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Psychophysical Dimensions of Tactile Perception of Textures

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Abstract—This article reviews studies on the tactile dimensionality of physical properties of materials in order to determine a common structure for these dimensions. Based on the commonality found in a number of studies and known mechanisms for the perception of physical properties of textures, we conclude that tactile textures are composed of three prominent psychophysical dimensions that are perceived as roughness/smoothness, hardness/softness, and coldness/warmness. The roughness dimension may be divided into two dimensions: macro and fine roughness. Furthermore, it is reasonable to consider that a friction dimension that is related to the perception of moistness/dryness and stickiness/slipperiness exists. Thus, the five potential dimensions of tactile perception are macro and fine roughness, warmness/coldness, hardness/softness, and friction (moistness/dryness, stickiness/slipperiness). We also summarize methods such as psychological experiments and mathematical approaches for structuring tactile dimensions and their limitations.

Index Terms—Factor analysis, Multidimensional scaling, Sensory evaluation

1 Introduction

HUMANS perceive the physical properties of materials or textures by touching their surfaces. Thus far, the perceptions of properties such as surface roughness and elasticity have been summarized in review articles [1], [2], [3], [4] from a psychophysical and neurophysiological point of view. However, a thorough discussion of the perceptual dimensionality does not exist in the literature. The dimensional structure of the perceptual space has attracted the interests of researchers in haptics, and many studies have been conducted attempting to specify this structure. However, the structures reported by these studies have varied, depending on the method of psychological experiment, the mathematical approach, the stimuli used in the experiments, and other differences in the methodology. For example, one research team asserted that the perception of texture was constructed by three dimensions i.e., roughness, hardness, and slipperiness, however, another team demonstrated that four dimensions were involved. These studies have not been comprehensively investigated after their publication. Furthermore, the experimental methods and analytical approaches employed in each study suffer from significant drawbacks and as a result the dimensionality constructed in each individual study is incomplete. The objective of this article is to investigate as many related works as possible and compensate for their individual incompleteness in order to find the common structure of perceptual dimensions. We also summarize experimental and analytical methods for structuring such dimensions along with their limitations for the benefit of those who attempt to develop perceptual dimensions.

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Definition of psychophysical dimension: We define tactile perception as the perception of the qualities and properties of material surfaces by touch. The shapes of objects are of no concern of this article. Because the dimensionality of the perception of tactile surfaces is still contentious, it is reasonable to focus only on surface perceptions, although haptic dimensions involving surface and shape perceptions would be more intriguing (and also more complicated). In general, human perception can be described by a hierarchy, which also holds for tactile perceptions. Following the studies by Chen et al. [5], [6], we assume that tactile perception is composed of psychophysical and affective layers. The psychophysical layer determines the perception of physical properties, such as surface roughness or the elasticity of materials. The affective layer is mediated by a mental process and includes perceptions such as richness, cleanliness, and kindness. In this article, we address the psychophysical layer. The psychophysical layer is more fundamental, and a common understanding or standardization of this layer will be useful for haptic researchers. For example, an understanding of human tactile dimensions is helpful in the design of tactile displays and sensors. The developers of these systems aim to extend their systems to make them multimodal. The generalization of tactile dimensionality indicates which dimension should be considered.

2 Methodology for Specifying Perceptual Dimensions

Here, we describe methodologies used for specifying the dimensions of tactile perception. In general, we first need to collect subjective data for various materials. Typical subjective data are the perceptual ratings of material properties using adjective labels or perceptual similarities between materials. Multivariate analyses are then applied to the collected subjective data in order to extract potential perceptual factors and

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TABLE 1
Combination of mathematical and experimental methods for structuring perceptual dimensions

	Factor or principal component analysis	Multidimensional scaling
Semantic differential method	○	△
Similarity estimation method		○
Classification method		○

Circle or triangle indicates more or less frequently used approaches, respectively.

dimensions. We summarize psychological experiments used for data collection and multivariate analyses in this section. Table 1 shows the combinations of psychological experiments and multivariate analyses that have been used in related works. A circle or triangle indicates that the corresponding combination has been used more frequently or less frequently, respectively.

2.1 Collection of Subjective Data

In this section, we introduce the semantic differential (SD), similarity estimation, and classification methods, which are used for acquiring subjective data. In the SD method, subjective data are collected using adjective labels such as rough or hard. Subjective data collected by SD methods are analyzed by a factor or principal component analysis. In the similarity estimation and classification methods, gross perceptual distances between two materials are acquired while the participants are asked to ignore certain types of physical material properties such as the roughness or elasticity. Perceptual distances are analyzed by multidimensional scaling (MDS) methods.

2.1.1 Semantic differential (SD) method

SD methods were originally established by Osgood et al. [7], and first applied to the study of the dimensionality of tactile perception by Yoshida [8] in 1968. Since then, a number of researchers employed this method. In an SD method, participants rate materials one by one using scales whose ends represent the two adjectives in an opposing pair such as “rough” and “smooth,” as criteria for evaluation. Five or seven grades were used in many cases. SD methods were used most frequently by researchers, including the authors of [8], [9], [10], [11], [12], [13], [14]. Instead of adjective labels, some researchers used onomatopoeic expressions [11], [12].

Strength & limitation: SD methods allow us to interpret fundamental tactile factors without additional experiments that are typically required for other methods because each factor is explained by a combination of adjective words. In contrast, fundamental factors extracted through SD methods are limited by the adjective pairs used in experiments. If adjective labels that represent a certain perceptual dimension are not involved, that dimension remains unextracted. Thus, the labels should be chosen such that they cover all potential dimensions.

2.1.2 Similarity estimation method

In many studies, participants rated the similarity of paired materials. Although various methods exist for rating the similarity, most of the similarity estimation methods fall into one of three groups: ratio judgment, grading, and visual analog scaling. In the ratio judgment method, participants estimate the relative perceptual distance of materials in a pair using arithmetic values. Ratio judgment methods were used in [15]. In the grading method, the similarity between two materials is graded using, for example, a seven-point scale. This method was used in [16], [17]. In the visual analog scaling method, participants rate the relative distance by placing a mark on a drawn line. For example, a line with “dissimilar” and “similar” labels on both poles can be used. Visual analog scaling methods were used in [18], [19].

Strength & limitation: Unlike SD methods, the number of dimensions constructed by this method is not affected by adjective words because it does not involve specific adjectives. The similarity data acquired by this method is analyzed by a MDS method. Hence, the drawbacks of MDS, which will be discussed in sec. 2.2.2, should also be considered. The main drawback of similarity estimation methods relates to the number of trials. The similarity between all possible pairs of stimuli needs to be tested in order to use classic MDS methods. Hence, researchers who use paired comparison methods tend to limit the number of texture stimuli. From limited types of textures, limited numbers of dimensions are revealed.

2.1.3 Classification method

In the classification method, participants classify many materials that are simultaneously presented to them into groups based on the similarities of the materials. Materials in the same group are supposed to be perceptually similar. Dissimilarity scores between materials are computed based on the classification. For example, the materials in the same group are assigned dissimilarity scores of 0, whereas the dissimilarity score between two materials in different groups is set to 1. The results from a sufficient number of participants produce similarity distances among the materials. Classification methods were used in [20], [21], [22], [23].

In the free arrangement classification method, which was used in [24], participants locate materials on a plane such that the geometric distances of materials accurately represent the perceptual distances of materials. The geometric distances are used to calculate the perceptual distances between materials. This method tends to limit the perceptual space to two-dimensions because the space is constructed based on the stimuli spread on a plane.

Strength & limitation: This method is participant-friendly in terms of time required for experiments, which allows us to test a sufficient number of textures. It is not possible to discuss the classification method in detail due to unsatisfactory literature relating to comparative research on the experimental methodology. However, one may consider that it is extreme to assume textures belonging to the same group have no dissimilarity. Furthermore, this method typically does not assume subclasses. Each stimulus belongs to only one class. These assumptions may lead to the loss of some distinctions between textures.

2.2 Multivariate analyses for subjective data

2.2.1 Factor analysis (FA)

In factor analysis, inherent factors are extracted from multivariate data after testing for correlations between variables. The number of factors is lower than the number of variables, whereas the factors represent a large portion of the variance in the original data. This analysis is applied to data acquired by SD methods. Let $\boldsymbol{x}_i$ $(i=1,\ldots,n)$ represent subjective data collected for n materials using p adjective pairs. $\boldsymbol{x_i}$ can then be represented by the scores of m factors $\boldsymbol{f}_i$, a factor loading matrix $\boldsymbol{A}$, and a unique factor $\boldsymbol{e}_i$. $\boldsymbol{x}_i$ can be written as follows:

$$\underset{p\times 1}{\boldsymbol{x}_i} = \underset{p\times m}{\boldsymbol{A}}\underset{m\times 1}{\boldsymbol{f}_i} + \underset{p\times 1}{\boldsymbol{e}_i} \quad (i=1,\cdots,n). \tag{1}$$

Each of the m factors is considered an independent factor that constitutes a perceptual dimension. Principal component analysis is also applied to data collected by SD methods. This analysis is similar to factor analysis in that the variation of original variables is represented by fewer factors.

2.2.2 Multidimensional scaling (MDS)

A multidimensional scaling method places materials on an r-dimensional space such that the perceptual distances between the materials are optimally maintained. Perceptual distances determined by similarity estimation or classification methods are often used to set the separation distances of materials. Some researchers selected the subjective distances between materials using data acquired by SD methods [8], [9].

When the perceptual similarities between materials j and k for all material pairs are given as $\boldsymbol{E}=(e_{jk}|j\neq k)$, $(j,k=1,\ldots,n)$, the coordinates of n materials on an r-dimensional space are determined by minimizing the following function:

$$Q=-\sum_{j=1}^{n}\sum_{k=1}^{n} e_{jk} \parallel \boldsymbol{y}_j-\boldsymbol{y}_k \parallel^2, \tag{2}$$

where $\boldsymbol{y_j}$ is the coordinate of material j. Each of the r dimensions is considered to be a potential perceptual dimension.

Limitation: The drawback of the MDS method is that the orthogonal rotation of the constructed space is indeterminate. An individual axis never corresponds to an individual psychophysical dimension. Many researchers have noted the difficulties of interpreting results from an indeterminate axis system. Thus far, methods for this interpretation have varied between researchers. Even worse, in some literature, this inconvenient nature of the MDS method is almost entirely neglected.

2.2.3 Imbalanced textures: limitations common to both analytical methods

Both analytical methods reveal a lower number of variables than is required to accurately describe the variations in the original data. If the original data is imbalanced in its density, then the characteristics of less dense data are unlikely to be detected. For example, moist or adhesive sample materials are less frequently used, whereas paper, fabric, rubber, stone, or leather materials, which are easily stored and prepared in laboratories, are often adopted. When using these common sample materials, factors representative of moist or adhesive materials are unlikely to be detected. An imbalance in the range of materials used is a problem common to most studies. None of the studies balanced or determined stimuli sets after a satisfactory discussion of the issue. A simple increase in the number of stimuli is not recommended because without careful consideration of the properties, this may not balance the range of materials. The balance of stimuli in the sample set should be considered rather than the quantity of stimuli.

2.3 Post hoc validation of dimensionality

The interpretation of factors or dimensions extracted by the above multivariate analyses is sometimes problematic. For example, we cannot judge with certainty whether a specific factor represents a perceived surface smoothness or elasticity in some cases. In other cases, it is virtually impossible to interpret and name a dimension even when its contribution ratio is large. An intuitive interpretation of factors and dimensions was used in some research studies. Thus, a validation of this interpretation is necessary. Validation is especially required for dimensions determined by MDS methods. In SD methods, the characteristics of individual factors can be estimated to some extent using the factor loadings of adjective labels. There are two methods for validating the interpretation. One method uses adjective labels, whereas the other exploits the physical properties of materials.

During validation using adjective labels, participants rate materials using adjectives. The properties of the dimensions are validated mainly based on the correlations between the adjective ratings and the scores of individual dimensions. For example, when the scores on a specific dimension have strong correlation with the ratings of "rough," we interpret this to mean that this dimension is related to roughness perception. Validation using adjective labels was performed in [19], [20], [21], [25].

During validation using the physical properties of materials, correlations between the scores of individual dimensions or factors and physical values such as the average roughness or Young's modulus are considered. For example, when the scores on a specific dimension have a strong correlation with the average roughness of materials, this dimension is considered to be related to roughness perception. Validation using physical properties was performed in [15], [18], [23].

2.4 Limitations of adjective labels

As described thus far, adjective labels are often used for the detection and validation of perceptual dimensionality. Hence, these methods suffer from the difficulties associated with selecting appropriate adjectives.

One problem is a limited vocabulary, i.e., when there is not an appropriate adjective to describe a certain dimension or factor. For example, some researchers attempted to separate the macro and fine roughness dimensions, and a few of them succeeded. The problem here is that adjectives indicating the opposite poles of macro and fine roughness are semantically similar: they are "flat," "smooth," and "even." Furthermore, when it comes to tactile perception, the vocabulary relating to physical properties of materials is limited. Hence, verbal methods always restrict the structuring of dimensionality. One comprehensive list of possible adjective terms relating to touch can be found in [26].

Another problem is a consensus among participants. Soufflet et al. found a case in which the consensus of adjective terms became a problem [27]. In their research using verbal labels, women tended to classify fabrics into smaller subgroups than men. Also, the majority of those who were working in the textile industry used "nervous" as a sensory property of fabrics, which did not correspond to any words used by the non experts.

3 Studies on Structuring Perceptual Dimensions

We searched for studies on psychophysical dimensions of tactile perception using scientific archives including Science direct, SpringerLink, google scholar, and Web of Science with the keywords such as "tactile," "texture," "dimension," "factor," "multidimensional scaling method (MDS)," "factor analysis," "principle component analysis," and "correspondence analysis." Among potential candidates, we selected ones investigating the dimensional structures of tactile perception. Those focusing on specific single dimensions such as roughness were excluded.

Table 2 lists several studies on the structuring of perceptual dimensions and the materials used in each experiment. The names of dimensions may differ from those in the original papers summarizing these studies. We qualitatively summarized the names by taking into account how they were discovered. The individual studies are described in detail in this section.

Yoshida 1968 (Roughness, hardness, warmness & moistness): In this experiment, 25 materials including silver, aluminum, vinyl, nylon, silk, and linen were used, and subjective data was collected using an SD method in which 20 adjective pairs were rated [8]. Twenty-five participants freely explored the materials with vision. Compared with the participants in other related works, they were allowed more freedom to touch the materials, so they could pinch and hold the materials. Using a factor analysis, four factors were extracted.

The first factor was described by "painful or not painful," "hard-soft," "cold-warm," and "rough-smooth" scores in descending order. It should be noted that "pain" does not fit the definition of a psychophysical dimension. As a result, we assume that the first factor was a mixture of hard/soft, cold/warm, and rough/smooth dimensions.

The second factor loaded "wet-dry," "heavy-light," "substantial or empty and hollow," and "smooth-rough." "Substantial or empty and hollow" was possibly connected with the weight or density of materials because its scores and those for "heavy-light" were highly correlated. We exclude the properties related to weight from the surface properties of textures. Hence, the second factor was a mixture of moist/dry and rough/smooth.

The third factor was strongly associated with "sharp-dull." This adjective pair was almost ignored without reason, and the dimension was called "hard-soft" that exhibited the second highest load even though it was half the load of "sharp-dull." It is not clear how participants interpreted the terms "sharp" and "dull."

The fourth factor was related to "elastic or not elastic." We assume that "elastic" represented the bending stiffness of materials, because the participants could hold and bend the materials. However, in most of the other studies, the participants were allowed to touch only the surface of the material, and some of these studies separated the properties related to the bending stiffness or thickness of materials from the perception of surfaces. We also follow the latter concept and focus on surface properties only.

Lyne 1984 (Hardness & roughness): Lyne et al. structured the perceptual space of eight types of tissue papers and paper towels using a similarity estimation method and MDS [18]. In their experiment, forty participants rated pieces of paper with visual and haptic perceptions.

They extracted and named three dimensions based on the correlationship between physical parameters: namely, surface softness, rigidity, and embossed properties. The surface softness dimension corresponded to hardness/softness. The perceived rigidity was strongly correlated with the bending stiffness, which we exclude from the surface properties of textures. The embossed dimension accurately represented the embossed patterns of paper surfaces. Pieces of paper embossed with a large square were located on one pole, and pieces of paper embossed with a small circle were located on the opposite pole. From reviewing the experimental data, it is clear that this dimension is related to macro surface patterns or paper roughness.

Hollins 1993 and 2000 (Roughness, hardness & slipperiness): Hollins et al. investigated the perceptual dimensions of 17 materials, including paper, plastic, and velvet [20]. In their experiment, twenty participants passively explored materials where the material beneath a finger pad moved. Participants conducted classification tasks, and subjective data were analyzed using a MDS method. As a result, three factors were extracted. By comparing the correlations between the factor scores and ratings acquired by adjective scales, they named each factor. The first factor was correlated mostly with smooth/rough, then with flat/bumpy, slippery/sticky, and cool/warm in descending order. Smooth/rough and flat/bumpy were regarded as semantically identical due to the high correlation between their results. The second factor was highly correlated with soft/hard. The third factor did not show strong correlations with any adjective scales and was slightly correlated with sticky/slippery ($r = 0.43$) and bumpy/flat ($r = 0.37$). They named this factor the "elastic factor" mainly because materials with prominent compressive properties were located along this factor, however, the definition of this factor was fairly unspecific.

Later, Hollins et al. re-investigated the structure of perceptual dimensions using a similarity estimation method [19]. They focused on personal differences of dimensionality rather than on its general structure. As a result, participants demonstrated two- or three-dimensional structures. The two-dimensional spaces were robustly constructed by rough/smooth and soft/hard scales. For some participants,

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TABLE 2
Reference table of studies on perceptual dimensions of tactile textures

Author	Year	Texture	Dimension 1	Dimension 2	Dimension 3	Dimension 4	Modality
Yoshida [8]	1968	25 materials	Hard/soft, Cold/warm, Rough/smooth	Moist/dry, Smooth/rough	Hard/soft		Visuo-hapt.
Lyne [18]	1984	8 tissues & paper towels	Hard/soft	Embossed (Roughness)			Visuo-hapt.
Hollins [20]	1993	17 materials	Rough/smooth, Warm/cold, Sticky/slippery,	Hard/soft	Not specified (Stiff)		Haptic
Hollins [19]	2000	17 materials	Rough/smooth	Hard/soft	Sticky/slippery		Haptic
Tamura [13]	2000	15 materials	Rough/smooth Hard/soft	Warm/cold	Moist/dry		Unknown
Picard [21]	2003	24 car seats	Hard/soft, Rough (Fine roughness)	Relief (Macro roughness)	Hard/soft		Haptic
Picard [25]	2004	40 fabrics	Hard/soft	Rough/smooth			Haptic
Soufflet [27]	2004	26 fabrics	Rough/smooth Hard/soft	Warm/cold			Haptic
Ballesteros [22], [24]	2005	20 materials	Rough/smooth	Hard/soft	Slippery/sticky		Haptic
Shirado [12]	2005	20 materials	Rough/smooth	Cold/warm	Moist/dry	Hard/soft	Haptic
Gescheider [28]	2005	7 raised dots	Macro roughness	Rough/smooth	Fine roughness		Unknown
Bergmann Tiest [23]	2006	124 materials	Hard/soft	Smooth/rough	Not named	Not named	Haptic
Tanaka [11]	2006	13 fabrics	Moist/dry, Rough/smooth	Hard/soft, Cold/warm			Haptic
Yoshioka [15]	2007	16 materials	Hard/soft	Rough/smooth	Sticky/slippery		Haptic
Summers [29]	2008	10 papers	Rough/smooth				Haptic
Guest [30]	2011	15 fluids	Slippery/sticky	Rough/smooth	Oily		Haptic
Guest [26]	2011	5 fabrics	Rough/smooth	Moist/dry	Hard/soft		Haptic

rough/smooth was strongly correlated with sticky/slippery. For those who demonstrated the three-dimensional spaces, rough/smooth and sticky/slippery were associated with different dimensions. This study concluded that the importance of sticky/slippery dimension varies between individuals.

Tamura 2000 (Roughness, hardness, warmness, & moistness): Tamura et al. acquired subjective data from participants using an SD method [13]. They used 15 materials, including aluminum, duralumin, rubber, and wood. Eleven adjective pairs were used and 20 participants joined the study. It was not clear whether participants were blindfolded. As a result of their factor analysis, Tamura et al. constructed three dimensions. The first dimension was correlated with hard/soft and rough/smooth ratings. The second dimension showed a strong correlation with warm/cold ratings. The third dimension was correlated with moist/dry ratings.

Picard 2003 and 2004 (Hardness, fine & macro roughness): In experiments conducted by Picard et al., twenty participants classified 24 materials on the basis of similarity [21]. Then, these similarities were analyzed by a MDS method. Four dimensions were extracted and specified by verbal labels applied to the materials. The materials were those used for car seats, such as velvet, plastic, and artificial suede.

The first dimension was frequently described by the labels of soft, mellow, smooth, and pleasant on the one side and harsh, rough, and hard on the other side. "Harsh" and "rough" are semantically close and exhibited similar correlation coefficients with the first dimension. Similarly, "mellow" and "soft" were close in terms of correlation coefficients. Hence, we consider that this dimension was a mixture of the rough/smooth and hard/soft dimensions.

The second dimension was mainly described by the terms thin and thick and was slightly correlated with the relief and smooth scales. We exclude the thickness of materials from the surface properties.

The third dimension was correlated with relief scales. The other side of the "relief" was "smooth," but these were not completely aligned.

The fourth dimension was slightly correlated with the hard and mellow scales. This was not identical to the first dimension because the fourth dimension was not correlated with the rough and smooth scales at all.

We consider that two types of roughness should be considered: macro and fine roughness. The features of macro and fine roughness were explained by "relief," and "rough," respectively. However, the opposing term for both these two types of roughness could be "smooth." "Smooth" was not rated as the exact opposite of "rough," or "relief," and it tended to be better aligned with "relief." This clearly demonstrates a vocabulary problem, i.e., it is not easy to assign appropriate opposing terms to two types of roughness.

Considering all the results, the dimensions were interpreted as follows. The first was mediated by the terms rough/smooth as well as hard/soft. The second was represented by thin/thick. The third and fourth were the macro-roughness (relief/smooth) and hard/soft dimensions, respectively.

Picard et al. also conducted similar studies involving fabrics [25]. Twenty blindfolded participants performed a classification task using twenty types of fabrics. Another twenty participants performed the same task using twenty different types of fabrics. The results from the two groups were separately analyzed using MDS methods. The dimensions were then interpreted using unipolar adjectives that were attached to clusters of similar fabrics by the participants. One slightly minor and two major dimensions were found for both groups. The perceptual spaces of the two groups were a fair match, and it was concluded that the space was constructed with the following three salient dimensions–rough/smooth, hard/soft (although it was stated that harsh/soft was more appropriate for these analyses), and thin/thick. Furthermore, it was suggested that, as dimensions, slippery/sticky and relief/silky were elicited by specific materials and were not salient.

Soufflet 2004 (Roughness, hardness, & warmness): Soufflet et al. constructed the perceptual dimensions of 26 fabrics using a classification method. Then, they extracted three potential dimensions. Eleven industrial experts and 40 novices joined the experiments. Participants were allowed to hold the fabrics in a dark room that moderated the effects of vision.

According to the correspondence between the adjective labels and fabrics, the first dimension was related with the labels "harsh," "rough," and "stiff." The label "soft" was placed at the other extreme of this dimension. This dimension is considered to be a mixture of hard/soft and rough/smooth, noting that the "smooth" label was not clearly align with this dimension.

The second dimension was represented by the thin/thick labels. Near the "thin" label, "smooth," "slippery" and "cool" labels were observed. "Warm" and "wooly" labels were placed near the "thick" label. This dimension is therefore considered to be a mixture of thin/thick and cool/warm dimensions. Also, non wooly fabrics may have tended to be slippery and smooth.

Soufflet et al. wrote that the interpretation of the third dimension was not easy, however, based on the corresponding adjective labels, they specified this dimension as stiff/supple: it represents the bending stiffness of fabrics.

Ballesteros 2005 (Roughness, slipperiness, & hardness): Ballesteros et al. investigated the perceptual space of 20 materials including tile, soap, adhesive tape, and a sponge [22], [24]. They used free classification and spatial arrangement methods in order to collect data for a MDS method. In [22], they reported a two-dimensional model from 16 participants. They named the factors from the characteristics of materials distributed on the constructed perceptual space. The first dimension was named the rough/smooth factor. The second dimension was named the slippery/sticky and hard/soft factor. In [24], they proposed a three-dimensional structure in which the three dimensions were rough/smooth, slippery/sticky, and hard/soft.

Shirado 2005 (Roughness, warmness, moistness, & hardness): Shirado et al. acquired subjective ratings of 20 materials such as metal, textile and wood using an SD method [12]. Thirty participants explored the materials without vision. They used 13 adjective and Japanese onomatopoeia label pairs such as *sara-sara/nuru-nuru* and *zara-zara/sube-sube*. The four factors were referred to as rough/smooth, cold/warm, moist/wet, or hard/soft based on the combination of factor loadings.

Gescheider 2005 (Macro & fine roughness): Gescheider et al. investigated the perceptual dimensions of raised-dot textures using the adaptation of Pacinian channels [28]. They prepared plastic trapezoidal dots that were arranged with inter-dot spaces ranging from 1.34 mm to 5.93 mm. Nineteen participants rated inter-texture differences using 15-grade scales. In order to reduce the stickiness of textures, talcum powder was rubbed on fingers of participants. Gescheider et al. used the adapted and unadapted conditions of Pacinian channels because their major objective was to investigate the role of Pacinian corpuscles on roughness coding. The adaptation was realized by 250 Hz vibration stimuli. The inter-texture difference data were analyzed by a MDS method, and three dimensions were extracted. The attributes of each dimension were predicted based on interviews with participants.

The first dimension was termed the blur dimension, which indicates "a degree to which individual dots cannot be felt, but instead blur together." The second dimension was termed the roughness dimension. The third dimension was termed clarity, which was defined as "a contrast between the dots and background." Later, these attributes were successfully validated through a magnitude estimation method, in which participants rated textures using three criteria: blur, roughness, and clarity.

Macro roughness (Pacinian-independent): The blur and roughness dimensions were both functions of dot spacings, whereas their profiles were clearly different. The scores in the blur dimension monotonically decreased with increasing dot spacing. On the other hand, the scores in the roughness dimension fell along an inverted u-shaped curve that was similar to profiles observed for the curve of the perceived roughness of gratings (e.g. [31]). The adaptation did not influence the blur and roughness dimensions. Hence, we speculate that blur represented Pacinian-independent macro roughness.

Fine roughness (Pacinian-dependent): The clarity dimension was affected by the adaptation of Pacinian channels, but not by the dot spacing. In additional experiments, it was found that the clarity dimension was related to the roughness of individual dots rather than the spaces between dots. Hence, the clarity dimension represented Pacinian-dependent fine roughness.

Gescheider et al. separately extracted the macro and fine roughness dimensions. Interestingly, when the participants were explicitly asked to rate the overall roughness of textured surfaces, these two dimensions were integrated. This study suggested that the attention or instruction given to participants could modify the constructed perceptual dimensions.

Bergmann Tiest 2006 (Roughness & hardness): Bergmann Tiest et al. investigated the perceptual space of 124 materials using a classification method involving twenty blindfolded participants [23]. The materials included wood, glass, paper, rubber, cloth, and plastic. The perceptual dimensions were constructed by a MDS method, and four dimensions were extracted.

The first and second dimensions were specified by hard/soft and rough/smooth factors, respectively, based on the correlations between relevant physical values. The other two factors were not clearly interpreted.

Tanaka 2006 (Roughness, moistness, hardness, & warmness): Tanaka et al. constructed the perceptual space of 13 textiles, including cotton, silk, and satin, using an SD method [11]. Twenty-one blindfolded participants rated textiles using seven adjective pairs. They extracted two potential factors using a factor analysis. The first factor was described by the labels moist/dry and rough/smooth. The second factor was described by the labels hard/soft, flat/downy, and cold/warm. Because all materials were textiles attached on flat boards, the labels flat/downy were considered to be semantically similar to hard/soft.

Yoshioka 2007 (Roughness, hardness, & slipperiness): Yoshioka et al. structured the perceptual dimensions of 16 materials, such as paper, rubber, denim, and suede, using a similarity estimation method [15]. They applied a MDS method to the dissimilarity scores acquired from eight participants. They extracted three dimensions and specified them by comparing the results of adjective ratings given to each material. According to the adjective ratings, these dimensions were described by rough/smooth, hard/soft, and sticky/slippery.

Summers 2008 (Roughness): Summers et al. constructed the perceptual space of ten types of paper that could be used for banknotes [29]. Using haptic cues without vision, participants selected one of three samples. Two of the samples were made of the same material. They were instructed to pick up the pieces of paper using one hand and pass it to the other hand. From the answer ratios of this task, d' between materials was calculated. Summers et al. then applied a MDS method to these d' values and extracted two potential dimensions. The first and second dimensions were predicted to be the rough and stiff dimensions, respectively. These dimensions were validated by ranking tasks in which participants ranked materials in order of their perceived roughness and stiffness. These ranks agreed well with the ranked scores of materials for individual dimensions. In addition, the ranked average roughness of a material's surface was consistent with the perceptual ranks. Their bending stiffness was consistent with the perceptual ranks of stiffness; hence, the stiffness dimension originated purely from the bending stiffness of paper, which we exclude from the surface properties of materials.

Guest 2011 (fluids) (Slipperiness, roughness, & oily): Guest et al. investigated the tactile perception of fluids such as oil, water, and cream, involving twenty participants [30]. Using index fingers, twenty participants explored fluids spread over plastic sheet, forearm, and thumb. They applied a factor analysis to scores given to 28 adjective labels and discovered five factors. Because they did not use semantically opposed pairs, but unipolar scorings, the factors were also unipolar.

The first factor, namely the watery factor, loaded "wet," "flowing," "slippery," "damp," "thin," and "cold" labels. The possible opposing factor was represented by the "thick," "rubbery," "draggy," and "sticky" labels. These two factors correspond to slippery/sticky. Furthermore, the cold/warm label may have been included although warm sample textures were not used. Thin/thick appeared in this dimension, but, it was not clear how participants interpreted this label. This factor did not literally indicate the thickness of textures because participants touched flat plates or skins on which the fluids were spread.

TABLE 3
Number of reports of tactile dimensions in 16 studies

Rough/smooth		Hard/soft	Cold/warm	Frictional	
17		14	6	10	
Macro	Fine			Moist/dry	Slipp./sticky
2	2			5	5

The second factor was named textured and mostly described by "gritty," "bumpy," "dry," and "rough" labels. This factor was interpreted as roughness factor. The opposing factor was described by the labels "smooth," "silky," "soft," "velvety," and "creamy" labels, and was therefore called the silken factor. These two factors represent rough/smooth, and possibly hard/soft, although "hard" label was not used in the experiments.

The last factor highly loaded "oily," "greasy," and "slimy" labels, and was clearly distinguished from the first factor. This factor was named oily.

Guest 2011 (fabric) (Roughness, moistness, & hardness): Guest et al. analyzed the tactile dimensions of five types of fabrics using a factor analysis [26]. The fabrics included cotton, latex, hessian, and silky and textured polyester. The number of materials was very small, and their aim was to determine whether tactile dimensionality depended on the location on the body contacting the surface. Thirty-five participants rated the materials using 33 unipolar adjective words. As a result similar dimensions were discovered for the different body sites.

The first factor positively loaded the labels "rough," "bumpy," and "prickly", and negatively "smooth." This factor was assumed the rough/smooth dimension.

The remaining three factors were unipolar. The second factor was associated with the labels "wet," "damp," "cold," and "greasy." A possible opposing factor was associated with "fuzzy," "fluffy," and "dry." These two factors indicated the moist/dry dimension. Further, they may have included the slippery/sticky and cold/warm dimensions, but these characteristics were not prominent.

The last factor was also unipolar, and described by the labels "hard," "firm," and "sharp." This factor may have been the opponent of "fuzzy," "fluffy," and "dry" factor mentioned above, and collectively represent the hard/soft dimension.

It is difficult to interpret the unipolar factors as bipolar ones, however, we consider that the extracted dimensions were the rough/smooth, moist/dry, and hard/soft dimensions in terms of bipolar dimensions.

4 Five Perceptual Dimensions

The above mentioned studies clearly do not share a common tactile dimension structure. They are complementary because each individual study was incomplete due to limitations of the methods or due to the imbalanced textures used in experiments. Here, we construct the commonality of dimensions taking into account the reasons for the variety of dimensions found in the above studies.

4.1 Three fundamental dimensions

Table 3 shows the number of reports of tactile dimensions or factors in related studies. For a broader category of materials, roughness (rough/smooth), hardness (hard/soft), and warmness (cold/warm) dimensions were very frequently observed. These three dimensions were consistently extracted. In addition, the perceptual mechanisms of these dimensions are clearly different (as described later in sec. 5). It is reasonable to refer to these dimensions as the fundamental dimensions of tactile perception.

When it comes to the magnitude of the contribution of these three dimensions, dimension 1 in Table 2 shows the most prominent dimensions or factors found in each study. According to the table, roughness or hardness was potentially the most prominent dimension. Furthermore, Bensmaïa et al. reported that roughness and friction rather than the warmness factor contributed to the perceived dissimilarities between materials [32]. It seems that among the three fundamental dimensions, hardness or roughness is more prominent than warmness, although their contributions vary across studies.

4.2 Dimensions of macro and fine roughness

Roughness perception can be divided into two dimensions. A few studies extracted separately the macro roughness, which was represented by the “uneven,” “relief,” or “voluminous” labels, and the fine roughness, which was mainly represented by the “rough” labels. Gescheider et al. clearly separated the fine and coarse roughness dimensions through experiments using the adaption of Pacinian corpuscles [28]. Picard et al. uncovered macro roughness referred to as relief, and fine roughness, which they referred to as roughness [21]. When we consider whether or not these two types of roughness dimension exist, it is helpful to focus on the perceptual mechanisms. As described in sec. 5, perception of macro and fine roughness perceptions are mediated by different mechanisms, and this supports the presence of two types of roughness dimension. Thus, we regard the perception of fine and macro roughness as belonging to different dimensions. Nonetheless, we should remark that the separation of perceptual mechanisms does not necessarily mean the separation of recognizable perceptual dimensions.

Why macro and fine roughness factors are hardly detectable: We consider here the major reasons that make it difficult to extract the macro and fine roughness dimensions separately. First, there is a significant overlap between the perception of fine roughness and macro roughness. (see sec. 5). Second, the rough/smooth adjective label, which has been most frequently used in related works, can be interpreted as both macro and fine roughness. Also, in describing the roughness with bipolar adjective pairs, similar words such as “smooth,” “even,” or “flat” can be substituted for the other poles. Thus, the specification of dimensions using adjective labels may obscure the existence of two types of roughness dimensions. Using appropriate attention and well described scales, the macro and fine roughness dimensions can be separated. For example, Gescheider et al. used scales with descriptions in order to maintain consistency with the words in their post hoc validation phases [28].

4.3 Frictional dimension

Slippery/sticky and moist/dry dimensions are mediated by friction: Possibly the most controversial dimension comes from friction. Several studies reported dimensions described by moist/dry [11], [12], [13], [30] and sticky/slippery [19], [15], [22], [30]. We consider that these dimensions come from the dimensions that are related to friction. Some studies reported that the perception of sticky/slippery and moist/dry was mainly attributed to friction forces or friction coefficients [33], [34], [15], [30], although other physical properties such as the elasticity and surface roughness also collectively determine the perception of moistness and stickiness [5], [6], [35], [36]. We focus on the fact that the sticky/slippery and moist/dry dimensions have never been extracted independently through a single experiment. It is reasonable to conclude that these two dimensions originate from a single dimension. We call this dimension the frictional dimension.

Frictional dimension tends to hide in the rough/smooth dimension: Some studies suggest a correlation between friction and roughness perception [37], [38], [39], whereas lubrication did not affect the perception of fine roughness [40]. Furthermore, Skedung et al. demonstrated using coated paper that perceived roughness was based on the surface roughness rather than finger friction [41]. We consider that the roughness and frictional dimensions are different partly because many studies extracted the sticky/slippery or moist/dry dimension and the rough/smooth dimension as different dimensions in a single study [13], [19], [12], [15], [22], [30].

The frictional dimension tends to be hidden in the roughness dimension because changes in surface roughness influence the frictional properties of textures. For example, Smith et al. showed the relationships between the roughness perception of raised dots and the variations of tangential forces (stick-slip effects) applied to them when a finger traversed raised dots [38]. When the surface roughness and friction were dependent, the roughness perception and friction showed strong correlations. In addition, in most of the studies considered, the number of sample textures that represent the frictional dimension was relatively small. Wet textures in particular were rarely used. From multivariate analyses, the frictional dimension is regarded as a minor dimension particularly in the case of imbalanced sample textures.

Oily and Watery: Finally, Guest et al. [30] suggested the possibility of two types of sub-dimensions, i.e., watery and oily, in the frictional dimension as a result of their research using plates covered with watery, oily, and creamy fluids. Because most researchers did not use such a wide range of oily or watery textures in their experiments, we do not have satisfactory information to discuss whether these are different dimensions. One possibility is that these are clearly differentiated by the presence of frictional vibration, namely stick-slip phenomena. Both watery and oily textures are slippery;

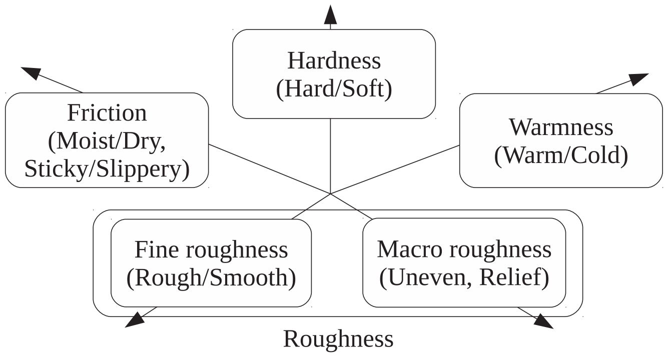

Fig. 1. Five psychophysical dimensions of tactile perception for materials/textures

however, watery ones causes the vibration whereas oily ones do not [30], [42]. Another possibility is that watery and oily dimensions align on the same dimension because the opposing adjective terms for these terms could be identical: “sticky” and “dry.” Oily textures are very slippery and viscous; hence, they are placed on the extreme of slippery/sticky dimension. In contrast, watery textures are placed in the neutral position along this dimension.

4.4 Five dimensions of tactile perception

Based on the considerations in the above sections, we summarize here the five possible psychophysical dimensions of tactile perception. These are the macro and fine roughness, warmness, hardness, and friction (wetness and stickiness) dimensions (Fig. 1). This dimensional structure is similar to the categorization that has been considered thus far. Bergmann Tiest, in his review article on perceptual mechanisms, classified tactile perceptions into four categories: roughness, compliance, coldness and slipperiness [4]. Bensmaïa also reviewed related studies on these four dimensions in his review article [3]. However, the reasons for this categorization were not highlighted; the present review underlies their categorization.

It is difficult to discover all five dimensions in a single study. Hollins et al. attempted to specify the perceptual dimensions using five adjective labels: rough/smooth (fine roughness), flat/bumpy (macro roughness), hard/soft, slippery/sticky, and warm/cool. However, their study ended in the extraction of only two or three of these five potential dimensions partly because of the limited number of textures involved [20]. In addition, in a subsequent study using virtual textures presented by a force feedback device, Hollins et al. failed to separate the perceptual dimensions of four physical stimuli: spring constant (hardness), kinetic friction coefficient, sinusoidal bump size (roughness), and vibration at 115 Hz [43]. The five perceptual dimensions listed above have not yet been extracted in a single experiment. Finding these dimensions in a single experiment is a task for future research studies. Factor analyses and multidimensional scaling methods reduce the likelihood of detecting weak dimensions; thus, the number of materials that represent individual dimensions should be balanced. In a semantic differential method and in the post hoc validation of dimensions, suitable adjective labels that describe the five dimensions should be used.

5 Perceptual Mechanisms of Individual Tactile Dimensions

The mechanisms of tactile perception have been studied in-depth, although some aspects are still not well understood. The progress of studies in this area will elucidate the perceptual dimensions because the perceptual mechanisms are intimately related to the tactile dimensions. Here, we briefly introduce the perceptual mechanisms of individual tactile dimensions in order to underlie the classification of five tactile dimensions. Further details and a discussion on related controversial issues are included in the review articles by Jones and Lederman [1], Lederman and Klatzky [2], Bensmaïa [3], and Bergmann Tiest [4].

5.1 Roughness/Smoothness (Macro and Fine)

The perceptual mechanisms of surface roughness vary depending on the fineness of the roughness. Many researchers pointed out that mechanisms are different above grating wavelengths of 1 mm and below grating wavelengths of hundreds of micrometers. For coarse surface roughness, it is known from neurophysiology studies that the spatial distribution of SAI units contributes to roughness perception [44], [45], [31] whereas the temporal information on skin vibration that is caused by exploring rough textures has an insignificant effect on the perception [46], [47]. In contrast, for finer surface roughness, the contribution of the vibratory information is clearer [48], [49]. Thus, FAI and FAII units are related to the perception of fine roughness.

5.2 Friction

Friction perception is mediated by the skin of the finger pad, although it tends to be categorized into force or proprioception. The perceptual mechanism of friction has not yet been elucidated. Skin stretch or adhesion of a finger pad to textures has been considered to mediate the perception of friction, and one remarkable suggestion is that the stick-slip phenomenon between a finger pad and a frictional texture influences the friction perception [50], [42]. Zigler considered that the perception of stickiness and wetness was attributed to the adhesion of finger pad skin to textures that were scanned by a finger [51], [52]. This idea is consistent with a report indicating that the magnitude of finger pad skin stretch is correlated to the perception of friction [53]. For such dynamic skin stretch caused by friction, all receptor classes could be activated [54], [55]. One may doubt that the frictional and fine roughness dimensions are the same. However, it appears reasonable that the perception of friction is based mainly on skin stretch related to textures, whereas the perception of fine roughness is based on vibration of the finger pad. Two interesting studies support this assumption. Taylor and Lederman investigated the perception of fine roughness using lubricant soap [40]. They concluded that roughness perception was insensitive to the frictional status of the surfaces. Nonomura et al. investigated friction perception of a flat surface using a variety of lubricant oils with different frictional properties [42]. For the flat surface, they used a fairly flat glass that did not cause skin vibration due to its surface patterns. They concluded that humans could estimate the magnitude of friction under such conditions. Finally, although the perception of slipperiness in prehension and the frictional property of textures should not be confused, there are numerous studies on slipperiness in grasping [56], [57], [58].

5.3 Warmness/Coldness

In material recognition, the importance of heat transfer during the contact of the finger pad with a material has long been recognized [59]. The perception of warmness and coldness of materials is attributed to the heat transfer property between textures and finger skin [6], [12], [60], [61], [62], [63]. The receptors of heat stimuli were not understood until recently, although the warm and cold points on skin and the warm and cold fibers in skin have been known for a long time. These points and fibers selectively respond to cold or hot stimuli. Recently, TRP ion-channels on free nerve endings have been identified as heat and coldness receptors [64], [65]. For instance, TRPV1 responds to heat stimuli above approximately 43°C. TRPV2, TRPV3, and TRPV4 also respond to stimuli that are warmer than human body temperature. These ion-channels are activated in different temperature bands. The perception of temperatures below human body temperature is mediated by receptors, such as TRPA1 and TRPM8.

5.4 Hardness/Softness

The perception of softness or elasticity is attributable to tactile cues [66], [67], although we tend to consider the perception of the spring constant of materials to be related to force information. In the mechanism for the tactile perception of softness, the contact area between the finger pad and the target object is important. In [68], [69], the researchers demonstrated tactile softness displays that controlled the contact area between their contactor and finger pad. However, it is not clear whether the pressure distribution in the contact area, the history of area changes, or another type of information is dominant.

6 Differences between modalities

6.1 Vision and touch

The structures of perceptual dimensions should be different in the visual and haptic modes. Comprehension of these differences will benefit designers of websites and catalogues. According to our classification of the five dimensions of tactile perception, the visual and haptic dimensions are not significantly different. However, there exist dimensions that are unique to visual perception, such as those relating to glossiness, contrast, and patterns of surface textures, whereas no dimensions clearly specific to tactile perception have been reported. The details of these dimensions are described in the following sections.

6.1.1 Five dimensions are shared between vision and touch

Three articles introduced in sec. 3 also compared the dimensionality between touch and vision. All of these agreed with the similarities of the tactile and visual dimensions.

Yoshida [17] and Picard [70] constructed the perceptual dimensions under haptic-only, visual-only, and visuo-haptic conditions for comparison. Both studies observed similar structures using the three conditions although some textures were significantly impacted by the variation of modality [70]. For example, a type of velvet was perceived as more uneven under the visual-only than under the haptic-only condition. A certain type of denim was evaluated as harder when only visual cues were available. Similarly, Ballesteros et al. reported that they acquired analogous dimensional structures when the materials were explored using haptic-only or visuo-haptic cues. For both conditions, they detected three dimensions: rough/smooth, hard/soft, and slippery/sticky. They also confirmed that the preferences of textures were very similar between haptic-only and visuo-haptic conditions. According to the above mentioned studies, perceptual dimensions constructed by haptic cues are also observed in those constructed by visuo-haptic and visual-only cues. Some textures could be mapped differently in these perceptual spaces.

6.1.2 Dimensions unique to vision

Some studies on the visual dimensions of textures suggested the existence of dimensions specific to vision. In particular, the glossy/glossless (bright/dark) dimensions can be concluded as unique to visual perception.

Glossiness (brightness): Some studies reported that the dimensions of glossiness and brightness were revealed in visual texture perception. Cho et al. extracted the brightness dimension from perceptual dissimilarity data using 60 types of material pictures [16]. Lee et al. [10] and Nagano et al. [71] constructed perceptual dimensions using SD methods involving visual cues only, and detected those represented by glossless/glossy (dark/bright) dimension. The dimension of gloss or brightness is clearly independent of the five psychophysical dimensions of tactile perception. For example, even hard and cold metal, smooth and soft satin, and slippery oil can be glossy.

Contrast & regularity (simplicity): Contrast- or regularity-related dimensions have been reported in the literature; these are uniquely visual dimensions. Rao et al. determined the dimensional structure of visual textures using 56 material pictures [9]. Three dimensions were discovered; namely, regular/irregular, high contrast/low contrast, and fine/coarse. Cho et al. reported four dimensions, which were associated with coarseness, regularity, contrast, and brightness [16]. These two studies discovered the contrast dimensions mentioned above. Furthermore, Nagano et al. detected simple/complex dimension, which corresponds to the visual regularity of surfaces. Hence, contrast and regularity appear to be unique to visual perception. However, unlike the glossy/glossless dimension, the classification of these properties as visual-specific is contentious because they are related with surface roughness. Contrast is affected by the shadows created by surface roughness. Regularity and complexity are related by the forms and patterns of surfaces. In order to conclude whether or not they fit into the tactile dimensional space, further cross-modal research is needed.

6.2 Concept and touch

Interestingly, a few research groups investigated the differences in dimensionality between touch and concept where visual or haptic stimuli were not used, and instead only words were used (referred to as the conceptual condition). As well as vision and touch, touch related dimensions were also observed in the dimensionality constructed by the conceptual condition.

Yoshida compared the perceptual dimensions between the tactile and conceptual conditions using a similarity estimation method [17]. His participants only listened to the names of materials. He then found similar distributions of materials on two-dimensional spaces, of which the first dimension was characterized by rough/smooth and hard/soft, and the second dimension was characterized by sticky/slippery. Guest et al. examined the dimensionality of 33 adjectives using a similarity estimation method [26]. They chose adjectives that could be used for the tactile assessment of the physical properties of materials. Three dimensions were detected, namely, the rough/smooth, moist/dry and warm/cold dimensions. These dimensions are consistent with those frequently observed for tactile perception. The rough/smooth dimension also included labels such as “sharp,” “jagged,” “bumpy,” and “hard” on the rough pole, and “silky” on the smooth pole. On the dry pole, “wooly,” “fuzzy,” “hairy,” and “fluffy” labels were used. On the moist pole, “wet,” “damp,” “greasy,” and “slippery” labels were observed.

7 Conclusion

We reviewed studies on the psychophysical dimensions, which were related to the perception of physical properties of materials, i.e., of tactile perception. The psychological experiments in each study were limited by an unsatisfactory adjective label vocabulary, an unbalanced or small number of materials, and other issues. Furthermore, mathematical approaches based on a factor analysis and multidimensional scaling method never ensure that all potential factors or dimensions are revealed. Hence, we constructed a reliable common dimensionality by investigating related studies in a complementary manner.

The roughness, warmness, and hardness dimensions were consistently extracted. A few studies reported that roughness perception could be divided into macro and fine roughness dimensions. These two types of roughness perception can be regarded as separate dimensions from the point of view of the neurophysiological mechanisms involved. Many studies extracted dimensions related to moist/dry and sticky/slippery labels. We summarized these dimensions as a single dimension that is mediated primarily by the friction of materials. Thus, it is reasonable to conclude that the tactile perception of materials is composed of five dimensions, namely, macro and fine roughness, warmness (warm/cold), hardness (hard/soft), and friction (moist/dry and sticky/slippery). Further studies on the perceptual mechanisms of each tactile dimension will confirm the classification.

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