METHODS & DESIGNS

Some principles and new methods of tactile stimulation

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The development of methods for investigation of tactile perception under natural conditions is justified by the observation that the sensitivity of a freely exploring body part often exceeds the sensitivity during passive stimulation (Katz, 1925). This paper (a) suggests methods for selective investigation of size, shape, and surface perception under natural conditions, and (b) presents some principles of quantification when objects are used as tactile stimuli. By means of these methods and principles, it is possible to construct any stiff object and to achieve a complete description of the stimulus variables.

Under natural conditions, man, with his adjustable tactile sense organs, actively selects and explores the multidimensional objects in his surroundings. In the laboratory, the experimenter of tactile perception, in obedience to the demands of stimulus control, is often obliged to deal with simple stimulus dimensions, such as pressure, air jet patterns, or two-point discrimination, and to apply his stimuli to a fixed, and thus passively stimulated, body part. The aim of this paper is to present some methods for investigating the tactile perception of multidimensional stimuli (objects) under conditions imitating the natural.

The stimuli to be described are solid nonelastic objects. If objects are to be used for discriminative purposes, the tolerance (95% β -confidence interval) of the specified parameters must of course be less than it is possible for the subject to discriminate; and the use of objects for matching procedures requires that identical sets of objects be manufactured. Because of this, most stimuli used for tactile presentation cannot be manufactured by ordinary techniques. It is a prerequisite that the items can be measured after manufacturing as a check of production and as a check of alterations of specifications due to wear and oxidation.

STIMULI FOR TACTILE PERCEPTION OF SIZE AND SHAPE

The precise definition of size is volume. The shape

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of an object is defined as the surface coordinates in a three-dimensional rectangular coordinate system. Two objects have the same shape when all corresponding linear measurements bear the same ratio. In practice, shape measurements are reduced to measurement of a few dimensions; a precise method of manufacturing the stimuli is therefore required.

Construction of the Size and Shape Stimuli

The formula

$$\left| \frac{x}{a} \right|^n + \left| \frac{y}{b} \right|^n = 1 \quad (1)$$

can be used to construct all closed curves from a square to a circle or from a rectangle to an ellipse,

$$a > 0, \quad b > 0, \quad n > 0,$$

simply by a change of the parameters a , b , and n (Figure 1). When the experimenter wishes to construct figures of the same area, the area should be specified in the formula:

$$\text{Area} = 4b \int_0^a \sqrt{1 - \left| \frac{x}{a} \right|^n} dx \quad (2)$$

A computer program is available by means of which it is possible to generate any selected figure from the curve family in Equation 1 such that all resulting figures have the same area. If the experimenter wishes to design his own program, this is easily done. In Formula 1, the strategy is a sine and cosine transformation of the variables a and b . Formula 2 can be solved by an IBM subroutine program (IBM, Note 1). Such figures have been used by Rattleff

Figure 1. Examples of closed curves generated from Formula 1 by variation of the parameters, a , b , and n . All figures have the same area.

(Note 2) to investigate visual perception of size and shape. If we restrict the figures to circles and ellipses, the area will be the same if the product ab remains constant.

If we specify the area by the use of Formula 2 and the parameters a , b , and n in Formula 1, and use the program on a computer-directed lathe, it is possible to produce any selected rotation-symmetrical object with the same volume and weight. In other words, shape will be the only variable parameter.

If the objects desired are not rotation symmetrical, they have to be manufactured on a computer-directed milling machine. The milling then has to be done successively in at least two planes at right angles to one another. To keep the volume constant, the volume integral must keep a constant value.

By means of these procedures, we have manufactured two identical sets of rotation symmetrical ellipsoids (spherical ellipses) and two identical sets of hexaeders (rectangular parallelepipeda) in polished aluminum (see Figure 2, and for a description of parameters, see Table 1).

Rotation-symmetrical stimuli for investigation of size perception can be made by keeping the ratio $a:b$ and the parameter n constant. However, weight changes with changing volume, and the objects have

Table 1
The Parameters of the Shape Stimuli*

Spherical Ellipses			Rectangular Parallelepipeda	
2a mm	2b mm	Number	2a mm	2b mm
28.02	27.99	1	22.57	22.54
28.50	27.76	2	23.01	22.37
29.98	27.52	3	23.49	22.11
30.00	27.04	4	24.01	21.89
31.01	26.60	5	24.47	21.64
31.99	26.18	6	24.98	21.44
33.97	25.41	7	25.49	21.23
35.97	24.69	8	26.48	20.81
38.00	24.04	9	27.50	20.47
39.98	23.45	10	29.48	19.74
41.99	22.85	11	31.49	19.11
43.98	22.33	12	33.51	18.50
45.97	21.85	13	37.48	17.51
48.01	21.37	14	39.52	17.06
49.98	20.94	15	44.53	16.06
53.97	20.17	16		
55.99	19.81	17		

*The objects for use as size and shape stimuli were manufactured in 99.5% pure hard aluminum; $\rho = 2.690 \text{ kg/m}^3$; $\lambda = 2.38 \text{ W/cm} \cdot \text{Kelvin}$; $c = 921 \text{ J/kg} \cdot \text{Kelvin}$; surface: fine polished; orientation: circular; R_a (in arcs at right angles to the orientation) = $.3\mu$; $R_{\text{max}} = 1.3\mu$; $S = 100\mu - 120\mu$ (99% range) K_B at mean line = $10 - 16\%$ (99% range); tolerance (for all linear measures of macrogeometry) = $\pm 0.03 \text{ mm}$; hardness: 343.23 N/mm^2 . The rectangular parallelepipeda have a square basis with side length = $2b$. The stimuli for size and shape stimulation had the same weight = 32.50 g , tolerance $\pm 1.22 \text{ g}$.

to be turned out concentrically to the rotation axis to remove the superfluous weight. The amount of substance to be removed in every case is easily computed by the program as the area between the outer and inner curve must be constant. If the objects are not concentrically turned out, they will have a torque that varies with the direction of manipulation.

We have manufactured 31 spheres in polished aluminum to use as size stimuli. The diameter increases in steps of 1.0 mm from 20.0 to 50.0 mm . The tolerance was $\pm 0.03 \text{ mm}$.

The spheres and spherical ellipses were manufactured on a Heyligenstadt® lathe. The parallelepipeda were manufactured on a SAJO® milling machine. The lathe and the milling machine were controlled by a punch-tape reader. The coordinates of the curves were calculated by means of

Figure 2. Some examples of the objects for shape stimulation listed in Table 1. All objects have the same volume.

Figure 3. Profile curve parallel to the long axis of object No. 15, first series. The surface is measured in the reference length (L). The mean line is drawn so that

$$\sum_{i=1}^n (y_i - y)^2$$

is minimized for n equally spaced measure points. R_a [= CLA = center line average] is the arithmetical mean of deviations from mean lines:

$$R_a = \frac{1}{n} \int_0^L |y| dx.$$

The lines $k_1 \dots, k_5$ are drawn parallel to the mean line. For a given niveau, e.g., k_4 , the bearing area fraction

$$K_B = \frac{\sum_{i=1}^p k_{4i}}{L}$$

(the added length of the k_4 lines divided by the reference length). This measure specifies the width of the gap between the peaks in different levels, and thus the room left for tangential activation of nails and epidermal ridges.

the program on an ordinary computer, and then transferred to punched tape. The tolerance in milling and lathing was the same 0.03 mm for the range of objects manufactured.

Torque

The torque of a stiff object is $= \sum_i m_i r_i^2 \cdot \omega$ ($\text{kg} \cdot \text{m}^2 \cdot \text{radian} \cdot \text{sec}^{-1}$); m_i is the mass of the i -th particle, r_i its distance from the axis of rotation, and ω the angular velocity.

It is now apparent that stiff, homogeneous objects of different shapes have a different torque even if the mass and rotation axis of the objects do not vary. This is because the distribution of the particles around the axis of rotation is not the same in stiff objects with different shapes.

When an object is manipulated, it has a priori an infinite number of rotational axes. The exception is the sphere, which has only one center for all rotation. When the sphere is hollow, as for example in an attempt to balance the weight with other objects, the

torque is dependent on size, but not on the mode of manipulation if the sphere is concentrically turned out. The distribution of the mass particles around the center of rotation is still uniform.

For nonhomogeneous spherical objects, the torque depends on the distance between the center of gravity and the axis of rotation, and thereby on the mode of manipulation. The worst case is that of an object filled with mobile particles; here the center of gravity also moves.

Unfortunately, systematic investigations of the influence of torque on tactile perception of objects have not previously been published, but Koseleff (1957) has shown that the torque has an influence on apparent heaviness.

SURFACE PARAMETERS

Roughness

Shape and size may be characterized as macrogeometric attributes. Roughness is, by

Table 2
Specifications of the Roughness Stimuli*

Object Number	First Series (Horizontal Parameters Varied)				Second Series (Vertical Parameters Varied)			
	S (μ)	K _B (at Mean Line)	R _a (μ)	R _{max} (μ)	S (μ)	K _B (at Mean Line)	R _a (μ)	R _{max} (μ)
1	50	.55	.65	3.40	353	.75	1.75	9.1
2	49	.74	.74	3.95	353	.75	1.78	9.3
3	104	.63	1.01	5.42	353	.50	3.57	14.9
4	109	.59	1.01	6.18	351	.48	3.61	15.7
5	201	.42	2.11	9.90	353	.41	4.47	22.1
6	203	.58	2.30	9.20	355	.40	4.52	22.3
7	215	.37	2.51	12.8	353	.34	8.01	29.7
8	215	.36	2.57	12.1	353	.38	8.11	30.1
9	249	.37	3.29	14.3	354	.34	9.40	38.7
10	256	.52	3.10	13.2	353	.34	9.65	39.9
11	297	.40	4.07	17.3	350	.25	10.9	44.2
12	300	.41	4.03	17.8	353	.25	11.1	43.4
13	312	.39	4.44	20.1	353	.41	13.2	51.3
14	313	.37	4.41	20.2	353	.41	13.2	51.7
15	353	.39	5.50	23.7	355	.33	15.2	61.9
16	353	.39	5.49	23.8	353	.35	15.4	61.1
17	488	.51	6.52	26.9	354	.35	16.9	68.2
18	490	.50	6.49	26.0	352	.38	17.0	68.4
19	453	.31	8.87	35.2	353	.33	21.9	78.6
20	455	.31	8.80	36.2	353	.33	22.0	78.7
21	488	.31	10.0	42.8	353	.42	23.6	87.2
22	493	.33	10.3	43.7	353	.42	23.7	86.7
23	793	.37	17.6	69.0	353	.42	23.4	96.9
24	808	.38	17.7	69.4	353	.42	24.4	98.0

*The stimuli for surface perception experiments were manufactured in pure polyoxymethylene Delrin®, DuPont. Hardness = 153.86 N/mm². Orientation: parallel. As is apparent from Table 2, it is not possible to maintain the vertical parameters constant when the horizontal parameters are changed.

definition, microgeometrical surface deviations (ISO, Note 3; SMS, Note 4). Traditionally, different grades of sandpaper, specified by the grit number, have been used as roughness stimuli. It will appear from the following that such stimuli are not specified in sufficient detail for this purpose.

A sectional view at right angles to a surface is a profile curve (Figure 3). A profile curve can be described by parameters according to international standards (ISO, Note 3). The biologically most important of these measures are shown in the figure.

Roughness measurements rely on optical and mechanical methods. The optical interference method should be used for measurements of very smooth surfaces with R_a from 0.001 to 0.020 μ . In addition, the trailing needle method (stylus instruments) in which a contact point, usually a diamond, moves over the surface is to be recommended (SMS, Note 4).

The horizontal parameters (S and K_B) are of special importance if the glabrous skin of primates is to be stimulated. Here the skin has epidermal ridges (cristae cutis). These are hemispheric, with a diameter of approximately 300 μ , and they seem to serve as mechanical amplifiers for the Meissner corpuscle (Cauna, 1954; Roland, Note 5).

To perceive roughness, it is necessary that the exploring limb be moved in contact with the surface, or that the surface move relatively to the exploring body part. Katz (1925) has shown that man can detect a difference in level of less than 1 μ , but only when the

fingers are moved across the profile. The spacing and K_B of the surface irregularities are important factors, because they determine the tangential activation of the epidermal ridges. The nail seems to be an even more powerful amplifier of surface irregularities (Kesten, 1956; Matthey, 1960), because the nail usually has an edge with a smaller radius of curvature and a far greater distance from the fixed point.

Therefore, in roughness experiments, the experimenter should state the specific part of the skin to be stimulated, and if the nails may be used. As auditory cues may result, the ears should be plugged. We have manufactured two series of cylindrical technical roughness norms, all of the same weight and lathed on the convex surface (Table 2). In the second series, only the vertical parameters vary (in the first, mostly the horizontal). However, in lathing it is not possible to vary the horizontal parameters without changes in the vertical parameters. The orientation of the surface was parallel to the edges of the cylinder.

Orientation

The profile curve is a two-dimensional description of microgeometrical surface deviations. As the surface deviations of objects are usually small ridges, description of the orientation of the ridges is necessary to complete the description of the surface. These ridges are the inevitable results of the manufacturing process. The orientation is dependent on the method of surface finishing. After lathing, it is parallel, as in

the objects shown in Table 2; this yields a simple stimulus pattern. More complex patterns with radial, cross-directed, circular, and radial orientation may be obtained by star-milling, honing, or lathing in two or more directions. For a description of complex patterns, profile curves should be taken at right angles to the orientation.

Other Surface Parameters

Humidity and adhesiveness change the perceptual character of the surface. Our surface norms were manufactured of a synthetic material, Delrin® (polyoxymethylen) with a surface which feels slightly slippery-greasy. This makes changes in humidity and adhesiveness from interindividual variations in sweat production negligible.

MATERIAL PROPERTIES

The objects in a stimulus set should all be of the same material to reduce unexpected variations of the stimuli.

Hardness

Hardness is a pressure measure. The SI unit is newton per square meter. Generally, the roughness (R_a) increases exponentially with decreasing hardness, provided that the same manufacturing process is used. Elastic objects change shape during compression, and the technical models for description of the shape alterations are not sufficiently accurate to account for the minute changes that might be perceived. An alternative method of testing elasticity and compressibility has been presented in a previous report (Roland, 1973).

Thermal Properties

The interrelationship of energy transfer between the skin, the object, and the surrounding air influence perception of an object. A cold object seems smaller than an object with the same volume, shape, and weight but with a temperature close to that of the skin surface. Probably the reason for this is that a certain group of mechanoreceptors in primates also responds to cooling (Hensel & Boman, 1960). If we place an object on the skin and the object has a thermal conductivity which differs from the thermal conductivity between skin and air, it will change the heat flow through the skin layers. The thermal conductivity (watts/meter x kelvin) depends on the material. But the total change in heat flow depends on the surface of the object. Therefore, the thermal stimulus depends not only on material, but on size and shape as well.

In general, the heat flow into and out of a solid uniform layer (n) is (Hardy & Stolwijk, 1966):

$$\rho_n \cdot c_n \cdot \Delta X_n \frac{dT_n}{dt} \quad (3)$$

where ρ is the density ($\text{kg} \times \text{m}^{-3}$), c is the specific heat ($\text{J} \times \text{kg}^{-1} \times \text{Kelvin}^{-1}$), ΔX is the thickness (m), T_n is the temperature in the center of layer n (kelvin), t is the contact time with the adjacent layers (seconds).

If the layer considered is the object, the heat flow for the system, skin-object-air, is:

$$m \cdot \frac{A}{V} \cdot c_{\text{obj}} \cdot \frac{dT_{\text{obj}}}{dt} = \lambda_{\text{skin-obj}} (T_{\text{skin}} - T_{\text{obj}}) - \lambda_{\text{obj-air}} (T_{\text{obj}} - T_{\text{air}}). \quad (4)$$

In this equation, m is the mass of the object; A , the contact area; V , the volume; c_{obj} , the specific heat of the object; and t , the manipulation time or time of contact between skin and object. On the right side of the equation is the thermal conductance between the centers of adjacent layers. It will therefore become apparent that the heat flow from skin to object is dependent on the size and shape of the object, if mass is held constant.

The mean thermal conductance from the center of a uniform layer, n , to the center of an adjacent uniform layer, $n + 1$, is

$$\lambda_{n+1/2} = \frac{2\lambda_n \lambda_{n+1}}{\Delta X_n \lambda_{n+1} + \Delta X_{n+1} \lambda_n} \quad (5)$$

($\text{W} \times \text{m}^{-1} \times \text{K}^{-1}$)

It is too restrictive an assumption that the skin is a uniform layer with only one characteristic thermal conductance. In the depths, we have a layer with a constant temperature, but in the surface layers, the temperature changes when an object is placed on the skin. Hardy and Stolwijk (1966) have developed a model that accounts for the heat transfer between eight different layers of the skin, which in principle makes use of the successive application of the generation equation:

$$\rho_n \cdot c_n \cdot X_n \cdot \frac{dT_n}{dt} = \lambda_{n+1/2} (T_{n+1} - T_n) - \lambda_{n-1/2} (T_n - T_{n-1}). \quad (4a)$$

The thermal stimulating properties of an object will be reduced if the heat flow in the system skin-air equals the heat flow in the skin-obj-air system. The easiest way of producing this is to choose a material with a thermal conductivity as near to the thermal conductivity for the skin-air conduction as possible. A minor reduction will be achieved for other materials if the starting temperature of the object is balanced by the use of Equation 4.

The time of manipulation might thus influence the perception of objects (Equation 4) when the objects

have thermal stimulating properties. We have therefore manufactured a device which releases the object into the hand of the test person and, at the same time, starts an electronic timer.

COMMENT

A review of the literature on tactile perception shows that most of the stimuli that have been used are either familiar objects, such as keys or scissors, or specially manufactured objects with more or less specified physical parameters. When common objects have been used, there have been no attempts to specify their physical properties. In these cases, we have insufficient information about the stimuli. Furthermore, common objects are representational forms, and as such they cause a strong verbal dependency in the testing. Nonrepresentational objects, usually geometrical shapes such as pyramids, hexaeders, or combinations of simple geometrical shapes, have been used as stimuli, and even random forms have been employed (Owen & Brown, 1970). However, these stimuli have shown coincident variations in size and shape, size and weight, size and material, or, if size and weight have been balanced, the objects have been filled with shot or lead pieces. Exceptions to this are the stimuli used by Kelvin (1954) and Weinstein (1962). But the surface properties have in no instance been recorded.

These objections to earlier methods may seem like pedantic fuss, but this is not the case: even the slightest physical difference is a candidate as cue-giver, especially when discrimination procedures are applied and when the touch organ (e.g., the hand) is allowed to move relative to the object touched (Katz, 1925; Caūna, 1954).

The methods we favor have advantages: the objects are nonrepresentational, fully specified as stimuli, allow separate investigation of size, shape, and surface parameters, and by appropriate choice of material even temperature parameters. With combinations of the techniques, it is possible to generate any selected solid object. The objects presented are suitable for use in any psychophysical procedure and even for visual presentation (Gibson, 1955). If used for visual presentation some further parameters such as background, slant, illumination, and thermal radiation capacity must be stated.

Disadvantages include concomitant variations in thermal properties with size or shape, when aluminum is used. This might be minimized, but variations in torque are inevitable. Apart from the specification of the objects, the experimenter should specify the following manipulation conditions: (1) permissibility of use of nails, (2) manipulation time, and (3) whether the objects are to be manipulated only *in* the hand, or whether they are allowed to be thrown or manipulated while lying on a

table. (In the last cases, the kinetic properties of the objects may give additional cues). A look at the curve family in Figure 1 leads to the impression that these figures have different areas; this impression is an optical illusion. In a similar way, the spheres, when tactually presented, give rise to illusions of weight differences, and the shape stimuli give rise to illusions of size differences. However, the tactile discrimination of size is much keener than the discrimination of the spheres on the basis of subjective differences in weight (Roland, Note 5).

Tactile exploration of an object is a complex affair compared with applications of single stimuli. However, there is no reason why the tactile perception under strictly specified stimulus conditions and appropriate psychophysical methods cannot be analyzed and interpreted physiologically and information-theoretically.

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