Chapter 1
Psychophysical Dimensions of Material Perception and Methods to Specify Textural Space

Shogo Okamoto, Hikaru Nagano, and Hsin-Ni Ho

Abstract This chapter explains the five types of perceptual dimensions in tactile perception of materials: namely, coarse and fine roughness, softness (hardness), warmness (coldness), and friction percepts. How these dimensions are specified is discussed, and the perceptual mechanisms of each dimension are outlined. Furthermore, experimental and analytical methods to specify these perceptual dimensions are introduced. Primarily, two types of analyses, factor analysis and multidimensional scaling, are described with appropriate experiments for data collection.

Keywords Texture • Roughness • Softness • Hardness • Friction • Warmness • Coldness • Perceptual dimension

1.1 Introduction

Human perceptual and affective experiences in touching products or materials are expressed by a semantically multilayered and multidimensional information space, as shown in Fig. 1.1. As discussed in the literature of perceptual and emotional responses of touch [15, 26, 53], the most primal layer is the psychophysical layer that is composed of the percepts of physical properties, comprising surface roughness and pliability of materials. Because this layer is regarded as an interface between human responses and physical stimuli, it is called the psychophysical layer or commonly the layer of texture. The higher layers are more cognitive and affective; they are mediated not only by physical stimuli but also personal background and the knowledge of objects to be touched. The preferential layer, which is composed of hedonic expressions, is more individual than the lower layers.

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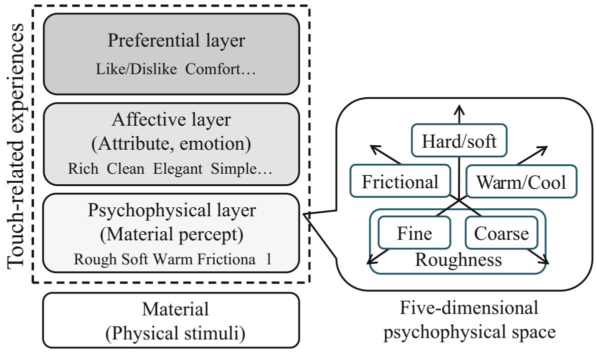

Fig. 1.1 Multilayered model of touch-related experiences. The *bottom layer* is composed of the percepts of physical properties of materials. The *middle layer* includes perceived attributes and emotional experiences. The *highest layer* pertains to personal preferences. The *lower layers* are more common among all people, whereas the *higher layers* are more individual

In this chapter, the structure of the psychophysical layer (texture) is discussed and explained in terms of their perceptual independence and mechanisms. The investigation of earlier studies on the textural dimensions leads us to a reasonable deduction that the space mainly comprises five types of perceptual dimensions [55]. The five perceptual dimensions are the percepts of fine roughness, coarse roughness, softness, warmness, and friction. We summarize the perceptual mechanisms of each dimension based on the psychophysics, contact mechanics, and neurophysiology in the field. Given that the texture is expressed in the multidimensional information space, we also introduce experimental and analytical methods to specify the dimensions that construct the textural space. The weakness of these methods are discussed, as well as their strength.

1.2 Five Types of Psychophysical Dimensions of Texture

1.2.1 Related Studies on Texture Dimensions

Thus far, the dimensional structure of tactile textures attracted the interest of many researchers. However, their conclusions are not necessarily consistent with each other. All studies differ in terms of materials, criteria (adjectives), and the modality involved in the research, which results in inconsistency between the studies.

The majority of the inconsistency may result from the differences in material samples and adjectives (criteria) used for judgment. Some studies used very limited number of samples that are insufficient to cover the wide aspects of human perception. Even if the number of material samples is adequate, an imbalanced sample set leads to an imbalanced result. Difference in the polarity of adjectives must be also considered. The majority of the studies used adjectival dyads such as “rough-smooth” and “hard-soft” for rating tasks. However, in some studies, unipolar

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descriptors were used and semantically opposite adjectives were not paired. The difference in modalities involved in psychological investigations is also a priority. In some studies, experimental participants were allowed to see their samples, whereas they were not in other studies. Furthermore, each study adopted different definitions of texture. The strictest definition of texture is the perception of topographic characteristics of the surface that do not include the senses of warmth or softness. Additionally, in some studies, the bending stiffness of fabrics or papers might have implicitly influenced the texture when they were actively held and explored by subjects. In contrast, in other studies, the material samples were attached to flat boards or the subjects' hand motions were controlled.

Table 1.1 summarizes the reports of related studies on textural dimensions. Because all studies used different but similar terms or descriptors, they are slightly changed from the original literature for consistency. Unipolar descriptors were also interpreted such that each dimension would become bipolar. Most studies specified the textural space as two- or three-dimensional. Clearly, they do not completely agree with each other. An important thing that we should try to accomplish is to reach a reasonable conclusion by conducting an overview of earlier studies. In the following part, these related studies are comprehensively discussed in order to rearrange the textural dimensions.

1.2.2 Sort-Out of Five Dimensions

Table 1.2 shows the number of dimensions reported in the abovementioned 20 studies. Based on these reports and the following aspects, the dimensionality of texture can be inferred.

- Rough-smooth, hard-soft, and warm-cold dimensions were robustly found under many different research conditions.
- Two types of roughness perceptions, namely coarse and fine roughness, were reported in some studies. Coarse roughness is described as voluminous, uneven, lumpy, coarse, and relief. This is distinguished from fine roughness that is typically described as harsh or rough. Furthermore, the perceptual mechanisms of these two types of roughness are clearly different, as described in Sect. 1.3.1.
- Percepts of roughness and friction were separately identified in many studies. These two types of percepts tend to be considered strongly linked with each other because friction is physically connected with its surface roughness. However, their perceptual mechanisms are different as described later.
- Moist-dry and sticky-slippery are likely to belong to the same (or very similar) dimension pertaining to friction. They have never been extracted as separate dimensions in single studies.

From these viewpoints, the textural space is conjectured to comprise five types of dimensions: fine roughness, coarse roughness, warmness (coldness), hardness (softness), and friction percepts. This classification also agrees with psychological and neurophysiological aspects [5, 7, 38].

Table 1.1 Early studies on perceptual dimensions of tactile textures in order of publication year

Literature	Dimension 1	Dimension 2	Dimension 3	Dimension 4
Howorth [35]	Rough/smooth, Hard/soft	Warm/cold		
Yoshida [81]	Hard/soft Warm/cold, Rough/smooth	Moist/dry, Rough/smooth	Hard/soft	
Lyne [47]	Hard/soft	Embossed (Roughness)		
Hollins [32]	Rough/smooth, Warm/cold, Sticky/slippery,	Hard/soft	Not specified (Stiff)	
Hollins [30]	Rough/smooth	Hard/soft	Sticky/slippery	
Tamura [73]	Rough/smooth Hard/soft	Warm/cold	Moist/dry	
Picard [58]	Hard/soft, Rough (Fine roughness)	Relief (Coarse roughness)	Hard/soft	
Picard [59]	Hard/soft	Rough/smooth		
Soufflet [67]	Rough/smooth Hard/soft	Warm/cold		
Shirado [63]	Rough/smooth	Warm/cold	Moist/dry	Hard/soft
Ballesteros [2, 3]	Rough/smooth	Hard/soft	Sticky/slippery	
Gescheider [24]	Coarse roughness	Rough/smooth	Fine roughness	
Bergmann Tiest [8]	Hard/soft	Rough/smooth	Not named	Not named
Tanaka [75]	Moist/dry	Hard/soft Rough/smooth	Warm/cold	
Yoshioka [82]	Hard/soft	Rough/smooth	Sticky/slippery	
Summers [72]	Rough/smooth			
Guest [27]	Sticky/slippery	Rough/smooth	Oily	
Guest [26]	Rough/smooth	Moist/dry	Hard/soft	
Baumgartner [4]	Rough/smooth Sticky/slippery	Hard/soft Warm/cold		
Ackerley [1]	Rough/smooth Hard/soft	Sticky/slippery (Moisture)	Warm/cold	

Table 1.2 Number of textural dimensions reported in 20 earlier studies

Rough/smooth		Hard/soft	Warm/cold	Frictional	
20		17	9	12	
Coarse	Fine			Moist/dry	Sticky/slipp.
2	2			6	6

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1.3 Perceptual Mechanisms of Individual Dimensions

The perceptual mechanisms of each textural dimension have been investigated by many researchers. Here, they are outlined from psychophysical, contact-mechanical, and neurophysiological aspects as shown in Table 1.3; other comprehensive studies [5, 7, 38] reviewing such mechanisms are also recommended for reference.

1.3.1 Roughness

1.3.1.1 Coexistence of Two Types of Roughness

The percepts of surface roughness are mediated by two mechanisms that depend on the degree of surface roughness. In the case of grating scales and dotted scales, which have been frequently used for investigating the roughness percept, the width of two neighboring dots or ridges becomes a criterion to separate the two mechanisms. When it is larger than the range of a few hundreds of micrometers to 1 mm, the surface roughness is called coarse or macroscopic roughness. In contrary, a surface roughness with a value smaller than this range is called fine roughness. This threshold range is compared with the width of finger print ridges [21].

Although the perceptual mechanisms of the coarse and fine roughness clearly differ, not many studies on textural dimensions have reported them independently as described in the above section. This is partly because these two types of

Table 1.3 Summary of perceptual mechanisms of five textural dimensions

Dimension	Exploratory motion	Principle	Receptors	Physical dominance
Coarse roughness	Push	Pressure distribution	SA units	Surface roughness
Fine roughness	Rub	Skin vibration	FA units	Surface roughness
Softness	Push	Contact area/ Pressure distribution	SA units (FA units)	Elasticity, stiffness
Hardness	Tap	Vibration	FA units	Mechanical impedance
Friction	Rub	Skin stretch, Frictional vibration	–	Friction
Warmness/ coldness	Push, Soft touch	Heat transfer	Free nerves (TRP channels)	Temperature, Thermal properties

*SA and FA: slow and fast adaptive. TRP: transient receptor potential. Appropriate exploratory motions for each dimension are also discussed in [52] roughness largely overlap, indicating that humans make use of the two types of perceptual mechanisms to deal with the wide range of surface roughness, and also to accurately estimate the common materials for which surface roughness lies within the overlapping range.

1.3.1.2 Coarse (Macroscopic) Roughness

Another definition of coarse roughness is that it is a type of roughness that humans can discern merely by pushing the surface with a finger without any relative motions between the finger and material. Hence, the percept of coarse roughness is presented by the pressure distribution within a contact area between the finger pad and asperities of material surface. The type of receptors that realize such perception are Merkel corpuscles, which are also known as SA I units; they exist densely in the hypodermis and respond to sustained skin deformation and pressure. Furthermore, some types of free nerve endings are also responsive to mechanical stimuli [61]. These receptors constitute dense pressure sensors spread across the skin surface and contribute to the percepts of coarse roughness [12, 18, 83]. When FA units that are other types of mechanical receptors in the skin are fully adapted, humans are virtually incapable of discriminating fine roughness, but the capacity to perceive coarse roughness remains intact [31, 33]. This also corroborates that SA and FA units govern the different types of surface roughness; coarse and fine roughness, respectively.

1.3.1.3 Fine Roughness

For the surface roughness of which asperities are finer than the density of Merkel corpuscles or the width of epidermal ridges, humans cannot discern the degree of roughness solely by the pressure information provided by pushing the surface. In this case, the temporal or vibratory information elicited by the relative motion between a finger pad and the surface contributes to the perception of roughness [6, 14, 43]. In short, fine roughness is coded by scanning the surface. In contrast, the percept of coarse roughness is scarcely influenced by such temporal information [34, 50]. The neural coding of skin vibrations is preferentially mediated by Meissner (FA I units) and Pacinian corpuscles (FA II units).

The vibration frequency of a finger pad relies on the fineness of surface asperities and relative speed of the finger. Finer roughness and faster exploration result in a higher frequency. However, mechanoreceptors in skin can respond to vibrations at a maximum of 1 kHz. For perception of finer roughness that leads to a much faster skin vibration, the degree of surface roughness (e.g., size of particles or height of asperities) rather than vibration frequency determines the roughness percepts. Miyaoka et al. [51] suggested this possibility from the evidence that humans can discriminate abrasive papers with particle sizes of several micrometers and rectangular single ridges with different heights of several micrometers with equal or comparable accuracies. This indicates that very fine roughness can be coded by the intensities of cutaneous deformations or resultant activities of vibration-sensitive mechanoreceptors.

1.3.2 Softness and Hardness

Softness percepts tend to be considered related to proprioception because the mechanical stiffness of an object is defined by the ratio of relative reaction force to relative surface displacement. However, in addition to other textural information, tactile cues play an important role [9, 69], and rather predominant over proprioceptive cues for soft materials whose Young's moduli are approximately 1 MPa [10]. A question that comes to mind is whether the object stiffness (e.g., spring constant) or material elasticity (e.g., Young's modulus) is more proximate to hardness that humans perceive. Bergmann Tiest et al. conducted an experiment where participants matched perceived softness of objects with different thickness (spring constant) and material (Young's modulus) [10]. As a result, the participants judged the perceived softness by integrating the two types of physical quantities or cutaneous and kinesthetic cues. Nonetheless, the cutaneous cue or material elasticity is perceptually dominant for softness percepts.

Skin deformation caused by the contact with materials provides their softness cues. It is not exactly specified what information gathered via skin deformation is used for softness percept; however, it is at least known that the contact area between the finger pad and material surface and pressure distribution on the contact area are deeply connected with perceived softness. Their relationships have been established decisively by psychophysical experiments using specific softness display devices [11, 23, 37, 62]. Specifically, when a finger pad is in contact with a soft material, the contact area is large and the contact load is widely spread over the area. In contrast, in the case of contact with a rigid material, the contact area is small with a large peak pressure. It is speculated that such differences in the pressure distribution contribute to the discrimination of material softness.

Regarding the receptive units related to softness percepts, slow adaptive units are considered to be potential mediators. However, during active contact between the finger pad and material surface, the skin dynamically deforms. From this viewpoint, fast adaptive units are also potentially concerned with softness perception.

As to the hardness percept, humans adopt another approach. Stiffness estimation based on finger pad deformation is not effective in the case of objects that are significantly stiffer than the finger pad. In such cases, the hardness of objects can be estimated by the damped natural vibration caused by tapping the object surface [42, 56]. The damped natural vibration with a single frequency component is characterized by its amplitude, vibration frequency, and decay coefficient. Although the mechanical impedance of an object influences all of these parameters, the most perceptually effective one is the vibration frequency. A higher frequency leads to greater perceived hardness of objects.

1.3.3 Friction

Sticky-slippery or moist-dry factors were found in some of the earlier studies as described above. These two factors are considered to be derived from the same factor because they have not been extracted together in a single study. Provided that both these factors are pertinent to friction, we comprehensively regard them as a single factor related to friction.

Roughness and friction percepts are sometimes considered to be dependent on each other [15, 49, 74] because the surface roughness physically influences its friction coefficients. In some studies, friction and roughness percepts were found to be correlated [20, 21, 65, 66]. However, roughness and friction percepts are actually independent. In a study using roughness samples with and without lubrication, the roughness percepts were not affected by the difference in friction [76]. Furthermore, in an experiment involving coated papers, the perceived roughness was negatively correlated with their friction coefficients [64]. Coated paper with larger surface roughness leads to a smaller real contact area with a finger pad, which causes weaker adhesion. As a result, its roughness perception negatively correlates with its friction perception. In many earlier studies on textural dimensions described in the previous section, the roughness and friction factors were separately extracted, and they were conjectured to be perceptually independent.

As a further classification of friction percepts, Guest et al. [27] suggested the separation of the percepts of watery and oily fluids from the results of experiments using liquid on a flat plate. The difference between these two types of percepts was attributed to frictional vibration caused by the repetition of stuck and slippery states between the finger pad and explored surfaces. Oily fluid is slippery with little frictional vibration whereas the purer water more frequently elicits such vibrations [54].

Because friction is a kind of force, a friction percept tends to be classified as proprioceptive; however, cutaneous cues are also a significant factor. In one report, when the force of 0.3 N was applied to a finger pad, cutaneous and proprioceptive cues equally contributed to the force perception [48]. For the perception of even smaller forces, cutaneous cues become more dominant. Although the perceptual mechanisms of friction remain to be studied, quasi-static shear deformation of finger pad is certainly used for the estimation of friction [60, 84]. The finger pad is deformed along its shear direction owing to the friction or interaction force during the exploration of material surfaces by a finger. Furthermore, the dynamic shear deformation of finger pad caused by the difference between static and kinetic friction coefficients is likely to provide human with frictional information of materials. Frictional vibrations caused by stick-slip phenomena between the finger and material present some aspects of friction [39, 54]. Additionally, when the finger pad transfers from a stuck state to slipping state, the contact area of finger pad rapidly decreases [77]. The friction-related dynamism of the finger pad has an intimate relationship with human percepts of friction. However, it is unknown whether humans can really estimate the static and kinetic properties of friction such as static and kinetic coefficients, based on such dynamism.

1.3.4 Warmness and Coldness

1.3.4.1 Physical Process

When the hand touches an object whose temperature is different from the skin temperature, heat transfer occurs between the two. For an object whose temperature is lower than the skin temperature, heat flows out of the skin during contact and coldness is perceived. On the other hand, for an object whose temperature is higher than the skin temperature, heat flows into the skin and warmness is perceived. In both cases, the degree of coldness or warmness is proportional to the amount of heat exchanged, which is in turn a function of the temperature difference between the skin and the object and the material properties of the object such as thermal conductivity and heat capacity.

In daily experience, we often find that a metal object feels colder than a wooden object of the same temperature. This difference comes from their difference in the material properties. The metal object feels colder because a large amount of heat flows out of the skin during contact due to its high thermal conductivity and heat capacity. The wooden object does not feel as cold because only a small amount of heat flows out of the skin during contact due to its relatively low thermal conductivity and heat capacity. In the case that the temperatures of a metal object and a wooden object are the same but higher than the skin temperature, the metal object would feel warmer than the wooden object because a larger amount of heat is exchanged with the metal object.

Several models have been proposed to predict the thermal interaction between the skin and an object during contact (for review, see [36]). Among them, Ho and Jones [28] proposed that the contact coefficient, which is the square root of thermal conductivity and heat capacity, can be used as an index to predict how much heat would be exchanged during contact. They also showed that people are able to discriminate between materials based on thermal cues, provided that the ratio of the contact coefficients of the materials is larger than 3. In the case of metal and wood, the contact coefficient of metal is 10 times larger than that of the wood, so people can discriminate between them reliably based on the difference in the perceived coldness.

1.3.4.2 Mechanisms of Temperature Sensing

Changes in skin temperature are encoded by warm and cold receptors. They are free nerve endings, with the warm receptors innervated by unmyelinated C fibers and the cold receptors innervated by small myelinated Aδ fibers. Because of the difference in fiber type, the conduction velocity of cold receptors is much faster (5–30 m/s) than that of warm receptors (0.5–2 m/s) [13]. The warm receptors respond to a temperature range between 30–50 °C with peak intensities around 45 °C. Cold receptors respond to a temperature range between 5–43 °C with peak intensities between 23–28 °C [19, 68]. In the neutral thermal zone between 30 and 36 °C, both warm and cold receptors discharge spontaneously at low rates and no thermal sensation is noted. When the skin temperature exceeds 45 °C or falls below 15 °C, responses from the nocioceptors result in the perception of pain.

The processes involved in converting thermal stimuli into electrical and chemical signals are mediated by the ion channels expressed in the thermoreceptors or the skin cells, called thermo-transient receptor potentials (thermoTRPs). To date, six ThermoTRP channels have been identified, which include four heat-activated channels and two cold-activated channels. Among heat-activated channels, TRPV1 and 2 are activated by painful levels of heat, while TRPV3 and 4 respond to non-painful warmth. Among the two cold-activated channels, TRPM8 is activated by non-painful cool temperatures, while TRPA1 responds to painful cold (for review, see [57]).

1.3.4.3 Psychophysical Characteristics of Temperature Perception

Humans can only perceive a thermal stimulus when it exceeds some specific threshold and this threshold depends on the stimulated site and whether the stimulus is warm or cold. In general the face is the most sensitive region and the extremities are the least sensitive. The sensitivity of the finger is in between and the warm and cold thresholds are about 0.5 and 0.3 °C, respectively [71]. Human thermal perception has been shown to have good spatial summation and poor localization for thermal stimuli at low intensities [70]. This is hardly noticed in the daily experience because concurrent tactile inputs can facilitate thermal localization. For example, when the hand makes contact with an object, the change in skin temperature and the deformation of the skin activate thermoreceptors and mechanoreceptors located in the skin. The cross-modal processing of the thermal and tactile inputs influences the localization and the perceived intensity of resulting thermal sensations [25, 29]. The time required to process a thermal stimulus depends on the response required. The simple reaction times to warming and cooling stimuli presented to the hand have been shown to be about 940 and 530 ms, respectively [22]. When the task is to respond to the thermal properties of a material based on the perceived coldness, it takes longer than the simple reaction time. It has been shown that it takes about 900 ms to discriminate a copper item from a wooded item, and the time increases with the number of the wooden items presented [44]. The time spent is considerably longer than the times required to respond to tactile properties. For example, it only took in average 400–500 ms to discriminating a hard item from a soft item.

1.4 Methods to Specify Dimensions of Material Perception

There are many variations in the methods available to specify the perceptual dimensions of tactile textures. Most of them are based on two types of multivariate

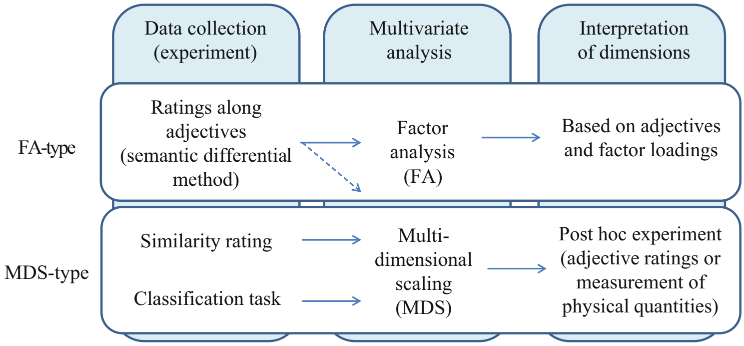

Fig. 1.2 Major approaches to specify textural dimensions. Methods are categorized into two approaches regarding multivariate analysis: factor analysis and multidimensional scaling. There are also three major experimental methods: semantic differential method, similarity rating, and classification task

analyses: factor analysis and multidimensional scaling, as shown in Fig. 1.2. In psychological experiments, subjective data must be collected such that the data conforms to either or both of these analyses. Here, these analyses and psychological experiments suitable to them are outlined.

1.4.1 Methods Based on Factor Analysis

Factor analysis, which is based on the eigenvalue decomposition of symmetric matrices in principle, constructs m types of components that are statistically orthogonal to each other from p types of variables that could co-vary ($m < p$). Each of the orthogonal components is considered as a dimensional axis of the space. Factor analysis is typically combined with a semantic differential method, in which a number of texture samples are rated one by one with adjective dyads as the criteria. For example, each material is judged in terms of multiple dyads including "rough/smooth" and "cold/warm."

For material sample i ($i = 1, \ldots, n$), the rating of a certain adjective dyad k ($k = 1, \ldots, p$) is assumed to be a linear combination of m types of latent factors and is expressed as

$$
\begin{aligned}
x_{ki} &= \mu_k + a_{k1} f_{i1} + \cdots + a_{km} f_{im} + e_{ki} \\
&= \mu_k + \boldsymbol{a}_k^T \boldsymbol{f}_i + e_{ki}
\end{aligned}
$$

where e_{ki} is a unique factor that is specific to x_{ki}, whereas a (factor loadings) is shared with x. $\boldsymbol{f}_i$ is the vector of factor score that corresponds to the coordinates of material i on the m-dimensional space. The average and variance of each element in $\boldsymbol{f}_i$ are 0 and 1, respectively. Furthermore, as restriction conditions, $e_i \perp e_j$ $(i, j = 1, \ldots, n)$ and $e \perp f$ hold, and the expected value of e_i is 0. For p types of adjective dyads, using p-variate vector ($\boldsymbol{x}_i \in \mathbb{R}^p$), the scores of material i is noted as

$$\boldsymbol{x}_i = \boldsymbol{\mu} + \boldsymbol{A}\boldsymbol{f}_i + \boldsymbol{e}_i$$

where $\boldsymbol{\mu} = (\mu_1, \ldots, \mu_p)^T$, $\boldsymbol{A} = (\boldsymbol{a}_1, \ldots, \boldsymbol{a}_p)^T$, and $\boldsymbol{e}_i = (e_1, \ldots, e_p)^T$ are the average ratings of adjective scales, matrix of factor loadings, and uniqueness of material i, respectively. $\boldsymbol{A}$ comprises the structures of independent factors and is given by solving

$$\boldsymbol{\Sigma} = \boldsymbol{A}\boldsymbol{A}' + \boldsymbol{D}$$

where $\boldsymbol{\Sigma} \in \mathbb{R}^{p \times p}$ and $\boldsymbol{D} = \mathrm{diag}(\mathrm{Var}(e_1), \ldots, \mathrm{Var}(e_p))$ are the covariance matrices of x_{ki} and e_{ki}, respectively. In order to facilitate the interpretation of $\boldsymbol{A}$, rotational operation is usually applied to $\boldsymbol{A}$ and $\boldsymbol{f}_i$.

A benefit of the method based on a factor analysis is that it is easy to interpret the meanings of perceptual dimensions acquired through the analysis because $\boldsymbol{A}$ is mediated by adjective words. This also means that it does not require some post hoc experiments to clarify the dimensionality. In contrast, a caveat is imposed on the selection of adjective dyads; they should cover all of the aspects of the set of material samples.

1.4.2 Methods Based on Multidimensional Scaling

The multidimensional scaling method specifies the coordinates of events on the m-dimensional space using the distance matrix of n events. Depending on the level of distance scale and completeness of distance matrix, several methods are available. The most famous methods are Torgerson's metric method (Young-Householder's theorem) [78] and Kruskal's MDSCAL [40, 41] for ratio and ordinal scales, respectively. The latter method can deal with matrices from which some values are missing.

For the multidimensional scaling approaches, there are two major methods to collect distance data: the dissimilarity rating and the classification method. In dissimilarity rating, participants of experiments rate the dissimilarity between two material samples using grades or visual analog scales. By averaging the dissimilarity rates among the participants, the final distance values are obtained. In classification method, each participant categorizes all samples into several groups based on their subjective similarities. Samples with similar textures are labeled as belonging to the same group. For each pair of materials, the number of times the two materials in the pair are categorized into different groups is counted. From these counts, the distance between two materials is defined. When the two materials are assessed to belong to different groups by the majority of the participants, the distance between these two materials is considered to be large.

Strictly speaking, data collected through the abovementioned processes belong to ordinal scales (non-metric); however, multidimensional scaling methods for metric scales have been sometimes used for these data partly because the higher levels of scales are generally preferred. Among methods or mathematical models to establish ratio or interval scales, a similarity choice model [45, 46], an overlap model [79, 80], the constant ratio rule [16, 17], and a complete method of triads [78] are famous. However, they are hardly used in the study of textural dimensions because these methods require a larger number of trials or comparisons. In addition, there are few studies to which scales and theories should be applied in constructing the textural dimensions.

Here, a metric multidimensional scaling method is introduced, given that the distance information conforms to the ratio scale. Let $\boldsymbol{x}_i$ be the coordinate of material i on an m-dimensional space with arbitrary origin. The distance between materials i and j is noted by d_{ij}, and $d_{ij} = d_{ji}$. Through material k, the inner product of $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ is calculated by

$$\begin{aligned} z_{ij} &= (\boldsymbol{x}_i - \boldsymbol{x}_k) \cdot (\boldsymbol{x}_j - \boldsymbol{x}_k) \\ &= \frac{1}{2}(d_{ik}^2 + d_{jk}^2 - d_{ij}^2). \end{aligned}$$

Using this equation, a matrix of inner products $\boldsymbol{Z} \in \mathbb{R}^{n-1 \times n-1}$ is computed by using the distance matrix $\boldsymbol{D} \in \mathbb{R}^{n \times n}$ which contains the element d_{ij}. On the basis of the principle of eigenvalue decomposition, $\boldsymbol{Z}$ is expanded as

$$\begin{aligned} \boldsymbol{Z} &= \boldsymbol{A}\boldsymbol{\Lambda}\boldsymbol{A}^T \\ &= \boldsymbol{A}\boldsymbol{\Lambda}^{\frac{1}{2}}(\boldsymbol{A}\boldsymbol{\Lambda}^{\frac{1}{2}})^T \\ &= \boldsymbol{X}\boldsymbol{X}^T \end{aligned}$$

where $\boldsymbol{X}$, $\boldsymbol{A}$, and $\boldsymbol{\Lambda}$ are the matrix of x_{ij}, eigenvectors, and eigenvalues, respectively. These computations, where $\boldsymbol{x}_k$ is regarded as the origin of the space, are called Young-Householder's theorem. In Torgerson's method, the origin is set to the center of all the materials. As a result of expansion, n or $n-1$ dimensional coordinates are assigned to the materials. Considering the magnitudes of eigen values, these materials are located on the m-dimensional space ($m < n-1$).

In order to interpret the meanings of the dimensions of the information space acquired by multidimensional scaling, additional experiments are needed because the multidimensional scaling merely provides the coordinate sets for multiple materials. For this purpose, either of the two representative methods can be used. The first method is based on adjectives, where individual materials are rated according to adjectival labels. This process is same as the semantic differential method. The adjective scores and the coordinates of materials are then compared to interpret the meanings of the dimensions. For example, if the coordinates along a certain dimension show a larger correlation with rough-smooth scores, then this dimension is considered to be characterized by roughness percepts. Another method is based on the physical quantities of materials. In this method, quantities such as the average surface roughness or Young's moduli of the materials are measured and analyzed in terms of correlations with the coordinates of the materials to judge the meanings of dimensions.

1.4.3 Selection of Material Samples and Adjectives

An element shared by the two abovementioned analyses is the approximation of matrix by eigenvectors with large eigenvalues. An approximated matrix expresses the large part of sample variations. If the samples are primarily distributed along a certain dimension, then this dimension is successfully extracted. However, other dimensions along which few samples are observed are ignored. For example, when the majority of samples differ in their surface roughness and have similar compliance, the dimension of roughness percept becomes prominent whereas that of softness diminishes. The same holds true for the selection of adjectives in a semantic differential method. If adjectives relating to roughness, such as rough, uneven, coarse, voluminous, and harsh, are intensively used for the rating task, then the roughness dimension is easily found. Considering these characteristics of multivariate analyses, material samples and adjectives should be selected in a balanced manner.

1.5 Summary

In this chapter, the perceptual dimensions of tactile textures were focused on. From early studies on textural dimensions, the five types of dimensions were extracted. There are two types of roughness percepts (coarse and fine roughness), as well as softness (hardness), warmness (coldness), and friction percepts. The perceptual mechanisms of each dimension were then introduced. Although the perceptual mechanisms of each dimension have been well-studied thus far, the integration of information from multiple textural dimensions is still a work in progress. Further studies are expected to elucidate material recognition and tactile textures.

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