Reading alphabetic shapes tactually. In *Sensory devices for the blind*. London, England: Arrowsmith, 1966. P. 389.

Boring, E. G. The sensations of the alimentary canal. *American Journal of Psychology*, 1915, **26**, 1.

Boring, E. G. *Sensation and perception in the history of experimental psychology*. New York: Appleton, 1942.

Cashdan, S. Visual and haptic form discrimination under conditions of successive stimulation. *Journal of Experimental Psychology*, 1968, **76**, 215.

Ekman, G., Hosman, J., & Lindstrom, B. Roughness, smoothness, and preference; a study of quantitative relations in individual subjects. *Journal of Experimental Psychology*, 1965, **70**, 18.

Gibson, J. J. Observations on active touch. *Psychological Review*, 1962, **69**, 477.

Gibson, R. H. Electrical stimulation of pain and touch. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Illinois: Thomas, 1968. P. 223.

Gliner, C. R. Tactual discrimination thresholds for shape and texture in young children. *Journal of Experimental Psychology*, 1967, **5**, 536.

Goff, G. D. Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology*, 1967, **74**, 294.

Katori, H. and Natori, N. The immediate reproduction of tactually perceived figures and the drawing process in reproducing the figures. *Japanese Journal of Psychology*, 1967, **38**, 121.

Katz, D. *Der Aufbau der Tastwelt*. Leipzig: Barth, 1925.

Katz, D. *Der Aufbau der Farbwelt.* Leipzig: Barth, 1930. (Translated as *The world of colour.* London: Kegan Paul, Trench, Trubner, 1935.) (a)

Katz, D. The vibratory sense. *University of Maine Bulletin,* 1930, **32**, 90. (b)

Krueger, L. David Katz' Der Aufbau Der Tastwelt (The World of Touch): A synopsis. *Perception and Psychophysics,* 1970, **7**, 337.

Lederman, S. J. The perception of surface roughness by touch. Unpublished Ph.D. dissertation, University of Toronto, 1973.

Lederman, S. J., & Taylor, M. M. Fingertip force, surface, geometry, and the perception of roughness by active touch. *Perception and Psychophysics,* 1972, **12**, 401.

Leo, T., & Vitelli, R. Kynematic aspects of project of unconventional locomotion vehicles. Paper read at the AGARD 21st Avionics Technical Symposium on "Artificial Intelligence," Rome, 1971.

Lindblom, U. The afferent discharge elicited by vibrotactile stimulation. *IEEE Transactions on Man-Machine Systems,* 1970, **11**, 2.

Lobb, H. Vision versus touch in form discrimination. *Canadian Journal of Psychology,* 1965, **19**, 175.

Meenes, M., & Zigler, M. J. An experimental study of the perceptions roughness and smoothness. *American Journal of Psychology,* 1923, **34**, 542.

Metfessel, M. Experimental studies of human factors in perception and learning of spelled speech. In *Proceedings of the international congress of technology and blindness.* Vol. 1. New York: American Foundation for the Blind, 1963. P. 305.

Nolan, C. Y., & Kederis, C. J. *Perceptual factors in Braille word recognition.* New York: American Foundation for the Blind, 1969.

Reiber, C. H. Tactual illusions. *Psychological Review.* 1903 (Monogr. Suppl. 4), also known as *Harvard Psychological Studies,* **1**.

Revesz, G. *Psychology and art of the blind.* New York: Longmans, Green, 1950.

Rock, I., & Victor, J. Vision and touch: An experimentally created conflict between the two senses. *Science,* 1964, **143**, 594.

Rogers, C. H. Choice of stimulator frequency for tactile arrays. *IEEE Transactions on Man-Machine Systems,* 1970, **11**, 5.

Rosenthal, R., & Rosnow, R. L. *Artifact in behavioral research.* New York: Academic Press, 1969.

Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science,* 1971, **175**, 307.

Stevens, S. S., & Harris, J. R. The scaling of subjective roughness and smoothness. *Journal of Experimental Psychology,* 1962, **64**, 489.

Sullivan, A. The cutaneous perceptions of softness and hardness. *Journal of Experimental Psychology,* 1927, **10**, 447.

Taenzer, J. C. Visual word reading. *IEEE Transaction on Man-Machine Systems,* 1970, **11**, 44.

von Békésy, G. Similarities between hearing and skin sensations. *Psychological Review,* 1959, **66**, 1.

Yoshida, M. Dimensions of tactual impressions (1). *Japanese Psychological Research,* 1968, **10**, 123. (a)

Yoshida, M. Dimensions of tactual impressions (2). *Japanese Psychological Research,* 1968, **10**, 157. (b)

Zigler, M. J. Review of Katz "Der Aufbau der Tastwelt." *Psychological Bulletin,* 1926, **23**, 326.