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Review

Tactual perception of material properties

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ABSTRACT

This paper reviews tactual perception of material properties such as roughness, compliance, coldness and friction. Psychophysical functions relating physical properties to perception are discussed, as well as discrimination thresholds. Also, the neural codes mediating some of these sensations are discussed. Furthermore, we take a look into how sensation of these material properties can be induced artificially in haptic displays. Lastly, the interactions between perception of the different material properties are explored.

1. Introduction

Tactual perception refers to every type of sensation related to the sense of touch, be it cutaneous (pressure, vibration, temperature), kinaesthetic (limb movement) or proprioceptive (position of the body) (Loomis & Lederman, 1986). Using these senses, a wealth of information about the world around us can be acquired. This is most notable when handling objects. Immediately, information is available about the object's size, shape, weight, temperature and material. This review article focuses on this last type of information. The tactual sense provides us with a number of aspects related to an object's material, most notably roughness, compliance, coldness and slipperiness. Roughness is related to the height differences on the surface of the material; compliance to the material's elasticity; coldness to the material's heat capacity and thermal conductivity; and slipperiness to the friction between the material and the skin. Two of these aspects, roughness and slipperiness, are surface properties, whereas the other two, compliance and coldness, are bulk properties. Another division can be made according to whether or not movement is required: Roughness and coldness can be perceived statically, whereas compliance and slipperiness have to be perceived dynamically, through squeezing or stroking, respectively. These divisions are summarised in Table 1. These different divisions show that although these aspects are all material properties, they cover a wide range of tactual perception. Although the study of tactual perception is still in its infancy compared to visual perception, roughness and compliance have been studied quite extensively already, and research into coldness and slipperiness is starting to develop. This paper attempts to give an overview of these fields. First, the four properties are treated separately. In a concluding section, the interactions between the properties are discussed.

2. Roughness

Of the four material properties mentioned above, roughness is the one studied the most in the context of tactual perception. This is not surprising, since roughness appears to be the most important feature for discrimination of haptically explored surface textures (Hollins, Faldowski, Rao, & Young, 1993; Hollins, Bensmaïa, Karlof, & Young, 2000; Bergmann Tiest & Kappers, 2006). This was established based on experiments in which the perceived dissimilarity between different materials was measured and analysed using multidimensional scaling (MDS). This technique enables the different materials to be positioned in a space of a given number of dimensions. The material positions were then correlated with subjective ratings (Hollins et al., 1993; Hollins et al., 2000) or objective measurements (Bergmann Tiest & Kappers, 2006). In both cases, roughness (either perceived or physical) was found to be most important. Given that roughness is so important, the following questions come to mind: What is haptically perceived roughness? How is it related to physical roughness? And how is it perceived?

Early experiments. Physically, the term roughness refers to height differences on the surface. These can be measured using a profilometer and be expressed in a number of ways, mainly relevant to the specification of the surface quality of machined parts. In perception, the term is less well defined and its meaning may depend on the stimulus set used. In general, a rough surface produces an uneven pressure distribution on the skin when touched statically, and vibrations when stroked. In early haptic roughness

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Table 1
Tactually perceived material properties.

	Surface	Bulk
Movement not required	Roughness	Coldness
Movement required	Slipperiness	Compliance

perception experiments, the stimuli were different types of paper (Meenes & Zigler, 1923; Katz, 1925). These experiments were of a mostly qualitative nature: Meenes and Zigler (1923) asked subjects to give introspective accounts of their experience while touching the papers in different ways. With static touch, they mainly reported uneveness of pressure, while with dynamic touch, roughness and smoothness were reported. Katz (1925) had subjects distinguish between the papers in different situations, such as with and without movement, and with different types of intermediaries between fingers and stimulus. He concluded that the vibration sense was much more important for roughness perception than pressure sensation.

Power function. More quantitative work was done by Stevens and Harris (1962) who let subjects perform magnitude estimation of the roughness and smoothness of emery cloths (similar to sandpapers), which are identified by a so-called grit number, being the number of openings per inch in the sieve used to sift the abrasive powder. They found that perceived roughness was related to grit number by a power function with an exponent of −1.5. Conversely, perceived smoothness was found to be related to grit number by a power function with an exponent of +1.5, showing that roughness and smoothness are opposites. The power function for roughness of sandpaper was confirmed by Ekman, Hosman, and Lindström (1965), Stone (1967) and more recently by Verrillo, Bolanowski, and McGlone (1999), but with widely varying exponents for individual subjects. These last authors compared roughness magnitude estimation using active (the subject moves his/her finger) and passive touch (the stimulus is moved over the subject's finger), but found no difference. With regards to roughness *discrimination* (as opposed to magnitude estimation), also no difference has been found between active and passive touch (Heller, 1989). This author also looked at the difference between sighted and blind observers but found none, showing that visual imagery does not play a role. To sum up, the perceived roughness of abrasive surfaces such as sandpapers and emery cloths can be described by a power function, and there is no difference between active and passive touch as long as movement is involved.

Duplex theory. There is, however, a difference between static and dynamic touch (Hollins & Risner, 2000). When subjects performed magnitude estimation of sandpapers that were either held stationary or moved over the subjects' index fingerpad, the familiar correlation between perceived roughness and particle size was observed for particles larger than 100 μm. The absence or presence of movement did not matter for the slope of the relationship there. However, below 100 μm roughness perception was seriously degraded without movement. Subjects reported a threefold increase in roughness as particle size increased from 9 to 100 μm when movement was involved, but without movement, there was only an increase of a factor of 1.3 over the same range, with perceived roughness completely levelling off below 30 μm. The data are reproduced in Fig. 1. This difference below 100 μm can be explained by considering the role of vibration in roughness perception. In the dynamic condition, both pressure and vibration cues are available. In the static condition, only pressure cues are available. This is sufficient for the coarser textures with particle sizes above 100 μm. Here, either pressure or vibration cues can be used. For the perception of fine textures, vibration cues are necessary. When these are not available, as is the case in the static condition, no difference in roughness is perceived for the finer textures. So,

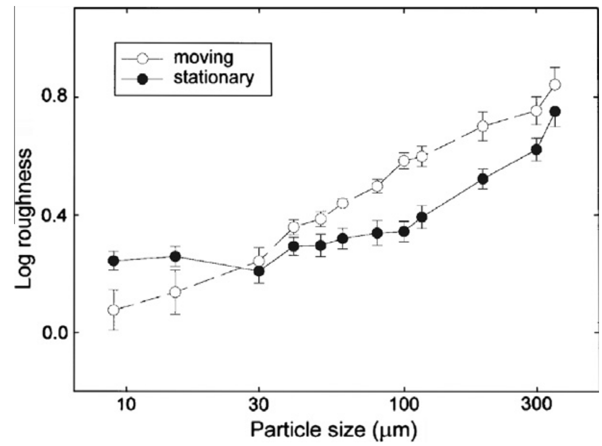

Fig. 1. Log of estimated roughness of sandpapers with different particle sizes in dynamic and static conditions. The estimates in the *moving* condition level off for particle sizes below 30 μm. The difference in slope between the left and right part indicates the limitation of static roughness perception. Reproduced with permission from Hollins and Risner (2000).

vibration is essential for roughness perception, but only with particle sizes below 100 μm. This was confirmed in an experiment in which the Pacinian receptors were rendered less sensitive through adaptation with a 100 Hz vibration (Hollins, Bensmaïa, & Washburn, 2001). The Pacinian receptors are those mechanoreceptors that are specifically sensitive to vibration. Adaptation impaired the discrimination of fine but not of coarse textures, showing that the perception of coarse textures does not depend exclusively on vibrations. Incidentally, vibrotactile adaptation also had no effect on roughness perception of grooved surfaces, since these can also be qualified as coarse textures (Lederman, Loomis, & Williams, 1982).

Rigid probes. It should be noted that it is not the frequency of the vibration that is associated with perceived roughness; this would lead to a direct dependence of perceived roughness on movement speed, which is not observed. Rather, perceived roughness is associated with the amplitude of the vibrations, weighted with the frequency response of the Pacinian receptors (Bensmaïa & Hollins, 2003; Bensmaïa & Hollins, 2005). The frequency response is the characteristic that describes how strongly the receptors respond to the amplitude of vibrations at different frequencies. Depending on the shape of this characteristic, vibrations at different frequencies contribute more or less to the perceived roughness. In addition to pressure-only (static touch) and a combination of pressure and vibration (dynamic touch), roughness can also be perceived using only vibration. This has been tested by using a rigid link interposed between skin and surface (Klatzky & Lederman, 1999). The rigid probe transmits vibrations, but not the pressure distribution. With the probe, discrimination between different levels of roughness was not as good as when using a bare finger, because less information is available. However, the rigid probe produced a greater perceived roughness for the smoothest stimuli, because the probe can enter the narrow space between the elements on the surface that a finger cannot enter. This shows once more that vibrations are particularly important when exploring relatively smooth surfaces, but that the different types of information may be combined to give the highest accuracy for coarser textures. The perceived roughness of these coarser textures is not subject to the effects of adaptation through prolonged exposure when the surfaces are touched directly, but is suppressed after (vibrotactile) adaptation when the surfaces are explored through a probe (Hollins, Lorenz, & Harper, 2006). This means that for these coarser textures, even though the vibrotactile information is present in the case of direct touch, roughness perception is based mainly on the spatial pressure distribution information.

Manufactured surfaces. When sandpapers are used as stimuli, as in most of the studies cited above, many factors come into play: the diameter of the particles, their shape (jagged or smooth), the particle density on the paper, etc. This multitude of factors makes it difficult to pinpoint what aspect or combination of aspects determines perceived roughness. That is why some authors used manufactured surfaces for a more systematic study of roughness perception. This gave them more control over the parameters to vary. Lederman and Taylor used aluminium plates with grooves with a rectangular cross-section (Lederman & Taylor, 1972; Lederman, 1974; Taylor & Lederman, 1975; Lederman, 1981, 1983). Perceived roughness increased strongly with increasing groove width (see Fig. 2) and less strongly with decreasing distance between the grooves. The authors also found an effect of fingertip force on perceived roughness. The perceived roughness could be predicted as a function of groove width, fingertip force and groove distance using a model based on the amount of depression of the fingertip into the groove (Taylor & Lederman, 1975). However, the predictive power of this model is limited to these grooved surfaces and does not extend to other rough surfaces. For instance, the model assumes an "infinite" depth of the grooves, and does not consider the role of the ridge height. In contrast, Miyaoka, Mano, and Ohka (1999) hypothesised that it could be the amplitude information of the stimulus surface that determined the perceived roughness. This was tested by performing discrimination experiments with sandpapers and ridged stainless steel plates. Subjects were able to discriminate between ridges differing $\sim$1 μm in height, suggesting that they could use the height differences of a similar relative magnitude present in the sandpaper stimuli to discriminate between the different roughnesses. Besides groove width, ridge height, and particle diameter, the spacing of raised dots on a surface was found to be of influence on the perceived roughness (Lamb, 1983; Hollins et al., 2001). It is likely that observers do not have a fixed method for roughness perception, but use whatever information is present. Therefore, perceived roughness of one stimulus will depend strongly on the other types of stimuli available in a set. On the one hand, this limits the usefulness of models relating the physical properties of one particular stimulus set to perceived roughness, because these models have to be different for each stimulus set. On the other hand, it means that the sensation of roughness can be invoked in a large number of ways, which might be useful in the context of artificially displaying haptic sensations. Either way, these studies have not yet provided a singular answer to the question of what exactly is perceived roughness.

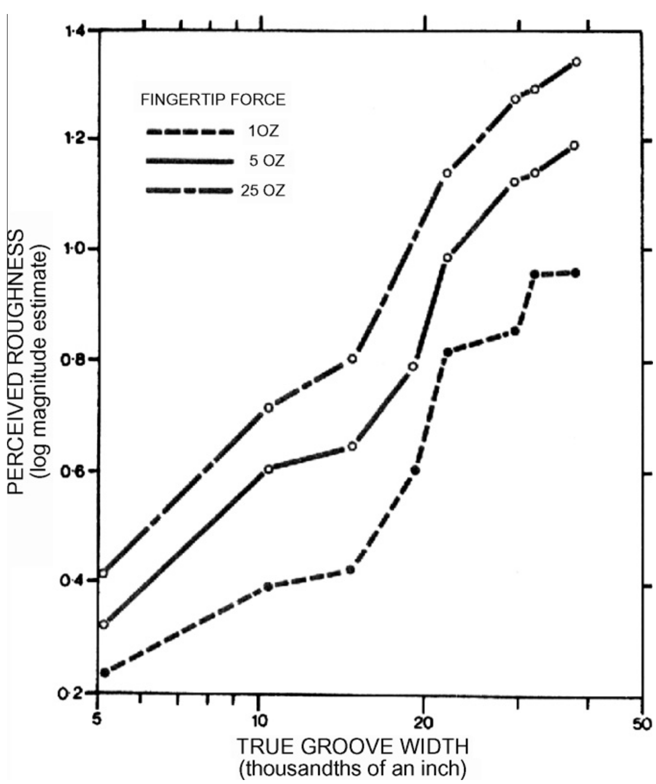

Fig. 2. Log of estimated roughness of grooved aluminium plates as a function of groove width. Estimates increase with increasing groove width and fingertip force. Reproduced with permission from Lederman and Taylor (1972).

Multidimensional sensation. It might very well be that what we call perceived roughness is not a singular sensation at all. In an experiment with many different materials, perceived roughness was shown to correlate with different physical roughness measures, depending on the subject (Bergmann Tiest & Kappers, 2007). Some subjects appeared to base their judgements more on the lower spatial frequencies present in the surface profiles of the materials, whereas others based their judgements more on the higher spatial frequencies. Other features besides the surface profile seemed to play a role as well, such as the materials' coefficient of friction. This had been observed before in the context of sandpaper stimuli: In addition to grit number, Ekman et al. (1965) found a positive correlation between perceived roughness and measured coefficient of friction. Besides friction, perceived roughness also shows a high correlation with the average rate of change of the tangential touching force (Smith, Chapman, Deslandes, Langlais, & Thibodeau, 2002). It appears that perceived roughness is not just one dimension of haptic material perception, but is a multidimensional quantity in itself. This means that what is called roughness can vary in more than one way. At the same time, this multidimensional sensation is determined by different physical parameters such as amplitude of the surface profile, spacing of the surface features and friction between skin and surface.

Adaptation and assimilation. Not only does perceived roughness depend on the physical properties of the surface and the way it is probed, but also on the spatial and temporal context (Kahrimanovic, Bergmann Tiest, & Kappers, 2009). A surface that is felt just after a smooth surface has been felt, feels rougher than the same surface when it is felt just after a rough surface has been felt. Since this contrast effect works both ways, it cannot be a result of fatigue in the receptors, but of processes at a higher level. Conversely, a surface felt with the index finger at the same time as a rough surface felt with the middle finger, feels rougher than the same surface felt simultaneously with a smooth surface. This assimilation effect in the spatial context shows that information of multiple fingers is integrated at a higher level.

Neural codes. Using magnitude estimation by humans and recordings from nerves in macaque monkeys, perceived roughness has been linked to neurophysiological events (Connor, Hsiao, Phillips, & Johnson, 1990). For embossed dot patterns with dot spacings ranging from 1.3 to 6.2 mm, the magnitude estimations correlated well with the spatial variance in impulse rate in Slowly Adapting type nerves, and to a lesser extent in Rapidly Adapting and Pacinian type nerves. This suggests that it is this variance that is used as a neural code for transmitting roughness for these fairly coarse textures. In the somatosensory cortex, the variability in firing rates between different afferents is then transformed into a sensation of roughness (Hsiao, Johnson, & Twombly, 1993). Roughness perception of finer textures (spatial period <200 μm) is based on vibration sensing and is mediated by the Pacinian system (Hollins & Bensmaïa, 2007). In this case, perceived roughness is coded as the intensity of the vibrations that are produced when the finger is scanning a surface, when these vibrations are weighted with the spectral responsivity of the Pacinian system. That is, the power in the vibration spectrum at those frequencies where the Pacinian system is the most sensitive (100–300 Hz) is weighted most heavily and the intensity (not the frequency) of the highest peak in the weighted spectrum determines perceived roughness (Bensmaïa & Hollins, 2005).

Rendered roughness. The fact that perceived roughness is associated with vibrations can be exploited in order to artificially generate the sensation of roughness. This is useful in haptic displays, which enable a user to feel and interact with virtual objects. In order to calibrate rendered roughness to the perceived roughness of sandpapers, Kyung and Kwon (2006) have performed an experiment in which observers were asked to match a vibrotactile stimulus from a 5×6 pin array to the memorised roughness of sandpaper samples. Perceived roughness turned out to increase with the logarithms of the vibration frequency and amplitude. However, there are many more ways of rendering texture (Campion & Hayward, 2008). In that paper, the authors analysed a number of rendering algorithms, and introduced a new one in which the texture of a virtual surface is displayed as changes in the generated lateral friction. The idea is that when the finger is ascending a bump on the surface, this feels as an increase of friction, while 'sliding down' a bump feels as decreased friction. The advantage of this algorithm is, that the force field it generates is almost conservative, meaning that the amount of energy needed to move through it does not depend on the path taken. Of course, this is just one criterion for what makes a good algorithm; other criteria favour other algorithms. This illustrates that the multitude of physical aspects that are interpreted as roughness are echoed by a multitude of possibilities for rendering roughness.

To sum up, although roughness is associated with many different physical properties of surfaces (height difference, friction, spatial period, dot spacing), roughness perception is mediated mainly through two distinct channels: a vibrationary component for the fine-structured surfaces and a spatial variance component for the coarser surfaces. The vibrationary component is sensitive to vibrotactile adaptation at receptor level, but roughness perception as a whole is subject to adaptation and assimilation effects at a higher level. The multidimensional quality of perceived roughness can be exploited in the context of rendering virtual surfaces.

3. Compliance

Physically, an object's compliance can be expressed in a number of ways: First, as the object's *stiffness*, which is the ratio between the force that is exerted upon it, and the resulting displacement. A softer object has a lower stiffness. Stiffness depends on the object's dimensions: a thick, narrow object can be compressed more than a thin, wide object made of the same material, using the same force. Another way of expressing compliance is through the material's *Young's modulus*. This is the ratio between pressure (force per unit area) and *relative* displacement, that is the displacement divided by the original length. For 'linear' materials, this way of expressing compliance is independent of the object's dimensions.

Magnitude estimation. The question is: how is compliance (or softness or hardness) perceived? What is the relationship between physical and perceived compliance? This was investigated by Harper and Stevens (1964), who performed a magnitude estimation experiment by letting subjects squeeze different types of rubber. They found a power function relationship with an exponent of 0.8 relating perceived hardness to physical stiffness. The same function with the negative exponent was found for perceived softness, showing that softness and hardness are direct opposites. To see how perceived softness depends on the way objects are touched, Friedman, Hester, Green, and LaMotte (2008) let subjects press down on or tap silicone rubber samples with their fingers or with a tool, using different forces. They found no difference between active pressing and tapping with the finger pad. Subjects who used more force in the active condition rated the stimuli at the hard end of the range as harder than those using less force, suggesting that perceived softness could depend on the force used. However, in the passive condition, no effect of force was found. Because perception was passive, subjects could only use cutaneous information about the pressure distribution on their finger in this case, and no kinaesthetic information. Thus, softness perception does not depend on kinaesthetic force information, but can be influenced by it. Using a tool, without direct contact, the stimuli at the hard end of the range were rated as softer than with direct contact. The relationship between perceived softness and physical stiffness was less steep when using the tool, showing that the direct cutaneous contact mainly intensifies the perceived hardness of relatively hard materials.

Discrimination. So, people can perceive softness and hardness in different ways. But how well can they distinguish between different levels of hardness? Discrimination experiments were pioneered by Coppen and Scott Blair. They had subjects choose the softer stimulus in pairs of rubber cylinders that varied in their hardness difference (Scott Blair & Coppen, 1939; Coppen, 1942). The percentage correct scores crossed the 84%-level (a widely-used threshold value) at a difference of 13% in stiffness. This can be interpreted as the Weber fraction for hardness discrimination. Somewhat counter-intuitively, discrimination is found to be a little better when samples are pressed down on with one finger compared to when they are pinched between thumb and index finger (Freyberger & Färber, 2006). Above, we saw that both cutaneous and kinaesthetic cues can be used to perceive softness. Srinivasan and LaMotte (1995) showed that for discrimination, cutaneous information is both necessary and sufficient. With an anaesthetised finger, without cutaneous cues, subjects could not discriminate between rubber samples differing 90% in stiffness. With passive touch, without kinaesthetic force and displacement cues, subjects could discriminate between specimens differing less than 75% in stiffness. This shows that cutaneous information is essential, but also that without kinaesthetic information, discrimination is impaired compared to a situation where all cues are present. Also when using a tool, subjects were found to be able to use cutaneous information in the form of the vibrations transmitted by the tool when tapping the stimulus (LaMotte, 2000). In addition to the purely cutaneous cues provided by the deformation of the surface, the ratio between force and displacement can be used for hardness discrimination, which is mediated by a combination of kinaesthetic (force and displacement) and cutaneous (force) information. Bergmann Tiest and Kappers (2009a) have investigated what the relative roles of these two sources of information is. By comparing discrimination thresholds measured with surface deformation (Weber fraction ~15%) and without (Weber fraction ~50%), they showed that about 90% of the information comes from surface deformation cues, and 10% from force/displacement cues. Furthermore, by using silicone rubber stimuli that did not consist of the same material all the way through ('sandwich' stimuli), they were able to decouple the object's stiffness and the material's Young's modulus for stimuli of identical dimensions. By asking subjects to match the hardness of these objects, they investigated whether stiffness or Young's modulus is the determining factor in hardness perception. The results (see Fig. 3) indicated that both play a role, but that judgements are based more on stiffness for the softer stimuli and more on Young's modulus for the harder stimuli. That is, subjects seem to pay more attention to the force/displacement (stiffness) information for the softer stimuli (which they can actually squeeze) and more attention to the surface deformation

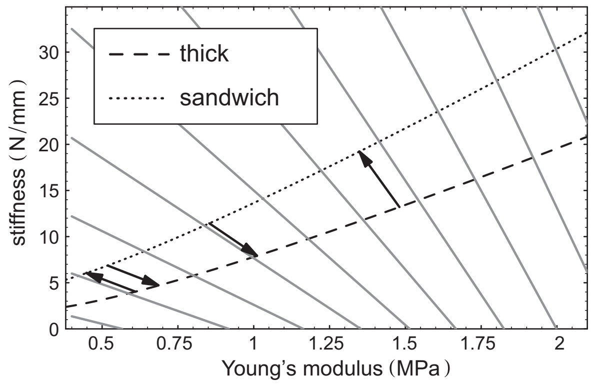

Fig. 3. Compliance matching. The arrows indicate matches made between stimuli that differ in their relationship between stiffness and Young's modulus (indicated by the dotted and dashed curves). The grey lines illustrate possible lines of equal perceived hardness. Reproduced with permission from Bergmann Tiest and Kappers (2009a).

information (as determined by the material's Youngs modulus) for the harder stimuli (which they can only indent a little bit).

Rendered compliance. The high importance of surface deformation information for compliance perception, as discussed above, has implications for the way compliance should be rendered. In fact, when using a haptic device that only provides force/displacement information, it seems that the perceived hardness is not directly correlated with the rendered stiffness. Instead, another measure called *rate-hardness* seems to be better correlated with perceived hardness (Lawrence, Pao, Dougherty, Salada, & Pavlou, 2000). This is defined as the initial force rate of change (in N/s) divided by the initial displacement velocity (in m/s). This suggests that perceived hardness of such a device is mainly based on the immediate response when tapping a virtual surface, instead of the longer-term response when such a surface is pressed. However, it would be better to try to include the surface deformation information in the haptic display. This information consists, among other things, of the size of the contact area as a function of the applied force. This *contact area spread rate* is related to the compliance of the touched surface (Bicchi, Scilingo, & De Rossi, 2000). A device mimicking this behaviour, combined with the display of force/displacement information, provides better discrimination performance than just force/displacement information, and also better than just contact area spread rate information (Scilingo, Bianchi, Grioli, & Bicchi, 2010).

In conclusion, compliance can be perceived through surface deformation, vibrations and force/displacement information, but the cutaneous cues seem to be the most important ones. With all cues present, Weber fractions for discrimination down to $\sim$15% can be attained. Devices that combine kinaesthetic and cutaneous information may be able to approach this value. It is clear that the pressure distribution on the skin plays an important role in compliance perception, but exactly *how* this information is used to form a percept of compliance, is unknown. Perhaps this can be investigated using state-of-the-art haptic devices that are capable of generating different pressure distributions.

4. Coldness

The coldness of an object at room temperature is another material property that can be perceived tactually. It is distinct from the object's temperature, which has nothing to do with the material. We experience some materials as 'cold', even though they are at room temperature, because of the heat that is being extracted from our hands when we touch them. What happens to the fingers when an object with a temperature below skin temperature is touched, was measured by Havenith, Van de Linde, and Heus (1992). Different materials (foam, wood, aluminium, ...) produced different cooling curves for the fingers. These could be modelled by exponential decay functions. The time constant of these functions was found to be inversely related to the logarithm of the contact coefficient of the material, which is the square root of the product of the material's thermal conductivity, specific heat, and density (Businger & Buettner, 1961). Similar cooling curves were observed with touching different kinds of fabric (Schneider & Holcombe, 1991). The initial steepness of these curves was highly correlated with subjective assessments of coolness[1] of the fabrics by human observers. Furthermore, measurements of cooling curves of different materials found in a car passenger compartment were found to be related to magnitude estimates of coldness by a team of experts (Sarda, Deterre, & Vergneault, 2004). So, perceived coldness of a material is directly related to the rate of heat extraction from the fingers when touching that material, which in turn depends on the material's thermal properties, such as thermal conductivity and specific heat, and the object's geometry.

Discrimination. The ability of humans to distinguish between different rates of heat extraction can be used for diagnostic purposes (Dyck, Curtis, Bushek, & Offord, 1974). A measure for cutaneous sensory ability can be used to track the degeneration or regeneration in various populations of nerve fibres in cases of neuropathy. For this purpose, normal values of heat extraction rate discrimination have been measured using discs of different thicknesses and materials, such as copper, glass, and PVC. Stimuli differing an order of magnitude or more in (initial) heat transfer rate could be successfully discriminated. Ho and Jones (2006a) further explored coldness discrimination in relation to the material's contact coefficient. In an experiment with six different materials (copper, steel, granite, ...), they found that a factor of three difference in contact coefficient was necessary for discrimination. However, the contact coefficient only takes into account the thermal properties of the material, and not the geometry of the object. That this is relevant was shown by Bergmann Tiest and Kappers (2008). They used 100×100 mm aluminium stimuli differing only in thickness (1–9 mm, with a reference stimulus of 5 mm) to perform discrimination experiments. Subjects touched only the top surface of the stimuli and were able to discriminate between stimuli differing 6 mm in thickness, just based on perceived coldness. Since all stimuli were of the same material, they all had the same contact coefficient, but still the thicker ones were perceived colder. This makes sense, because with a larger volume, the total heat capacity is larger, and with increasing thickness, the thermal conductance in the plane also increases. Therefore, the heat transfer rate upon contact will also be larger for thicker stimuli, and these will therefore feel colder than thinner stimuli. The experiments were done at different temperatures (10–40 °C). At 40 °C, the sense of cold and warm was reversed compared to room temperature; that is, thinner stimuli were now perceived colder than thicker ones. This reversal phenomenon was already observed by Katz (1925). Through interpolation, Bergmann Tiest and Kappers (2008) pinpointed the reversal point at 34 °C, see Fig. 4. To characterise the discrimination threshold for coldness perception more precisely, it would be desireable to have a closely-spaced range of materials in terms of heat transfer rate. However, such materials are hard to find. For this reason, Bergmann Tiest and Kappers (2009b) have used a device to artificially extract heat from the finger at certain rates. This enabled them to measure the discrimination threshold for thermal time constant, which is the time constant of the exponential function that describes finger cooling. It is inversely related to

[1] in the non-popular sense of the word.

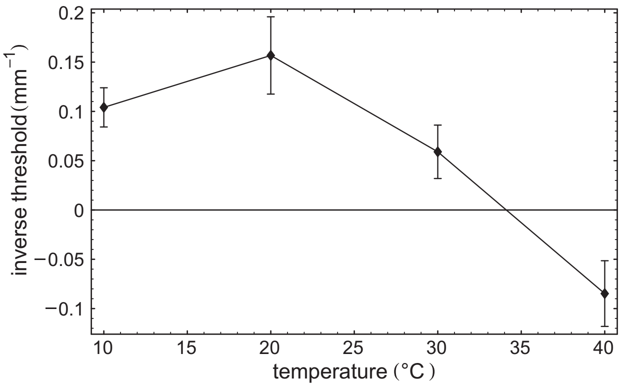

Fig. 4. Inverse thresholds for discrimination of aluminium plates of different thicknesses based on perceived coldness, for different stimulus temperatures. Plotted are the reciprocals of the thresholds to accommodate near-infinity values. The negative threshold at 40 °C means that the notion of warmness and coldness have reversed at this temperature. Reproduced with permission from Bergmann Tiest and Kappers (2008).

the thermal diffusivity of the material, which is the ratio of thermal conductivity over specific heat and density. Subjects were able to discriminate between simulated materials with thermal diffusivities differing by 43%. When the thermal diffusivity was halved, the absolute discrimination threshold also halved, in accordance with Weber-like behaviour. Since the thermal diffusivity is known for many materials, this can help us predict which materials can be discriminated based on thermal cues and which cannot.

Modelling. However, to make exact predictions valid for many different situations, more insight is needed into what exactly is happening thermally when an object is touched. For this reason, mathematical models for the heat transfer have been developed. Sarda et al. (2004) used a two-dimensional finite-element numerical model to calculate the time course of the temperature for a finger in contact with different materials. They found that the detailed two-dimensional model was approximated quite well by a simpler one-dimensional model. Benali-Khoudja, Hafez, Alexandre, Benachour, and Kheddar (2003a) used an electrical analogy to model heat transfer between a finger and a surface. This model also takes into account the blood flow in the finger and the contact resistance between finger and surface. The role of this contact resistance was further explored by Ho and Jones (2006b), who used a semi-infinite body model to describe the heat flux between a finger and a surface, taking into account the roughness of the fingerpad and the surface. However, that model does not take into account the role of the geometry of the object that is being touched. In a simple one-dimensional finite-element model by Bergmann Tiest (2007), this effect is taken into account and shown to play a significant role. Using this model, the heat transfer rates in the experiment with the aluminium stimuli of different thicknesses (Bergmann Tiest & Kappers, 2008) could be calculated and the measured discrimination threshold could be expressed in terms of the minimum detectable difference in heat transfer rate, yielding a value of 36%. This is quite comparable to the thermal diffusivity threshold value of 43% (Bergmann Tiest & Kappers, 2009b), which should be directly related to heat transfer rate. This shows that theoretical models, experiments with real stimuli and experiments with artificial extraction of heat come together nicely. However, at the moment not enough data are available to give a complete description of the processes involved in coldness perception.

Rendering. In general, the sensation of coldness of a material is induced artificially by cooling the finger with a Peltier thermoelectric element. This is a device that transports heat from one side to the other when an electrical current is passed through it. However, opinions differ on the exact way in which the finger should be cooled. Ino et al. (1993) simply re-displayed measured cooling curves for a fingertip touching different materials. Benali-Khoudja, Hafez, Alexandre, and Kheddar (2003b) suggested using cooling curves based on separately measured thermal time constants. Yamamoto, Cros, Hashimoto, and Higuchi (2004) used a different approach still in which the device was maintained at a lower temperature than the predicted final contact temperature until contact was made. This lower temperature was chosen in such a way that after contact was made, the temperature would settle 'naturally' at the predicted contact temperature. Deml, Mihalyi, and Hannig (2006) based their cooling curves on the thermal properties of the materials and a set of differential equations describing the temperature at a number of different layers in skin of the finger. Alternatively, Ho and Jones (2004, 2007) opted for a static temperature display that corresponded to the initial contact temperature that would be established given the material's contact coefficient. Which of these methods is best, is not easily decided. The evaluation criteria used by the different authors cannot be compared directly. In all experiments, subjects were able to distinguish or identify different simulated materials, so we can conclude that the perception of coldness, like roughness, can be invoked in many different ways. The challenges of rendering coldness are discussed in further detail by Jones and Ho (2008).

In summary, it is clear that differences in perceived coldness can be used for material identification. The minimally required difference in thermal parameters for discrimination ranges from about 40% to 200% or more, depending on whether one looks at thermal diffusivity, contact coefficient or heat transfer rate. In addition to the material's thermal properties, the thermal contact resistance between finger and object, and the geometry of the object should be taken into account. Coldness of materials can be artificially displayed by cooling the finger along a curve, the precise description of which is still under debate, but its general shape is similar to an exponential decay. Other questions also remain: for example, the influence of the manner of touching (brief or prolonged, with a single finger or the whole hand) is still unexplored. New experiments and more extensive modelling may help resolve these issues.

5. Slipperiness

The material property of slipperiness is related to the friction that occurs when one surface (e.g. a finger) slides over another. The frictional force works in the opposite direction of the motion. Its magnitude is usually more or less proportional to the magnitude of the contact force perpendicular to the surface, but can also depend on the speed of movement. The ratio between the frictional force and the normal force is called the *coefficient of friction*. Physically, friction and roughness are quite distinct, but perceptually and linguistically, there may be some overlap. Still, people can feel clear differences in resistance for different materials when they move their finger over the surface. Thus, they can use perceived slipperiness for haptic material identification. It is therefore surprising that relatively little is known about haptic perception of slipperiness. One reason might be that friction itself is an elusive property, since it is always defined with respect to the two surfaces interacting and also depends on humidity, normal force and speed of movement. In that sense, it is not just a property of the material, like the other three discussed above, and therefore not unambiguously measurable. Also, the interactions on micro-scale between the two surfaces that determine the friction are not well described. Therefore, predicting the amount of friction between two surfaces based on other material properties is difficult.

Correlation with friction. Regarding the perception of slipperiness (or its opposite), Zigler (1923) wrote about the perception of stickiness, but this referred to the adhesive kind: he let subjects describe the sensation of touching a pencil's rubber which was dipped in liquid glue. As mentioned above, Ekman et al. (1965) looked at friction, but they asked their subjects to estimate roughness, not slipperiness. Therefore, to my knowledge, the first psychophysical investigation into slipperiness perception was by Smith and Scott (1996), only 14 years ago. They found a correlation coefficient of 0.85 between the coefficients of friction of a number of smooth surfaces and subjective estimates of slipperiness (see Fig. 5). Grierson and Carnahan (2006) looked at different exploratory procedures for slipperiness perception and found that movement was essential for an accurate perception of slipperiness. However, humans are able to adjust the grip force applied to objects that are picked up to the slipperiness of these objects (Johansson & Westling, 1984; Cadoret & Smith, 1996). Therefore, they must also be able to perceive slipperiness statically (without slip). It is proposed that the grip force is adjusted automatically based on input from cutaneous receptors during occurrences of 'micro-slip', miniscule movements over the skin of the object that is otherwise held statically. Grierson and Carnahan (2006) concluded that there must be a dissociation between perception and action in this respect, because when people perform an action (picking up an object), they can determine slipperiness statically, whereas for conscious perception of slipperiness, movement is required.

Cue combination. Measurements of the discrimination threshold for slipperiness perception were conducted by Provancher and Sylvester (2009) using a force feedback device. They found thesholds ranging between 18% and 27% for coefficients of friction between 0.8 and 0.2. However, these thresholds were not measured with real materials, for which other aspects besides forces play a role, such as skin stretch. The inclusion of skin stretch led to an increase in perceived friction compared to displaying just force information. This means that slipperiness is perceived through multiple channels: kinaesthetic (forces) and cutaneous (skin stretch). The cutaneous information about slip is mediated by nerve fibres of either the Rapidly Adapting type or the Pacinian type, depending on whether the slip of a single dot or a textured surface is perceived, respectively (Srinivasan, Whitehouse, & LaMotte, 1990). It is likely that the cutaneous component of slipperiness perception is mediated in the same way.

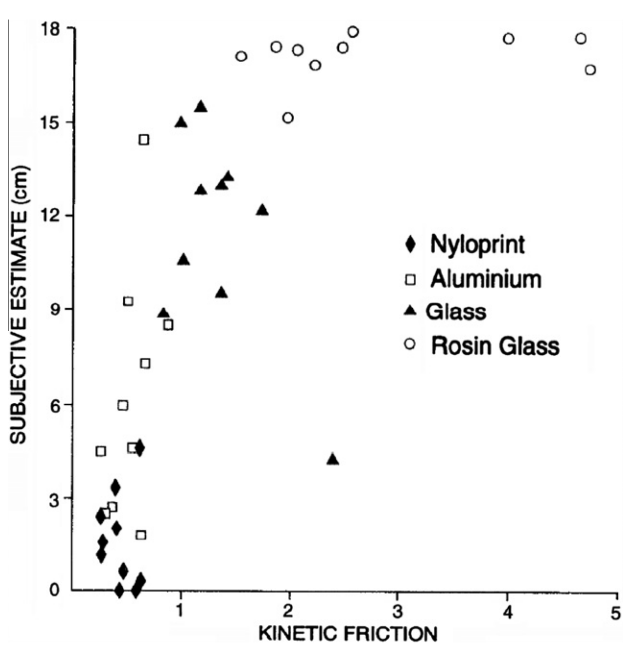

Fig. 5. Estimates of perceived stickiness as a function of measured coefficients of friction for 10 subjects and four materials. Reproduced with permission from The American Physiological Society from Smith and Scott (1996).

To conclude, humans are able to perceive different levels of slipperiness quite accurately by combining cutaneous and kinaesthetic cues. However, research into this aspect of haptic perception of material properties is still in its early stages. For example, we do not even know how the perceived intensity scales with the physical intensity (linearly, through a power function, or otherwise). In this respect, there is a lot of room for more fundamental research.

6. Interactions

Though the study of tactual perception of these material properties is interesting in itself, even more insight into tactual perception of material properties can be gained by looking at the interactions between properties. We have already seen that perception of roughness and slipperiness might be related. A rough material, with many surface features sticking out, might 'grip' the skin more, causing the sensation of friction. Because people have learned to make this association, the reverse could also true and a high coefficient of friction might induce the sensation of roughness. Indeed, with sandpapers, friction was found to contribute to the perception of roughness (Ekman et al., 1965; Bergmann Tiest & Kappers, 2007), but this appears not to be the case for grooved surfaces (Taylor & Lederman, 1975). For surfaces with arrays of raised dots, there is a significant correlation between friction and perceived roughness, but the determining factor seems to be the rate of change of tangential force (Smith et al., 2002).

Another interaction that relates to the small-scale geometric structure of a surface is the effect of roughness on contact area. When the skin touches only the tips of the surface features on a rough material, the effective contact area is greatly reduced compared to touching a smooth surface. Therefore, the rate of heat transport will also be smaller for a rough surface, causing smooth surfaces to feel colder than rough surfaces.

Conversely, a compliant material will form itself around the finger when touched, causing an increased contact area compared to a rigid material. This will have an effect on perceived slipperiness, because a larger contact area means a larger frictional force. Also, the increased contact area allows a larger rate of heat extraction from the finger, causing soft materials to feel colder.

Due to sharp points on the surface, a rough material might induce more intense sensations when squeezed, causing an intensified cutaneous force perception. This could have an effect on the compliance perception, causing a rough material to feel harder. But since the role of force cues in compliance perception is very limited compared to surface deformation cues, this effect is expected to be very small.

Many of these interactions have not yet been studied very intensively (if at all), but potentially yield new insights into the way material properties are processed by the sensory system. Observing the interactions mentioned here would provide confirmation of the ideas from the previous sections about how sensations and physical material properties are related.

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