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Haptic Invitation of Textures: Perceptually Prominent Properties of Materials Determine Human Touch Motions

Hikaru Nagano, Shogo Okamoto, and Yoji Yamada, *Member, IEEE*

Abstract—In daily life, certain textures and materials invite our touch motions. To seek the nature of such haptic invitation, we conducted a series of experiments consisting of sensory evaluations and ranking tasks for 36 materials to ascertain their perceptual properties and their degrees of haptic invitation. In addition, we recorded the human touch motions elicited by these materials. The results showed high degrees of haptic invitation for materials with perceptually prominent textures, which indicates that such textures frequently invite human touch motions. We also developed a Bayesian network model that represented the probabilistic relationships between invited touch motions and the properties of textures. The model substantiated the observation that different types of textural prominence led to different types of invited touch motions. These results collectively suggest that materials with prominent textures frequently encourage humans to touch them, using appropriate or specified touch motions.

Index Terms—Textural prominence, touch behavior, textural perception, material property.

1 Introduction

CERTAIN textures and materials in daily life invite human touch motions. Some materials are more likely to elicit this phenomenon, which we refer to as haptic invitation. Some examples include the indented surfaces of embossed papers, smooth-textured surfaces of furs, and high elastic silicon rubbers. Haptic invitation has the potential to be used for various purposes given that many researchers have reported favorable effects of touch on consumers' intentions when making purchases [1], evaluating products [2], and evaluating brands [3]. Furthermore, haptic invitation can be applied to products that have the potential to attract a consumer's touch, poster advertisements that seek to grab the attention of a passersby, and art works that seek to motivate the audience to touch them. Thus, studies of haptic invitation were recently conducted to investigate various materials and objects that are conducive to touch [4], [5].

Several researchers have developed methods for using materials and objects that frequently invite human touch. Nagano et al. [4], [6] revealed that linear combinations of the visual properties of materials described degrees of haptic invitation with a degree of accuracy ranging 70–80%. They found that although glossiness and surface shapes strongly affect haptic invitation, surface colors hardly affect it at all. Klatzky and Peck [5] reported that simple objects were more inviting to human touch than complex objects, and that humans wanted to touch moderately textured objects more than rough objects.

Although methods have been investigated to design materials' haptic invitation by adopting effective properties, the question remains of how people actually touch such materials. Invited touch motions are likely related to the mechanism of haptic invitation, but these have not yet been investigated. This question of how people touch materials was partly evoked by many research findings addressing differences in touch motions or behaviors. Lederman and Klatzky [7] reported that hand movements varied during haptic object exploration, depending on the desired properties of objects, such as heaviness and hardness. In addition, hand dynamics and contact forces for these prototypical hand movements were quantitatively investigated by Jansen et al. [8]. Giboreau et al. [9] qualitatively assessed that textile experts used different types of gestures to evaluate different properties of fabrics. Whereas circular or linear finger movements are used to evaluate rough, relief, and slippery surfaces, localized pressure applied through fingertips is used to evaluate the softness and thickness of materials. In addition, other studies showed that motions or behaviors were related to textural perception. Gamzu and Ahissar [10] demonstrated that scanning velocities are adapted to the grating frequency. Kaim et al. [11] reported that both contact forces and velocities are affected by the pliability of objects. The relationships between the perceived roughness of surfaces and contact forces [12], [13] and those between surface friction and tangential forces [14] have also been investigated. However, the relationships between texture-invited touch motions and textural properties have not been thoroughly investigated. Finally, the present authors postulated the idea that invited touch motions vary for different types of materials [15]. We conjecture that this difference in touch motions may be a clue to elucidating some of the mechanisms of haptic invitation. Therefore, in this study, we sought to experimentally investigate one possible mechanism of haptic invitation based on the following two propositions.

Proposition 1: Materials with perceptually prominent textures frequently invite human touch motions. Human touch motions may be effectively invited by materials with

- *The authors are with the Department of Mechanical Science and Engineering, Nagoya University, Nagoya, Japan.*
  E-mail: see http://www.mech.nagoya-u.ac.jp/asi/en

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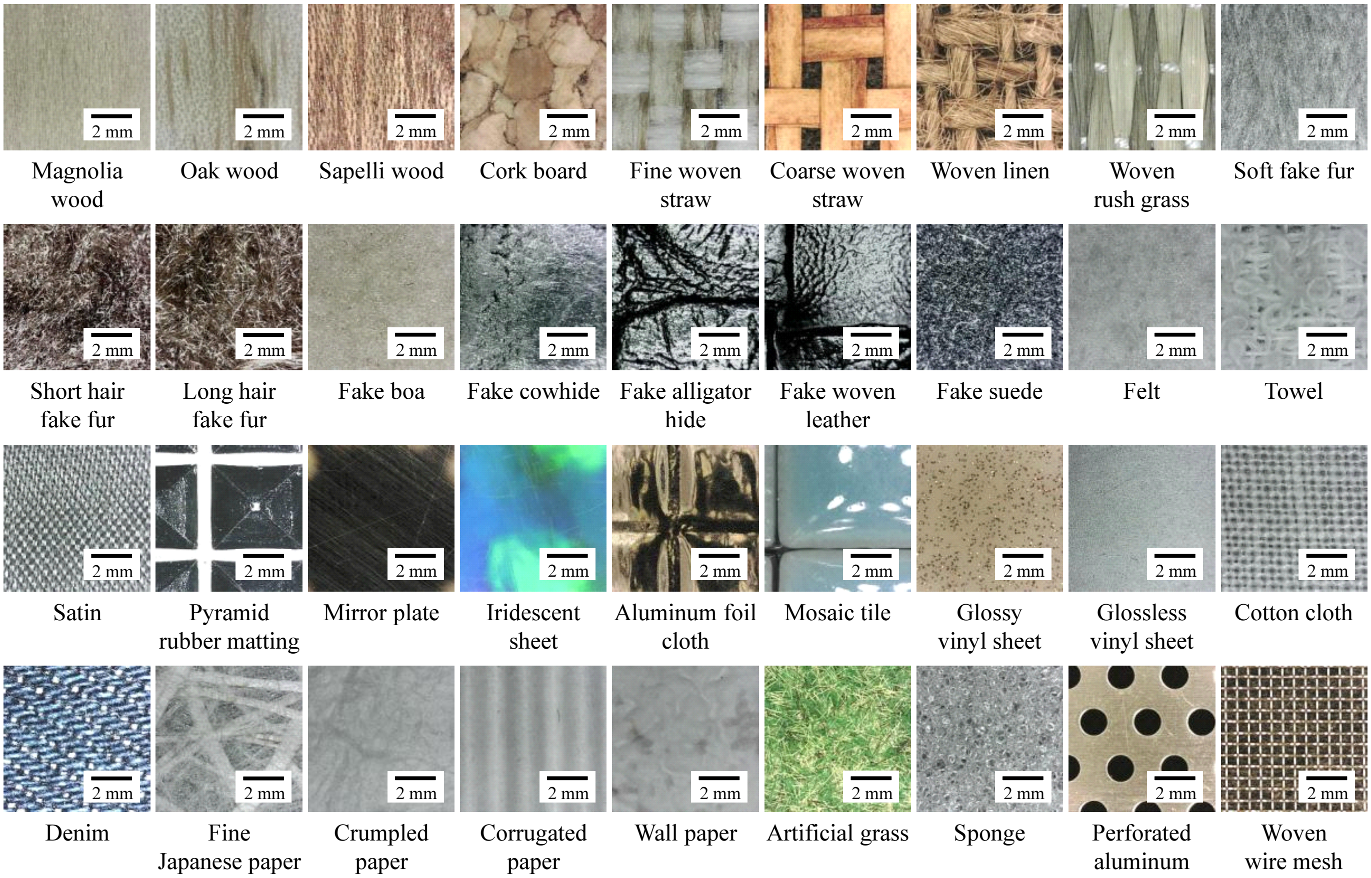

Fig. 1. Thirty-six materials

prominence in textures such as roughness, hardness, and glossiness. Here, textural prominence indicates that one perceptual property is more conspicuous than other properties (see also sec. 3.1). We conducted sensory evaluations to quantify the textural properties of materials; then, from the quantified properties we obtained, we calculated their degrees of textural prominence. In addition, we conducted ranking tasks for materials to specify their degrees of haptic invitation. To test proposition 1, we compared the degrees of textural prominence with the degrees of haptic invitation.

Proposition 2: Invited touch motions are influenced by different types of prominence in textures. An example of this is that, apparently, soft materials may frequently invite pushing, whereas other materials do not. Different types of textural prominence may affect which type of touch motions are likely to be induced, such as stroking or rubbing. To test proposition 2, we observed the different touch motions invited by different materials and investigated the relationships between invited touch motions and textural properties.

2 Experiments

Three experiments were performed, in which 14 volunteers (nine males and five females, aged 19–24 years, with no history of deficits in tactile processing, including 10 participants with corrected vision) participated in all three experiments. In experiment 1, the participants visually evaluated the textural properties of materials that were consecutively presented to them by using a semantic differential method. In experiment 2, the degrees of haptic invitation of materials were calculated based on ranking methods. In experiment 3, the participants touched materials that strongly invited their touch. Human touch motions were measured using a camera and a six-axis dynamic force sensor. All experimental procedures, including the recruitment of participants, were approved by the Ethics Committee of the Graduate School of Engineering at Nagoya University.

2.1 Stimulus

Thirty-six materials, which are shown in Fig. 1, were used in this study. These were selected from 40 materials through preliminary experiments. In these experiments, five volunteers (five males, aged 21–24 years) ranked the 40 materials, and the degrees of haptic invitation were calculated as shown in supplementary figure 1. We excluded four materials with the highest standard deviations of the degree of haptic invitation. The remaining 36 materials, with relatively small individual differences, were selected for the main experiment. A wide variety of materials such as woods, papers, furs, and fabrics were included.

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2.2 Experiment 1: Sensory evaluation

The participants evaluated the materials, without touching them by using a seven-point scale in terms of six bipolar adjective pairs: “rough-smooth,” “uneven-flat,” “hard-soft,” “warm-cold,” “sticky-slippery,” and “glossy-glossless,” which we designate as percieved textures of the physical properties of material surfaces, including surface hardness and warmness. The evaluation forms provided these terms in both English and Japanese. Five adjective pairs without “glossy-glossless” were selected based on their commonality with regard to the tactile dimensionality of textures [16]. In addition to these five pairs, glossiness may be an important factor in the visual perception of textures. We instructed the participants that “uneven” and “rough” meant roughness perceived without and with lateral hand motions, respectively.

As shown in Fig. 2a, a large white plate with a 140 mm × 140 mm square window was placed on a material so that the participants could see only the surfaces and not the sides of the materials. At the beginning of each experiment, we specified the positions of the material and the participant’s head. The distance and angle between the head and material were set to be 600 mm and 45 degrees, respectively. In addition, we instructed the participants to maintain their head positions during experiments to retain their relative positions between head and material. The materials and adjective pairs were presented to each participant in random order.

Ratings from 1 to 7 were assigned on a seven-point adjective scale that was used to perform measurements in the experiments. These ratings were normalized for a single participant such that the mean and standard deviation became 0 and 1, respectively. In supplementary table 1, the mean ratings of the six textural properties and individual varieties are listed.

The degrees of textural prominence were calculated from the absolute values of six textural properties. Smaller absolute values of the textural property indicate that the materials evaluated are neutral in terms of that property. In contrast, larger absolute values indicate that materials take extreme values on that bipolar axis. The degree of prominence for a material specified by j (j =1–36) was determined as follows:

$$\begin{aligned} Pr_j = {} & \max(|x_{jk}|, k = 1, 2, \cdots, 6) \\ & -\mathrm{ave}(|x_{jk}|, s.t. |x_{jk}| \neq \max(|x_{jk}|)). \end{aligned} \quad (1)$$

where x_{jk} is the evaluation value of an adjective pair specified by k (k =1–6) for material j. The degree of prominence was assigned as the difference between the maximum value among the six evaluation values and the averaged value of the remaining five evaluation values. Thus, the degree of prominence represents the extent to which the most impressive property among six properties is prominent, compared with the other five properties. In supplementary table 2, the mean prominence values of materials and their standard deviations among the participants are listed.

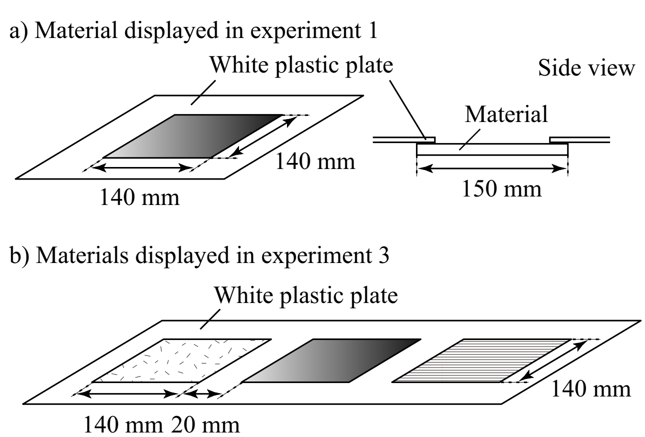

Fig. 2. Presentation method of materials

2.3 Experiment 2: Ranking 36 Materials

We calculated the degrees of haptic invitation of the materials on the basis of the ranking methods that were introduced in a previous study [4]. The participants ranked 36 materials in order of the extent to which they felt inclined to touch them. The materials were simultaneously presented to each participant. In the earlier study [4], the majority of participants answered that it was easier to choose materials with higher and lower degrees of haptic invitation and that it was not easy to rank the other neutral materials. These opinions suggested that the ranks of haptic invitation should not be treated as equal interval scales. We then converted the ranks to interval scales as expected values of a standard normal distribution [17]. These values represent the degrees of haptic invitation of the materials. The degree of the ith-ranked material was assigned as the expected value of the ith largest observation in a sample of size n from a standard normal population. The degree of the ith-ranked material was determined as follows:

$$E(x_{i|n}) = \frac{n!}{(n-i)!(i-1)!} \int_{-\infty}^{\infty} x \cdot a(x) \cdot b(x) \cdot \phi(x) dx \quad (2)$$

$$a(x) = \left[\tfrac{1}{2} - \Phi(x)\right]^{i-1} \quad (3)$$

$$b(x) = \left[\tfrac{1}{2} + \Phi(x)\right]^{n-i} \quad (4)$$

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\tfrac{1}{2}x^2\right) \quad (5)$$

$$\Phi(x) = \int_0^x \phi(z) dz. \quad (6)$$

The degrees of haptic invitation for a given texture were averaged across the participants.

2.4 Experiment 3: Observation of touch motions

Among the three materials offered to them, participants touched the one material that they felt most strongly invited their touch. The materials were placed under a white plastic plate, as shown in Fig. 2b. If only one material was shown in each experiment, the participant would only be able to touch that one. Therefore, to avoid this unnatural situation, three materials were shown to the participants.

We instructed the participants to close their eyes before the experimenter arranged the three stimuli. They were instructed to “keep your eyes closed until you hear a beep sound,

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after which freely touch the one you feel most inclined to touch," in which a sound cue became a reference for the participants' response times. Their hand movements were not restricted at all by instructions; however, most participants touched materials with their index finger. This was clearly done because they knew that a camera captured the motion of their index finger with an attached marker.

Combinations of three materials were determined based on the average ranks of haptic invitation. One of three materials was randomly selected from among the 12 materials that exhibited the highest degrees of haptic invitation among 36 materials. At random, a second material was selected from the lowest 12 materials, and a third was selected from the remaining 12 materials. Hence, 12 combinations were presented to each participant in random order. Then, using the 24 materials that had not been touched in the first round, eight more combinations were determined through a process similar to that described above, and were then presented to the participant. In total, each participant thus received a unique set of 20 combinations (12 and eight in the first and second rounds, respectively). The material sets for the first participant were only based on his or her ranking of materials and those of the preliminary experiments involving five volunteers (five males, aged 21–24 years). The degrees of haptic invitation were updated every time new degrees were obtained in experiment 2. The ranking in the preliminary experiment was not exactly same as the final rankings in the main experiment. For example, the rank of fine woven straw changed most: from ninth to 23rd.

Human touch motions to materials were measured as shown in Fig. 3. The tip position of each participant's index finger was measured using a camera (Firefly MV, Point Grey Research Inc., Richmond, Canada, 640 × 480 pix, 60 fps). This position was detected from a red marker that was fixed on the metacarpophalangeal joint of the index finger. The contact forces were measured using a six-axis dynamic force sensor (MINI 2/10, BL AUTOTEC. LTD., Kobe, Japan) at a sampling frequency of 60 Hz. The sensor was fixed under a metal plate on which the materials were placed.

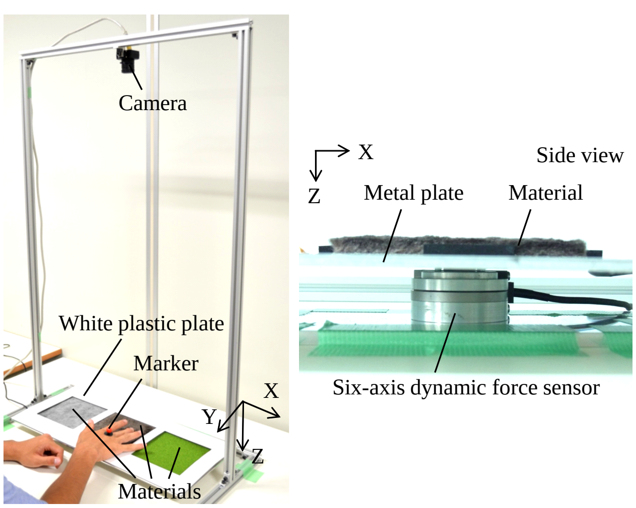

Fig. 3. Measurement of touch motions to textures

3 Proposition 1: Prominence Invites Touch

To test proposition 1, which posits that materials with prominent textures frequently invite human touch motions, two analyses were conducted. In the first analysis, degrees of haptic invitation were compared with degrees of visual prominence in textures. These degrees of prominence were based on the results of experiment 1. In the second analysis, materials were classified into two groups (touched and untouched materials) based on the results of experiment 3. A comparison between the two groups was then performed, in terms of degrees of prominence.

3.1 First analysis: Correlation between textural prominence and haptic invitation

The degrees of both textural prominence and haptic invitation were averaged across the participants and then compared, as shown in Fig. 4. The correlation coefficient was 0.54 ($t(34) = 3.7$, $p = 7.6 \times 10^{-4}$). Materials with higher degrees of prominence more effectively invited human touch. This finding supports proposition 1. However, because our finding is simply correlation and its coefficient is not substantially high, we should remember the possibility that the relation between prominence and haptic invitation is mediated by other factors.

Some of the six ratings may have been correlated with each other. In such a case, our definition of prominence value ineffectively specifies the textural prominence. To organize a set of uncorrelated ratings, we applied a factor analysis to the six ratings. As a result, as listed in Table 1, the textural properties were effectively represented by three factors. The degrees of textural prominence that were calculated from these uncorrelated variable sets were well correlated with degrees of haptic invitation, with a correlation coefficient

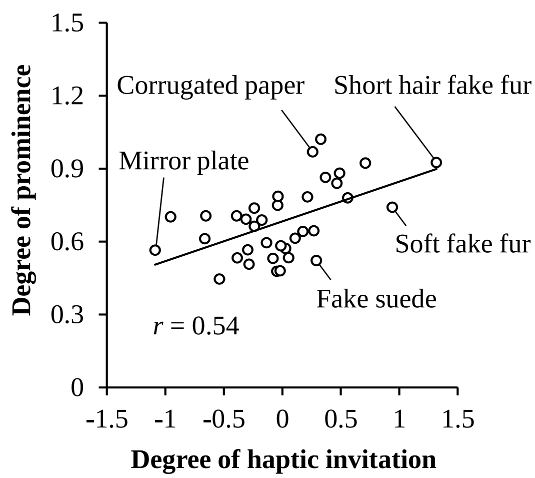

Fig. 4. Correlation between textural prominence and degree of haptic invitation. The solid line is a regression line.

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of 0.63 ($t(34) = 4.8$, $p = 3.5 \times 10^{-6}$). The visual prominence values calculated by factors specified for a material set yielded higher correlation with the degrees of haptic invitation than those the general prominence values calculated by the six textural properties. The resultant structure of factor analysis depends on the stimuli set. With different material sets, we may be led to other factorial structures. In the latter analysis, to maintain generality, we used six textural properties rather than the three factors acquired here.

3.2 Second analysis: Comparison between degrees of prominence of touched versus untouched materials

The stimuli were divided into groups of touched and untouched materials. Because each of the 14 participants took part in the 20 trials in experiment 3, the touched and untouched groups contained 280 and 224 samples, respectively. Fig. 5 shows the number of touches for all materials in comparison with the degree of haptic invitation specified in experiment 2. These numbers are well correlated with the degrees of haptic invitation. The two groups of touched and untouched materials were compared in terms of their average degrees of prominence. As shown in Fig. 6, the degrees of prominence of touched materials were significantly greater than those of untouched materials ($t(502) = 6.7$, $p = 6.3 \times 10^{-11}$). In other words, the materials that invited the participants' touch had more prominent textures; this finding is also consistent with proposition 1.

TABLE 1
Results of factor analysis: Factor loadings of six adjective pairs

	Factor 1	Factor 2	Factor 3
Micro roughness	0.96	0.00	−0.26
Macro roughness	0.73	0.06	0.06
Hardness	−0.11	−0.83	0.15
Warmness	0.10	0.94	−0.33
Friction	0.78	0.35	−0.30
Glossiness	−0.21	−0.48	0.85
Contributing rate	0.56	0.27	0.09
Cumulative contributing rate	0.56	0.83	0.92

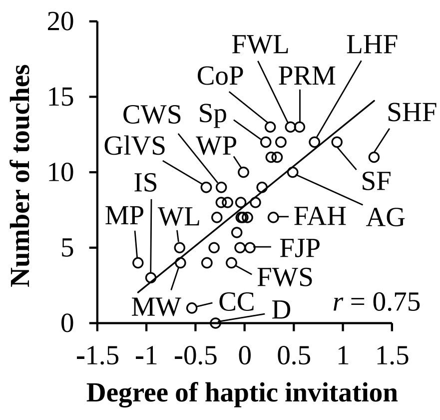

Fig. 5. Relationships between the number of touches and degree of haptic invitation. LHF: Long hair fake fur, FWL: Fake woven leather, PRM: Pyramid rubber matting, CoP: Corrugated paper, SHF: Short hair fake fur, Sp: Sponge, CWS: Coarse woven straw, WP: Wall paper, GlVS: Glossless vinyl sheet fur, SF: Soft fake fur, IS: Iridescent paper, AG: Artificial grass, FAH: Fake alligator hide, WL: Woven linen, MP: Mirror plate, FJP: Fine Japanese paper, FWS: Fine woven straw, D: Denim, CC: Cotton cloth, MW: Magnolia wood.

4 PROPOSITION 2: TOUCH MOTION DEPENDS ON PROMINENCE

To test proposition 2, which posits that invited touch motions are influenced by different types of textural prominence, we constructed a Bayesian network model that offers conditional probabilities between the invited touch motions and the properties of textures. The model simply connects the simultaneous occurrence of events, which enabled us to quantitatively analyze statistical relationships while negating the need to discuss any mathematical relationships between them. Using touch motions as evidence, the model estimated the properties of textures that frequently invite such motions. From the results of these estimations, we were able to address proposition 2.

4.1 Construction of a probabilistic model

From the results of experiments 1 and 3, we extracted nodes that constructed a probabilistic network. There were three types of nodes: properties of textures, touch motions, and touch mode. A touch mode node is a meta node that represents types of touch behaviors. This node was determined from the ensemble of touch motions. The primitiveness of touch motions makes them helpful to interpret the physical interactions between touch and materials. In contrast, touch modes are more intuitive in the exchange of a lack of detailed information about motion dynamics. These nodes were all discrete variables, and are described in detail below.

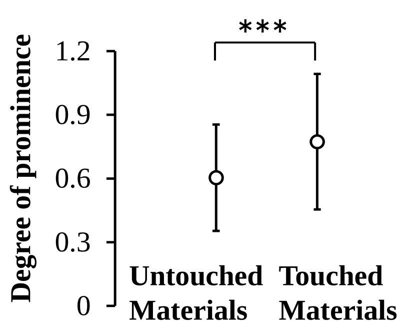

Fig. 6. Degrees of prominence of touched and untouched materials. The error bar and asterisk symbols *** indicate the standard deviation of prominence and significance level of $p < 0.001$, respectively.

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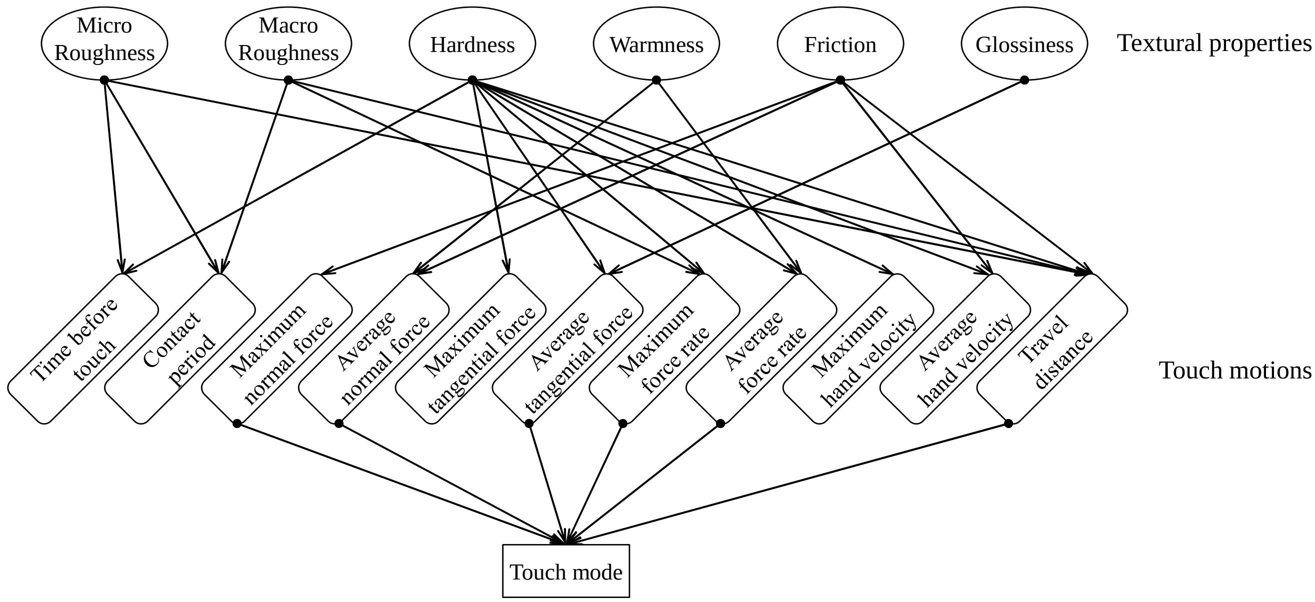

Fig. 7. Bayesian network model connecting textural properties, invited touch motions, and touch mode

4.1.1 *Properties of textures*

We created six nodes based on the adjective ratings "rough-smooth," "uneven-flat," "hard-soft," "warm-cold," "sticky-slippery," and "glossy-glossless," which were taken from experiment 1. These ratings were quantified into three levels with two boundaries (-0.43, 0.43) that divided the occurrence probability equally into three. For example, for one participant, the standardized "rough-smooth" rating of soft fake fur was -1.1 ($+$: rough; $-$: smooth), which was lower than -0.43. Therefore, the *micro roughness* node was labeled "smooth." The six adjective ratings were quantified in the following manner.

Micro Roughness: Smooth, moderate, or rough.

Macro Roughness: Flat, moderate, or uneven.

Hardness: Soft, moderate, or hard.

Warmness: Cold, moderate, or warm.

Friction: Slippery, moderate, or sticky.

Glossiness: Glossless, moderate, or glossy.

4.1.2 *Touch motions*

Human touch motions were measured using a camera and a force sensor. The measured data were normalized for each participant, and we produced 11 nodes from the normalized data. As in the case of the textural properties, the following nodes were all discretized into their qualitative states with two boundaries (-0.43, 0.43).

Time before touch: Short, moderate, or long. The *time before touch* node was determined from the period between the time at which a sound cue was presented to a participant, and the time at which the force signal began to change. For example, for one participant, the normalized value of *time before touch* for cork board was 2.2 ($+$: long; $-$: short), which was higher than 0.43. Therefore, the *time before touch* node of cork board was assigned the label "long."

Contact period: Short, moderate, or long. The *contact period* node was determined as the period during which a material was being touched.

Maximum normal force: Weak, moderate, or strong. The *maximum normal force* node was determined from the maximum Z-axial force exerted while the participant was in contact with a material.

Average normal force: Weak, moderate, or strong. The average Z-axial force during contact determined the *average normal force* node.

Maximum tangential force: Weak, moderate, or strong. The *maximum tangential force* node was the maximum resultant force of the X and Y-axial forces applied to a material.

Average tangential force: Weak, moderate, or strong. The average X-Y resultant force during contact determined the *average tangential force* node.

TABLE 2
Average touch motion values of each touch mode. The asterisk symbols $***$ indicate the significance level of $p < 0.001$

	Touch mode			
Touch motion	Push	Rub	Stroke	Soft touch
Time before touch	-0.02	0.13	-0.08	0.06
Contact period	0.10	0.11	0.70***	-0.85***
Max. normal force	1.74***	-0.06	-0.11	-0.63***
Ave. normal force	1.83***	-0.07	-0.16	-0.60***
Max. tangential force	0.74***	1.35***	-0.03	-0.70***
Ave. tangential force	0.27	1.65***	-0.02	-0.58***
Max. force rate	1.46***	-0.45***	0.00	-0.51***
Ave. force rate	1.80***	-0.62***	-0.20***	-0.39***
Max. hand velocity	-0.53***	-0.02	0.35***	-0.14
Ave. hand velocity	-0.94***	-0.31	0.25***	0.24
Travel distance	-0.53***	-0.18	0.77***	-0.56***

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Maximum force rate: Low, moderate, or high. We defined the ratio of the Z-axial force to the X-Y resultant force as the force rate. This node was the maximum value of the force rates while the participant was in contact with the material.

Average force rate: Low, moderate, or high. This node is the average force rate.

Maximum hand velocity: Slow, moderate, or fast. We calculated the participants' hand velocities from the time series data of their hand positions that were captured on camera. The maximum value of hand velocities during participants' contact with a material determined the *maximum hand velocity* node.

Average hand velocity: Slow, moderate, or fast. This node is the average hand velocity while a participant is in contact with a material.

Travel distance: Short, moderate, or long. The *travel distance* node was determined from the total distance traveled by a hand while it was in contact with a material.

4.1.3 Touch mode

We defined the *touch mode* node as being representative of the typical modes of invited touch motions. Using a cluster analysis that employed Ward's method [18], we classified the 280 trials in experiment 3 into a number of groups on the basis of the 11 touch motions, as described above. The Euclidean distances between trials were calculated from the values of the 11 touch motions. Ward's method adopts these Euclidean distances as a dissimilarity matrix and merges the two trials with the minimum dissimilarity into a new cluster. Repetitive fusions decreased the number of clusters into four. Table 2 lists the average values of touch motions for each touch mode. The figures with asterisk symbols are significantly different from zero, and represent the feature of the mode.

Touch mode: Push, rub, stroke, or soft touch. Based on the features described in Table 2, the four types of touch mode were assigned as push, rub, stroke, and soft touch. For example, the mode with strong normal forces and slow hand velocities was called "push." We next describe some examples of touch motions that characterize these four modes: push (*max. and ave. normal force*: strong, *max. and ave. hand velocity*: slow), rub (*max. and ave. tangential force*: strong, *max. and ave. force rate*: low), stroke (*max. and ave. hand velocity*: fast, *travel distance*: long), and soft touch (*max. and ave. normal force*: weak, *travel distance*: short).

4.1.4 Model structure

The Bayesian network structure was determined from the discretized data of six properties, touch motions, and touch mode, by using a greedy search algorithm with Akaike Information Criterion [19] as the evaluation score. The arcs of the network were restricted such that they did not mutually connect textural properties. The same rule was applied to touch motions. In addition, the arcs between textural properties and touch mode were not permitted. The constructed model is presented in Fig. 7.

4.2 Probabilistic estimation

To test proposition 2, we investigated the probabilistic relationships between the textural properties and the touch motions or mode. The probabilities of the textural properties were estimated using the touch motions and mode as evidence. As shown in Fig. 7, two connected nodes have a statistical relationship, and potentially a causal relationship. We do not mention all of these connections, but we focus on the connections with the largest probabilistic deviations for each textural property. Hence, we describe seven connections as follows.

4.2.1 *Micro roughness* (rough/smooth) and *travel distance*

To investigate the relationships between the *travel distance* and *micro roughness* nodes, we estimated the probabilities of the *micro roughness* node from the *travel distance* node that was given as evidence. The estimation results are listed in Table 3. Cells with probabilities of 0.45 or higher are highlighted in gray. This value is the border of the statistically significant interval ($\chi^2(2) = 5.99$, $p = 0.05$, $N = 93$) in the occurrence number of events between the probability set (0.453, 0.273, and 0.273) and the expected set (0.333, 0.333, and 0.333). The probabilities of *micro roughness* being rough were the highest, at 0.62 and 0.55, when the *travel distance* nodes were long and moderate, respectively. When the participants experience apparently rough materials, it is reasonable for them to stroke these materials broadly to effectively produce vibrotactile cues. Such skin vibration caused by exploratory movements plays a significant role in the perception of micro roughness [20], [21].

4.2.2 *Macro roughness* (uneven / flat) and *maximum force rate*

We estimated the probabilities of *macro roughness* by using the *maximum force rate* as evidence. As shown in Table 4, when the *maximum force rate* node was low, the probability of

TABLE 3
Probabilities of *micro roughness* when *travel distance* is given as evidence

Estimated result: Micro roughness	Evidence: Travel distance: Short	Middle	Long
Smooth	0.35	0.26	0.24
Middle	0.25	0.19	0.14
Rough	0.40	0.55	0.62

TABLE 4
Probabilities of *macro roughness* when *maximum force rate* (normal / tangential forces) is given as evidence

Estimated result: Macro roughness	Evidence: Maximum force rate (normal / tangential forces): Low	Middle	High
Flat	0.53	0.32	0.25
Middle	0.15	0.24	0.17
Uneven	0.32	0.44	0.58

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macro roughness being flat was 0.53. This trend implied that, for flat materials, the normal forces were relatively weaker than the tangential ones. Flat materials were also accompanied by large travel distances. Because overly large normal forces hinder such hand movements, this low force rate is strategic for the perception of flat surfaces. In addition, given that the *maximum force rate* node was high, the network estimated that the probability of *macro roughness* being uneven was 0.58. Participants tended to touch uneven materials with relatively stronger normal forces than tangential ones. In the perception of macro roughness, lateral hand movements are not necessary to a great extent, because surface unevenness is perceived as the unevenness of pressure sensations rather than as vibrotactile information [20], [22]. Therefore, touch motions with high normal to tangential force ratios are potentially appropriate for perceiving the surface unevenness of materials.

4.2.3 *Hardness* (hard/soft) and *average force rate*

As shown in Table 5, given the state of the *average force rate* node as evidence, the network estimated the probabilities of the *hardness* node. When the *average force rate* node was high, the probability of *hardness* being soft was the highest, at 0.61. In other words, the normal forces for apparently soft materials were relatively stronger than the tangential forces. The perception of softness or elasticity seems to be related to information received from the contact area of the finger pads, such as spatial pressure distributions, and the relationships between the force and the contact area or the force and the displacement that takes place during pushing by fingers [23], [24], [25]. Therefore, in the experience of material softness, touch motions with a high *average force rate* were appropriate.

4.2.4 *Warmness* (warm / cold) and *average normal force*

Table 6 lists the probabilities of the *warmness* node when the *average normal force* is given as evidence. When the *average normal force* node was strong, the probability of *warmness* being warm was the highest, at 0.48. In other words, participants tended to use strong normal forces for touching apparently warm materials. Touch motions such as pushing increase the contact area between fingers and material, which allows human to effectively perceive surface warmness because a large contact area enhances heat transfer. This strategy is especially effective for warm-looking materials, and not as effective for cold-looking ones. This is because when the potential difference between the temperature of the skin and that of the material is large enough for humans to detect, a measure that fosters heat transfer is not required. On the other hand, because the heat transfer between the skin and a warm material is limited (here, being warm means that its temperature is close to that of human skin), the reduction in thermal resistance owing to higher pressure and the resulting large contact area is effective for detecting subtle differences in temperature.

4.2.5 *Friction* (sticky / slippery) and *maximum normal force*

We estimated the probabilities of the *friction* node from the *maximum normal force* node that was given as evidence. As shown in Table 7, when the *maximum normal force* node was strong, the probability of *friction* being sticky was 0.56. Furthermore, given that the *maximum normal force* node was weak, the network estimated that the probability of *friction* being slippery was 0.55. When participants touched slippery materials, they tended to use weak normal forces. The use of strong normal forces for sticky materials allowed participants

TABLE 5
Probabilities of *hardness* when *average force rate* (normal / tangential forces) is given as evidence

Estimated result: Hardness	Evidence: Average force rate (normal / tangential forces)		
	Low	Middle	High
Soft	0.33	0.44	0.61
Moderate	0.25	0.21	0.19
Hard	0.42	0.35	0.19

TABLE 6
Probabilities of *warmness* when *average normal force* is given as evidence

Estimated result: Warmness	Evidence: Average normal force		
	Weak	Middle	Strong
Cold	0.39	0.25	0.17
Moderate	0.30	0.33	0.35
Warm	0.31	0.42	0.48

TABLE 7
Probabilities of *friction* when *maximum normal force* is given as evidence

Estimated result: Friction	Evidence: Maximum normal force		
	Weak	Middle	Strong
Slippery	0.55	0.31	0.27
Moderate	0.12	0.32	0.17
Sticky	0.33	0.37	0.56

TABLE 8
Probabilities of *glossiness* when *average tangential force* is given as evidence

Estimated result: Glossiness	Evidence: Average tangential force		
	Weak	Middle	Strong
Glossless	0.60	0.44	0.39
Moderate	0.12	0.13	0.06
Glossy	0.28	0.43	0.55

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to experience their large frictional properties, and weak normal forces were appropriate for them to effectively experience the surface slipperiness of materials. These findings are supported by previous studies [26], [27], which reported the relationships between the shear deformations caused by tangential forces applied to finger pads and the perception of friction.

4.2.6 *Glossiness* (glossy / glossless) and *average tangential force*

Table 8 lists the probabilities of the *glossiness* node when the *average tangential force* is given as evidence. When the *average tangential force* node was weak, the probability of *glossiness* being glossless was the highest, at 0.60. On the other hand, when the *average tangential force* node was strong, the probability of the textures being glossy was 0.55. Because glossy materials tend to look frictional, explanations similar to those given in sec. 4.2.5 are also valid here. For glossy and apparently frictional materials, the participants touched them with large tangential forces. Such forces cause substantial stretching of the skin, which enables humans to experience a large degree of friction.

4.2.7 *Touch mode* and six properties of textures

The probabilistic relationships between the six properties and *touch mode* are listed in Table 9. When the *touch mode* node is "push," the probability of *hardness* being soft is 0.55, and that of it being hard is 0.18. Apparently soft materials are likely to invite the push mode, whereas hard materials are not. On the other hand, the rub mode is likely to be invited by hard materials. Stroke and soft touch modes are not strongly related to the apparent softness of materials (*hardness*). As shown in Table 9, each textural property, except for *friction*, is probabilistically linked with *touch mode*.

TABLE 9
Probabilities of six properties of textures when *touch mode* is given as evidence

		Evidence: Touch mode			
		Push	Rub	Stroke	Soft touch
Estimated result: Micro roughness	Smooth	0.28	0.33	0.20	0.38
	Moderate	0.30	0.16	0.17	0.20
	Rough	0.42	0.51	0.63	0.42
Estimated result: Macro roughness	Flat	0.23	0.42	0.44	0.44
	Moderate	0.22	0.20	0.14	0.17
	Uneven	0.55	0.38	0.42	0.39
Estimated result: Hardness	Soft	0.55	0.25	0.39	0.43
	Moderate	0.27	0.18	0.30	0.20
	Hard	0.18	0.57	0.31	0.37
Estimated result: Warmness	Cold	0.15	0.43	0.33	0.45
	Moderate	0.40	0.24	0.32	0.27
	Warm	0.45	0.33	0.35	0.28
Estimated result: Friction	Slippery	0.28	0.42	0.37	0.41
	Moderate	0.28	0.20	0.23	0.19
	Sticky	0.44	0.38	0.40	0.40
Estimated result: Glossiness	Glossless	0.43	0.33	0.54	0.44
	Moderate	0.32	0.12	0.14	0.33
	Glossy	0.25	0.55	0.32	0.23

4.2.8 Multiple evidences did not specify textural properties

We estimated the probabilities of textural properties given multiple touch motions as evidence, in addition to the estimations from single evidence as described above. It is of interest to us to determine whether the types of textures can be fully identified from the observed touch motions. Unfortunately, these probabilities were not significantly higher than those inferred by single evidence, which indicates that the textures are unlikely to be fully identified by the motion parameters used in the present study. However, the established network is still valuable for discussing the trends of textures and touch motions with moderate probabilistic deviations.

4.3 Probabilistic estimations support proposition 2

Table 10 summarizes Tables 3–9 and lists the likely connections between the touch mode and textural properties. As listed in the table, the touch mode is probabilistically connected to the prominent properties of texture. In addition, such connections are not accidental but are intuitively reasonable in terms of the previously described human perceptual strategies. These probabilistic trends fairly indicate that certain prominent textures tend to invite certain hand movements.

The push mode is frequently invited by apparently uneven, soft, or warm materials. This mode is represented by strong normal forces and small travel distances. As described earlier, such a motion is appropriate for testing these textural properties. A pushing motion allows us to experience a material's spatial unevenness within the contact area, its softness via the pressure of our finger pads, and its warmness via the heat transfer that is enhanced by the increased contact area. Further, lateral hand movements are dispensable to the experience of unevenness, softness, and warmness.

The rub and stroke modes are often used for exploring rough materials. This is intuitively reasonable because these modes, which include lateral hand movements, produce the information needed to decode surface roughness. Meanwhile, the rub mode is often invited by glossy materials, whereas the stroke mode is invited by glossless ones. One of the

TABLE 10
Touch modes and textural properties that are likely to invite touch motions. The representative materials in the table satisfy all of the listed textural properties. For example, the average ratings of fake woven leather were uneven, soft, and warm.

Touch mode	Property of texture	Representative materials
Push	Macro roughness: uneven (55%), Hardness: soft (55%) Warmness: warm (45%)	Fake woven leather, Sponge
Rub	Micro roughness: rough (51%), Hardness: hard (57%), Glossiness: glossy (55%)	Perforated aluminum, Woven wire mesh
Stroke	Micro roughness: rough (63%), Glossiness: glossless (54%)	Artificial grass, Coarse woven straw
Soft touch	Warmness: cold (45%)	Satin

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major differences between these two touch modes lies in the magnitude of the tangential forces. The rub mode involves larger tangential forces than the stroke mode. Tangential forces are linked with the perception of friction. The rub mode is better suited to glossy materials than the stroke mode because the large tangential forces of the rub mode are more relevant to the experience of potentially high coefficients of friction.

The soft touch mode has a probabilistic link with apparently cold materials. This mode has weak normal forces and short contact periods. Such a motion is sufficient for heat transfer between a person's fingers and a cold material, a circumstance in which the temperature difference is large, and this heat can thus be detected by the fingers' temperature-sensitive receptors. The soft touch mode is an economic motion for feeling the coldness of materials.

The above mentioned results demonstrate that types of prominent textures influence invited touch motions, a finding that supports proposition 2.

5 Conclusion

We conducted a series of experiments to investigate the potential mechanism of haptic invitation, which is a phenomenon in which the textures of materials invite human touch motions. The many analyses of the results positively indicated two propositions underlying haptic invitation. First, materials with visually prominent textures frequently invite human touch motions. Second, invited touch motions are influenced by the types of prominent textures.

With regard to the first proposition, a positive correlation coefficient of 0.54 was observed between the degrees of haptic invitation and textural prominence. This coefficient increased to 0.63 in the case that the prominence values were calculated based on the factorial values that integrated the correlated textural properties. Furthermore, the degrees of textural prominence of materials that invited touch motions in experiment 3 were higher than those of materials that were not touched. These results support the first proposition; namely, that materials with a prominent texture effectively invite human touch. However, the coefficient values were not substantially large and the correlation always indirectly linked two events. The prominence may be one contribution, and other factors may also pertain to haptic invitation.

With regard to our second proposition, we constructed a Bayesian network model that represented the probabilistic relationships between the invited touch motions and the properties of textures. The model corroborated the idea that invited touch motions and touch modes vary, depending on the different types of prominence in textures.

As described above, perceptual prominence in textures tends to invite human touch motions, and types of prominent textures are likely to invite appropriate touch motions. Haptic invitation increases the probability that people will make contact with textures as haptic inputs, which can be sensed through economic motions for textures, unlike passive visual or auditory stimuli. We interpret the haptic invitation of material as a phenomenon in which the textural prominence of a material encourages us to feel it. One rational role of this phenomenon is to maintain the system whereby individuals recognize tactile textures, because the increase in the probability of touching prominent textures may be instrumental in activating human perceptual systems.

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Hikaru NAGANO received B.S. and M.S. degrees in engineering in 2010 and 2012, respectively, from Nagoya University. He is currently a Ph.D. candidate in the Department of Mechanical Science and Engineering, Nagoya University, as well as a Research Fellow with the JSPS, Tokyo, Japan, from April 2013. His research interests include haptic and visual perception of texture.

Shogo OKAMOTO received a B.S. degree in engineering from Kobe University in 2005, and M.S. and Ph.D. degrees in information sciences in 2007 and 2010, respectively, from the Graduate School of Information Sciences, Tohoku University. Since 2010, he has been an assistant professor at the Graduate School of Engineering, Nagoya University. His research interests include haptic interfaces and human-assist technology.

Yoji YAMADA (M' 91) received a Ph.D. degree from the Tokyo Institute of Technology, Japan, in 1990. He has been an associate professor at the Toyota Technological Institute, Nagoya, Japan since 1983. In 2004, he joined the National Institute of Advanced Industrial and Science Technology (AIST), as a group leader of the Safety Intelligence Research Group at the Intelligent Systems Research Institute. In 2008, he moved to the Department of Mechanical Science and Engineering, Nagoya University, as a professor.