Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility

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Abstract

In this paper, results of a free sorting task of 124 different material samples are analysed using multidimensional scaling. The relevant number of dimensions for haptic perception of materials is estimated to be 4. In addition, the haptic material space is calibrated by means of physical measurements of compressibility and roughness. The relation between objective and perceived compressibility and that between objective and perceived roughness could be described by an exponential function.

Key words: Touch, Material perception, Multidimensional scaling, Roughness, Compressibility
PsycINFO classification: 2320

1 Introduction

Research into the way materials or material parameters are perceived by means of touch has until now been limited. There has been quite some research into texture perception using artificially produced surfaces, e.g. Lederman (1981); Klatzky et al. (1989); Connor et al. (1990). However, the perception of more 'natural' materials, occuring in an everyday context, has received less attention. Most previous studies have focused on a very specific kind of material or have used only a small number of different materials. Also, the way haptic

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perception of materials relates to physical material parameters is not very well known. Meenes and Zigler (1923) had 4 observers feel 12 types of paper and report their sensations. With static passive touch, they mainly reported uneveness of pressure, while with dynamic passive touch, roughness and smoothness were reported. Evidently, dynamic touch (movement) is important for texture perception. Therefore, in our experiment we will use dynamic touch.

Stevens and Harris (1962) let observers judge the subjective roughness and smoothness of 12 emery cloths in terms of numbers. Emery cloth is an abrasive made from powdered aluminium oxide. They found that the roughness judgments were related to the grit numbers of the emery cloth by a power law with an exponent of -1.5. The grit number refers to the number of openings per unit of area in the sieve used to sift the emery powder. As was expected, the smoothness judgments were found to be the reciprocal of roughness, with an exponent of $+1.5$. The grit number is roughly inversely proportional to the particle size, but it is not entirely clear how this relates to actual roughness as a physical parameter, i.e. the amount of height difference on the surface. Therefore, the numerical results of this study are only appropiate for sandpapers and emery cloths. Something similar was done by Ekman et al. (1965) with 10 subjects and 5 sandpapers plus a piece of cardboard and a piece of writing paper. In addition, they had the pleasantness of the stimuli rated on a preference scale and looked at the individual differences between subjects. Moreover, they measured the coefficient of friction of their stimuli and found a power function relation with the subjective roughness judgments: greater friction was associated with greater perceived roughness. Although the correlation with friction is a useful result, the very limited stimulus set cannot guarantee its general applicability. Besides friction, perceived roughness also shows a high correlation with the average rate of change of the tangential touching force (Smith et al., 2002). Therefore, the perception of roughness may relate to a number of different physical parameters. The experiment by Stevens and Harris (1962) was repeated by Stone (1967), but with attention to the individual differences between observers. He found quite a spread in the exponents which were generally smaller than those reported by Stevens and Harris. He suggested that the difference with respect to Stevens and Harris was caused by differences in the stimuli, supporting the idea that grit number is not a very reliable material parameter. Based on these conclusions, it is clear that we must find a way to reliably characterise roughness that is generally applicable.

Heller (1989) used also abrasives to study the haptic perception of roughness in sighted and blind observers. He found no difference in judging accuracy between sighted and blind observers, and no difference between active (the subject moves his or her finger) and passive (the subject keeps his or her finger still and the experimenter moves the object) touch. The mode of (dynamic) touch apparently does not influence texture perception. Therefore, in our experiment we can use the active mode of touch, which is experimentally less complicated, without loss of generality. Miyaoka et al. (1999) again used sandpapers to determine the roughness discrimination threshold in terms of particle size. They argue that the subjects use the amplitude information of surface unevenness for the fine-surface-texture discrimination tasks. This means that we can use the information from a surface profile to characterise roughness. Miyaoka et al. measured cross-sections of their stimuli with a contact-profile meter and observed that the measured amplitudes did not always coincide with the nominal particle sizes. Unfortunately, they did not use the cross-section profiles to find a quantity to express the discrimination thresholds in. Therefore, the threshold values only apply to sandpapers. Another set of sandpaper experiments was conducted by Hollins and Risner (2000). They determined that discrimination was more difficult using static touch than using dynamic touch in the case of fine textures, but not in the case of coarse textures, suggesting that two different mechanisms are involved. They went on to letting subjects judge the roughness of sandpapers in terms of numbers, similar to Stevens and Harris. The results showed the subjective roughness levelling off at the fine-texture end in the case of static touch, but not in the case of dynamic touch, supporting the involvement of two different mechanisms. However, this study suffers from the same drawbacks as that by Stevens and Harris, namely the uncertainties in the relation between particle size and physical roughness and in the relation between perceived roughness and the number supplied by the subject. Hollins and coworkers also performed important work using multidimensional scaling (MDS) with haptic perception which will be discussed later in this section.

Much earlier though, Yoshida (1968a,b) performed MDS on 25 material samples using the judgment of 25 subjects on 15 adjective scales (1968a) and the direct estimation of similarity by 8 subjects (1968b). The results of these two methods differed somewhat, suggesting that dissimilarity judgments and judgments on adjective scales may relate to different perceptions. The dimensionality of the resultant space was not reported, but the main contrast was between 'metallicness' vs. 'fibrelikeness'. Although the stimulus set was varied, it was probably too small to provide a full picture of the haptic material space. Also, the choice of which adjectives to include introduces some partiality in the experiment. Hollins et al. (1993) performed a similar study, but used a grouping method to obtain the similarity data, thus avoiding the subjectiveness in the choice of adjectives. 20 subjects were instructed to divide 17 stimuli in at least 3 and at most 7 groups. The more often two stimuli occured in the same group, the more similar they must be. From the MDS analysis the authors concluded that the perceptual space was most likely 3-dimensional. By letting the stimuli be judged on 5 adjective scales, they could identify 2 dimensions: smooth/rough and hard/soft. However, it is perhaps unrealistic to expect more dimensions with such a limited number of stimuli. For instance, to 'fill' a 4-

dimensional space, one needs at least $2^4 = 16$ stimuli just to have one in each 'corner' of the space. It is unlikely that of the 17 stimuli used, 16 are exactly in the right locations for this. Hollins et al. (2000) again used 17 stimuli, but this time they asked 5 subjects to directly estimate the dissimilarity of all pairs. They performed MDS analysis on all subjects separately. The number of dimensions ranged between 2 and 3. By fitting the ratings on 5 adjective scales in the MDS spaces, they identified the first two as rough/smooth and soft/hard, and the third as sticky/slippery, but this one was less dominant and not present with all subjects. Again, however, because the number of stimuli was limited, this experiment does not exclude the existance of a higher number of dimensions in the haptic material space. Another paper that used MDS to analyse haptic perception deals with a very specific type of material: car seat fabric (Picard et al., 2003). 20 participants sorted 24 car seat materials in groups on the basis of perceived similarity. An MDS analysis of these similarity data yielded a 3- or 4-dimensional texture space. The subjects also rated the simuli on 10 adjective scales. By fitting these adjectives into the MDS space, the authors were able to identify two orthogonal dimensions: soft/harsh and thin/thick. However, since the stimuli were all fabrics and limited in number, it is impossible to extrapolate these results to material textures in general.

To sum up, we can say that the previous research into the haptic perception of materials used a small number of stimuli and/or a very specific kind of material (sandpaper, car seat fabrics). The results are often correlated with quantities that may not be well-defined, such as grit number, or very subjective, such as adjective ratings. In the present study, we attempt to gain more insight into the process of haptic perception of materials by using a large number of materials (124), spanning a very broad range of tactual perceptions. The stimuli are to be explored by active, dynamic touch. We would like to know the number and the relative importance of material characteristics involved in tactile perception. In order to avoid the difficulties for the subjects associated with translating a sensation into a number, and to not limit the subjects to specific adjectives, a free-sorting task was selected for the psychological characterisation. (A spatial arrangement task (Goldstone, 1994; Ballesteros et al., 2004) was not an option, because then the subject is restricted to two dimensions while a higher number is most likely necessary). With the aid of MDS analysis, the grouping task is used as a tool to obtain measures of perceived material properties; in that way it is comparable to a magnitude estimation task.

In addition to the psychological characterisation, we try to quantify the relevant material parameters in terms of physical units, independent of the particular set of materials used. Because the dimensions rough/smooth and hard/soft were most often mentioned in the literature, we decided to look into the parameters roughness and compressibility. It should be noted that, though similar terms are used for them in the English language, these physical parameters need not coincide exactly with 'rough' or 'hard' as perceptions. However, it is our intended goal to compare psychological data with physical measures and not with subjective measures. Correlating the psychological characterisation with the physical measurements will result in new, objective information about the haptic perception of a wide range of materials.

2 Method

A free-sorting experiment was performed to measure the perceived similarity and dissimilarity of the stimuli. Using the dissimilarity data, MDS analysis was performed to find the number of relevant dimensions of the haptic material space and to position the stimuli within this space.

2.1 Stimuli

The 124 stimuli were comprised of a range of materials as wide as possible, including woods, ceramics, cloths, plastics, glass, metals, abrasive materials, paper, cardboard, foams, rubber, felts etc. They were chosen to reflect the range of materials that are encountered in an everyday context. They are listed in table 1.

Table 1: The stimuli, with measured compressibility and roughness values. The asterisk (*) indicates materials that were used unmounted.

n°	description	compressibility (10^8 N/m/m^2)	averaged roughness (μm/$\sqrt{\text{mm}^{-1}}$)
1	glossy cardboard	1.4	9.3
2	glossy paper	8.8	3.9
3	normal paper	5.7	5.8
4	waxy paper	14	8.3
5	thin PE foam	0.21	17
6	carpet	0.25	54
7	corrugated cardboard	3.7	19
8	synthetic felt	0.23	24
9	cotton (jeans)	0.20	35
10	cotton (T-shirt)	1.3	25
11	polyester fabric	2.6	12
12	cotton fabric	1.4	18
13	polyester towel	1.1	47
14	plastic carrier bag	2.2	5.4

Table 1: (continued)

n°	description	compressibility (10^8 N/m/m^2)	averaged roughness (μm/$\sqrt{\text{mm}^{-1}}$)
15	printed plastic	18	11
16	paper towel	1.7	31
17	linen carrier bag	2.5	12
18	backside carpet	0.86	23
19	wrapping paper	7.7	14
20	plastic folder front	14	6.7
21	plastic folder back	1.3	12
22	thin cardboard	6.9	19
23	leather chamois	0.41	26
24	rubber glove outside	1.4	19
25	rubber glove inside	0.94	9.4
26	PE glove (bumpy)	0.37	6.0
27	blotting paper	0.43	29
28	ring binder non-slippery side	9.4	5.1
29	ring binder slippery side	0.70	6.0
30	ring binder backside	8.0	4.6
31	dustcloth	0.099	33
32	thin felt	0.10	30
33	medium felt	0.26	24
34	dossier folder rough	1.6	16
35	dossier folder smooth	1.5	37
36	dossier folder inside	0.15	11
37	plastic ring binder	2.5	5.8
38	'slow' plastic foam	0.083	39
39	medium rubber foam	0.30	43
40	fine steel wire mesh	0.79	13
41	coarse steel wire mesh	1.1	54
42	brass wire mesh	0.31	44
43	coarse copper wire mesh	0.22	44
44	fine copper wire mesh	0.22	18
45	thin rubber foam	2.0	27
46	rubber	15	4.1
47	waxed tissue	2.6	6.0
48	insulating cardboard	0.89	9.2
49	scouring sponge	0.029	54
50	PE foil	5.3	5.3
51	thin teflon	6.2	5.0
52	thick teflon	13	4.8
53	thick felt	0.21	33
54	kitchen cloth	0.35	29

Table 1: (continued)

n°	description	compressibility (10^8 N/m/m^2)	averaged roughness (μm/$\sqrt{\text{mm}^{-1}}$)
55	thick paper	3.1	8.0
56	emery cloth Sianor J P O	2.2	8.3
57	sanding cloth Sianor J P 180	2.1	26
58	sanding cloth Sianor J P 120	1.1	27
59	sanding cloth Sianor J P 60	6.3	52
60	sanding cloth Siarol P 240	2.3	13
61	sandpaper Siawat P 360	3.4	25
62	sandpaper Siawat WA P 600	11	7.5
63	sandpaper Siawat WA P 1200	4.7	6.3
64	emery paper Sianor B 1M	3.0	7.6
65	emery paper Sianor B 1C	2.9	11
66	emery paper Sianor B 4/0	0.58	4.6
67	structured paper ‘Prisma’	4.7	8.5
68	structured paper ‘Struisvogel’	1.5	33
69	structured paper ‘Picot’	3.4	14
70	structured paper ‘Viltmarkering’	5.1	16
71	structured paper ‘Griffe’	6.9	12
72	pressed sheeting material	1.3	6.8
73	block of synthetic material *	0.94	13
74	hard board smooth side	3.6	9.2
75	hard board rough side	2.7	33
76	thick steel sheeting	7.4	13
77	brushed aluminium sheeting	19	3.4
78	steel sheeting with holes	7.3	47
79	painted aluminium sheeting	12	9.3
80	thin steel sheeting	4.5	4.2
81	brass sheeting	40	5.3
82	copper sheeting	34	5.1
83	ribbed aluminium block *	-	9.9
84	bakelite (?) sheeting	3.2	5.6
85	thin synthetic sheeting	9.2	14
86	thick synthetic sheeting	5.7	12
87	circuit board material	8.6	7.9
88	PVC	28	4.3
89	hard plastic sheeting	9.0	3.2
90	transparent plastic sheeting	12	6.0
91	plexiglass *	15	5.4
92	thin plastic sheeting	0.92	6.2
93	nylon	2.1	11
94	block of plastic *	13	4.2

Table 1: (continued)

n°	description	compressibility (10^8 N/m/m^2)	averaged roughness (μm/$\sqrt{\text{mm}^{-1}}$)
95	plasterboard *	3.7	9.8
96	flexible plastic sheeting	25	6.2
97	plastic engraving material	13	2.8
98	board of synthetic material	16	6.7
99	finished chipboard *	0.98	5.2
100	MDF *	40	4.4
101	bumpy adhesive plastic	13	15
102	woodlike adhesive plastic	5.9	18
103	grooved adhesive plastic	7.9	5.8
104	silky adhesive plastic	3.6	6.1
105	smooth glass	8.9	5.0
106	glass with coarse structure	24	11
107	ribbed glass	11	7.7
108	glass with medium structure	57	25
109	matt glass	67	5.2
110	glass with fine structure	57	16
111	whitewood *	9.3	21
112	teak *	0.48	12
113	veneered chipboard *	46	5.5
114	painted soft board	0.42	16
115	plywood	3.4	6.4
116	oak veneer	6.8	10
117	plastified chipboard *	13	10
118	beech *	29	13
119	thick rubber foam *	0.16	33
120	very thick rubber foam *	1.2	26
121	wall tile	20	7.6
122	glazed floor tile	28	6.9
123	smooth floor tile	63	5.5
124	structured floor tile	25	15

The table also includes measured values for compressibility and averaged roughness that were obtained in the manner described below.

All materials were cut into squares of 10×10 cm. Most materials (110) were glued to pieces of 9 mm thick MDF board of the same size. For the thicker materials, double-sided adhesive tape was used. For the thinner ones, in order to avoid feeling the structure of the adhesive tape, spray-on glue was used. The other 14 material samples (mainly woods and thick foams) had enough rigidity and thickness of themselves to be used unmounted. These are marked

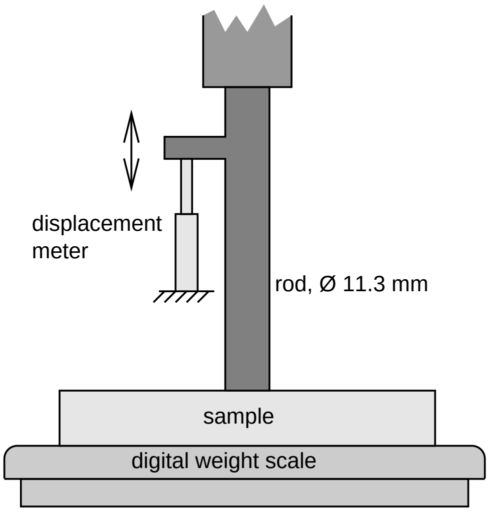


Fig. 1. Schematic illustration of the compressibility measurement setup.

with an asterisk in table 1.

Each sample was made in twofold; one set was used for psychological characterisation while the other set was used for the physical measurements of material parameters. Haptically important material parameters that come to mind are roughness, compressibility (softness), thermal conductance, heat capacity, friction etc. Because in informal conversations after the experiment subjects most often mentioned terms like 'rough', 'smooth' and 'soft', and because the dimensions hard/soft and rough/smooth often occured in the literature, we decided to focus on compressibility and roughness. Below, we discuss the measurements of these parameters.

2.1.1 Compressibility

Compressibility is defined here as the pressure (force per unit area) needed for a certain deformation of the material. In this definition, an easily compressible (soft) material has a low compressibility number. It is related to the *bulk modulus* [1] of a material by multiplication with its thickness. Because our subjects were only allowed to touch the surface of the material, thickness was ignored.

The compressibility of our samples was measured by applying a force with a rod and simultaneously recording the displacement of this rod. A dedicated setup was built for this purpose, as shown schematically in Fig. 1. The rod was made of brass which has a negligible compressibility. The diameter of 11.3 mm was chosen so that the area was in same range as that of a fingertip.

[1] The bulk modulus of a material is one of the standard elastic material properties found in many reference works. See for example Young and Freedman (2004).

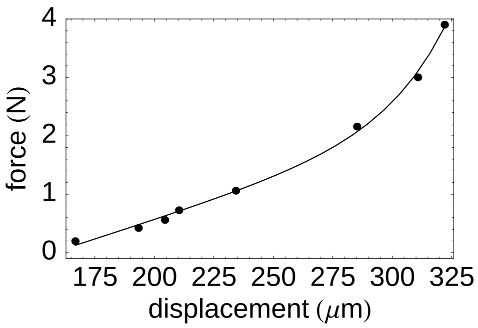


Fig. 2. Measured compressibility curve of a cotton sample (dots) with fit (solid line).

The force F was measured with a digital scale with 1 g (9.8 mN) precision. The displacement Δx was recorded with a digital displacement meter with an accuracy of 1 μm, and was corrected for the displacement of the scale, which was measured separately. For each sample, 8 points were recorded with forces ranging from $\sim$0.2 – $\sim$4 N. This is the range of force typically used in active touch, as was determined in a small experiment, in which a stimulus was felt on top of the scale. This range is also compatible with the forces reported by Louw et al. (2005). A function of the form

$$F = a(\Delta x - b) + c \exp(\Delta x - b) \tag{1}$$

was fitted to the data of each stimulus, with a, b and c free fit parameters. This function accounts for the linear behaviour that is expected for materials with a constant bulk modulus (first term), but also for the nonlinear behaviour that we observed in our measurements at higher forces (second term). An example of such a measurement is shown in Fig. 2. Note that the displacement on the horizontal axis is only relative because of the varying thicknesses of the materials.

To get a compressibility measure that is independent of the size of the contact area, the slope at the lowest measured displacement was divided by the cross section of the rod, 100.0 mm^2. The compressibility is then expressed in units of N/m/m^2. The slope was obtained from the function that was fitted to all 8 data points for maximum accuracy. The slope at the lowest data point was used instead of, for example, the average slope, because this is what one encounters first when one starts touching a material. For most stimuli, the slope was fairly constant up to $\sim$2 N of force. The values for all stimuli are shown in table 1. Since stimulus 83, the aluminium block, was not mounted on an MDF board with adhesive tape, its compressibility value was outside the measureable range. In the analysis that follows, a fictitious value of 10^{10} N/m/m^2 was used.

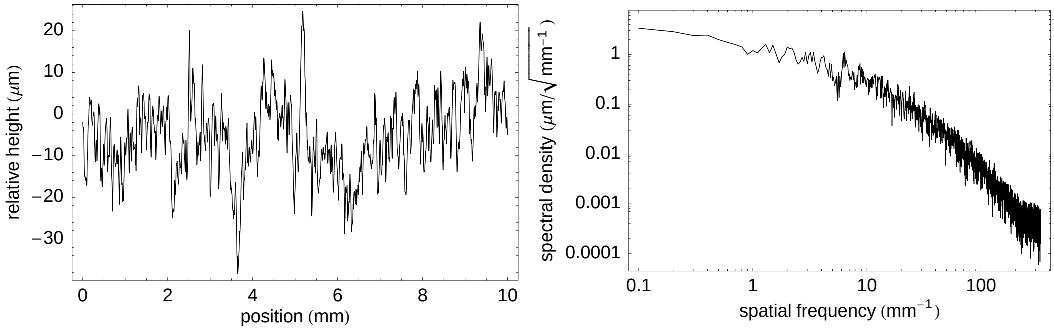


Fig. 3. Left: height profile of stimulus 56, a fine sandpaper, as measured with the UST. Right: square root of the single-sided power spectral density of the profile shown on the left.

2.1.2 Roughness

Roughness, as a physical concept, is the amount of height difference on the surface. This may be very different depending on the scale at which one looks. A surface may contain big lumps or very small features with the same height differences, but these will feel very different. Therefore, to characterise roughness, we should look at different scales or spatial frequencies.

In order to measure the physical roughness of the stimuli, a 1-dimensional surface profile was obtained of all samples using a 'Universal Surface Tester' from Innowep GmbH. This apparatus uses a stylus to maintain a constant force on the material while it moves in one direction. The stylus had a diamond-shaped tip with an angle of 60° and was set to a force of 10 mN. While the sample moved at a speed of 0.5 mm/s, 6666 height measurements were made, 1.5 μm apart. An example of the resulting height profile is shown in Fig. 3 (left). The surface profiles of stimuli 6 (carpet) and 49 (scouring sponge) fell outside the dynamic range of the apparatus. These stimuli received a roughness value equal to the maximum encountered with the other stimuli.

In order to quantify the physical roughness at different spatial frequencies, a single-sided power spectral density was calculated for each stimulus. 'Single-sided' means that only the positive half of the frequency spectrum is taken into account. A Welch window function was employed to reduce edge effects (Press et al., 1986). An example is shown in Fig. 3 (right). These spectra indicate the roughness at different spatial frequencies. The roughness number given in table 1 is a weighted average over the spectrum, obtained as described below in section 3.4.

There is a correlation between compressibility and roughness (soft materials are often rough), but as is visible in Fig. 4, our stimulus set also includes a substantial number of samples that deviate from this trend. It is clear that a large part of the roughness/compressibility space is filled up by the stimulus set, illustrating the diversity of the set.

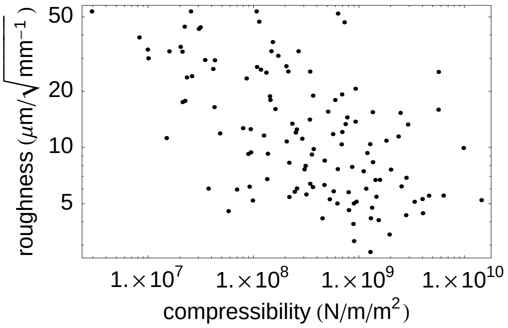


Fig. 4. Measured averaged roughness plotted against measured compressibility of the stimuli.

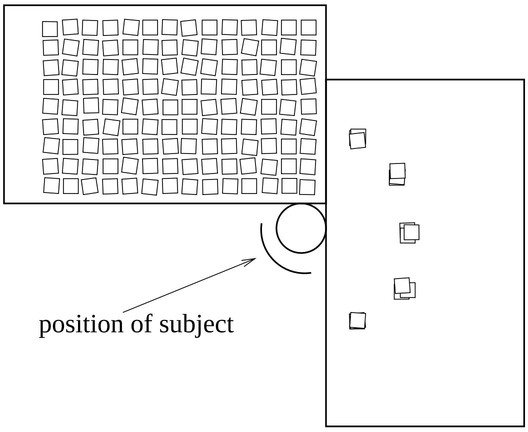


Fig. 5. Layout of the free-sorting experiment.

2.2 Subjects

Twenty paid subjects (8 male and 12 female university students, 18–26 years old) participated in the experiment. 17 were strongly right-handed, two moderately right-handed and one was strongly left-handed according to Coren's test (Coren, 1993).

2.3 Procedure

The subjects participated one at a time. Before the experiment proper began, each blindfolded subject was allowed to feel every stimulus once, while the stimuli were laid out on a table. Then, he or she was seated as indicated in Fig. 5. The stimuli were presented one by one in random order flat on the table, which had ridges that prevented the stimuli from sliding. The subject was allowed to use active dynamic touch to explore the surface. No restrictions were given as to the number of hands or the parts of the hand (finger, palm) to be used. The subject was asked to group the samples according to how similar they felt. Only after he or she had decided to which group the stimulus belonged could the subject pick it up and put in on a pile on the other table. The subject was allowed to feel all stimuli in the piles he or she had created and to rearrange the piles at any time. There should be at least two groups, but there was no upper limit set. The number of groups made averaged 13.8 and ranged from 5 to 33. The time taken was between 16 and 65 minutes, 33 minutes on average.

2.4 Analysis

In the analysis, each pair of stimuli was awarded one point when they occured in the same group. The points for all subjects were added together to form one similarity matrix. This was transformed into a dissimilarity matrix by normalising it to unity and subtracting it from 1. On this dissimilarity matrix, unweighted classical multidimensional scaling was performed. Following Torgerson (1958), the MDS procedure consisted of calculating a matrix of scalar products and determining an initial configuration by singular value decomposition. This configuration was then optimised for a given number of dimensions by iteratively minimising the S-stress (Schiffman et al., 1981). In this way, a stress number was calculated for 1–10 dimensions.

In order to correlate a measured physical parameter with the MDS results, the orientation of a vector $\vec{p}$ in MDS space that best matches the compressibility of the samples has to be found. To this end, the physical data is divided by the highest figure in the dataset (so that its range matches the maximum dissimilarity between stimuli) and shifted by -0.5 so that each stimulus is now associated with a compressibility number q_i in the range of -0.5–0.5. Then, the distance between the location of each stimulus in MDS space $\vec{x}_i$ and the scaled vector $q_i\vec{p}$ is minimised for all stimuli. Minimisation is done by setting the derivative of the sum of squared distances equal to zero:

$$\frac{d}{d\vec{p}} \sum (\vec{x}_i - q_i\vec{p})^2 = 0 \tag{2}$$

Solving this equation yields for the vector $\vec{p}$ the expression

$$\vec{p} = \frac{\sum q_i \vec{x}_i}{\sum q_i^2}. \tag{3}$$

The orientation of this vector indicates the best match for the orientation of this physical parameter in MDS space, while its length is a measure for its relative importance.

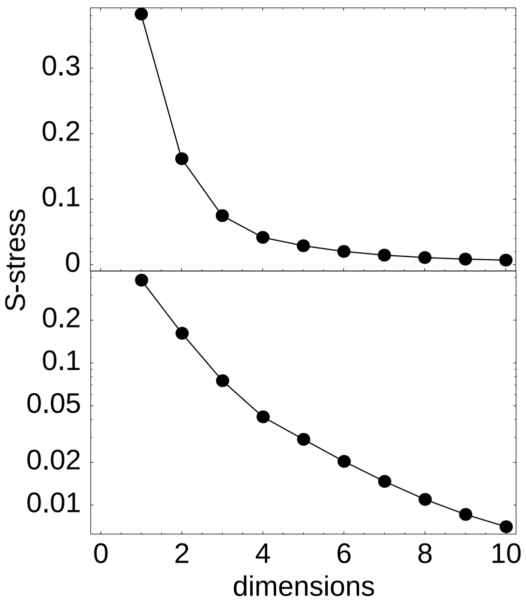


Fig. 6. S-stress plot of the MDS space with 1–10 dimensions, on a linear (top) and logarithmic axis (bottom).

We can now propose that the distance between two stimuli parallel to this line is proportional to their perceived difference in compressibility. This means that the location of a stimulus projected onto this line is a measure of its relative perceived compressibility. In order to see the relation between a measured and a perceived property, we can plot the measured parameter against the distance in MDS space from the origin to the position of each stimulus projected onto the vector $\vec{p}$. This distance d_i is given by the inner product

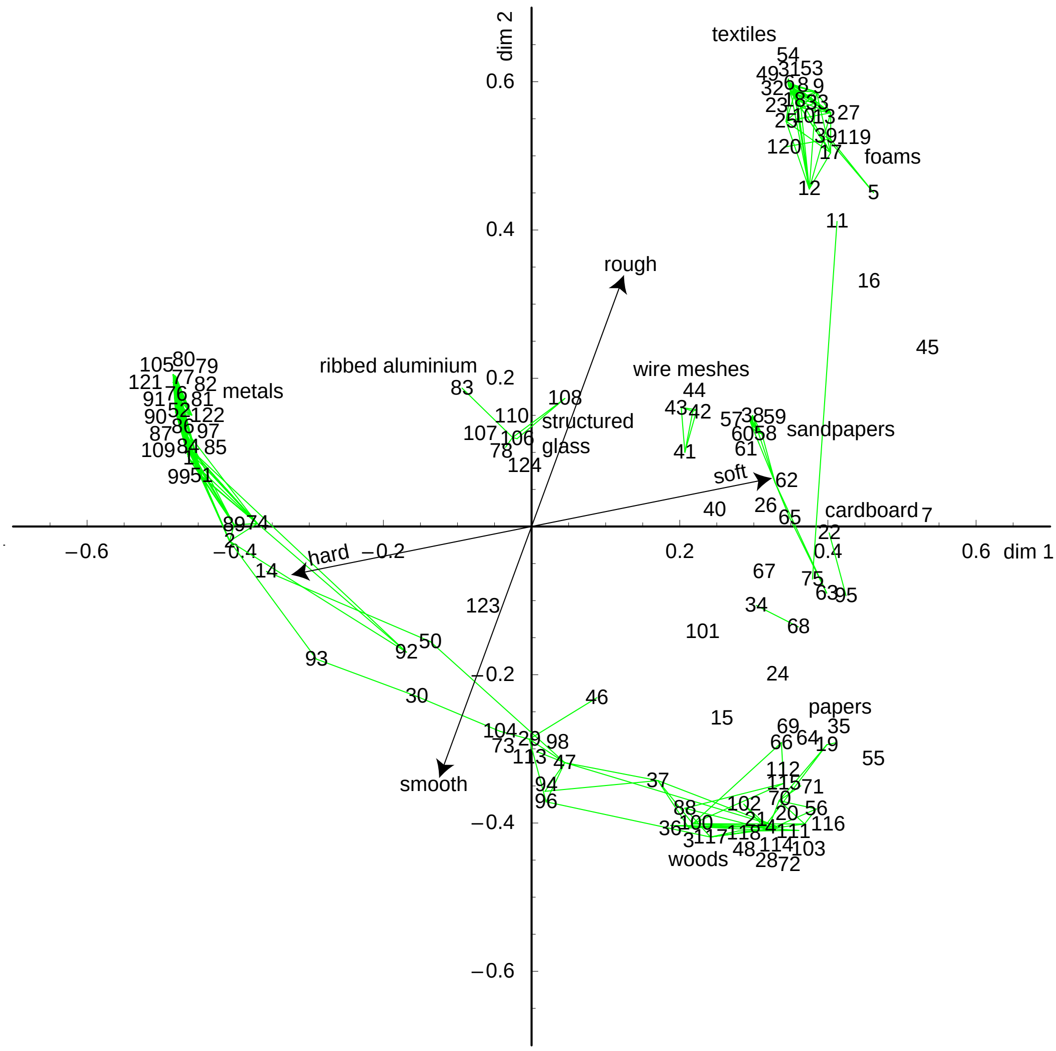
$$d_i = \frac{\vec{p} \cdot \vec{x}_i}{|\vec{p}|}. \tag{4}$$

3 Results

3.1 Dimensionality

The stress function is shown in Fig. 6. In the linear plot (top), we can see a decreasing slope in stress with increasing numbers of dimensions. However, a distinct 'elbow' is not visible. Since the stress function resembles an exponential function, it would look like a straight line when plotted on a logarithmic scale. In the logarithmic plot (bottom), a change in steepness is visible at 4 dimensions. Therefore, this number is most likely the relevant number of dimensions for the haptic material space.

The configuration of the 124 stimuli in 4 dimensions is shown in two 2-dimensional planes in Fig. 7. The positions of the stimuli are indicated by their number. Some positions are plotted slightly off-set for the benefit of legibility. Light lines connect stimuli which have a dissimilarity of less than 0.4 (recall that the maximum is 1). This number is chosen in such a way that it makes visible the structure of the configuration (a lower number shows too few and a higher number shows too many lines). There are some distinct clusters visible. The smooth metals (stimuli 76–82) are clustered together with the smooth glass (105, 109) and ceramic tiles (121, 122). In the first two dimensions (first plot), this cluster is at the end of a continuous band which connects to a clustering of woods (111, 112, 116, 118) and papers (19, 55, 69–71). From there it goes upwards via some rougher papers (34, 68) and cardboard (7, 22) to sandpapers (57–63). All the way at the top we find the textiles (6, 8–13, 17, 31–33, 53, 54) and foams (5, 39, 119, 120). Inside this 'horseshoe'



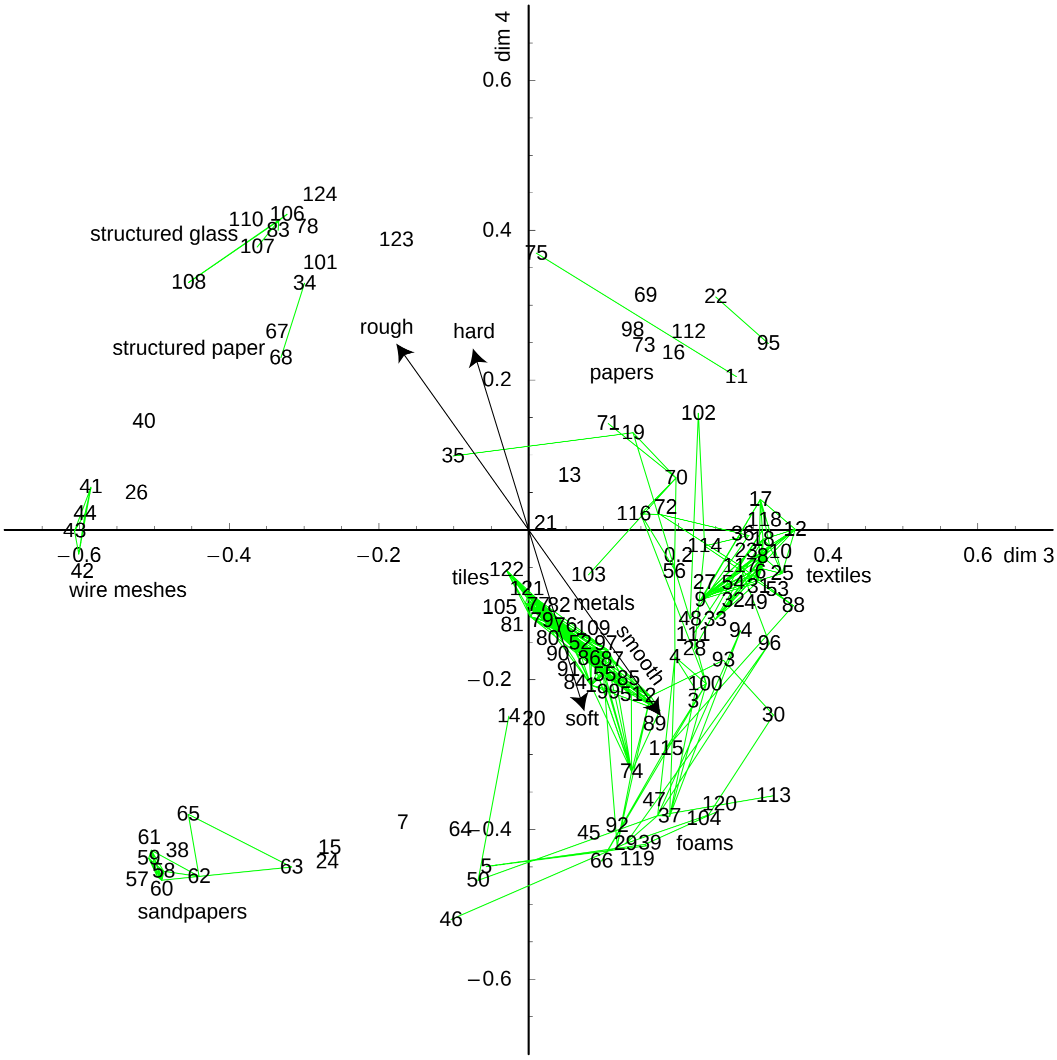


Fig. 7. 4-dimensional MDS configuration (2 dimensions per plot). The light lines connect stimuli with a dissimilarity of less than 0.4. The arrows labeled ‘hard/soft’ and ‘smooth/rough’ indicate the fitted vectors representing compressibility and roughness, respectively.

shape, some additional clusters are located: Wire meshes (41–44) and also structured glass (106–108, 110) together with the structured floor tile (124) and the block of ribbed aluminium (83). In dimensions 3 and 4 (second plot), similar clusters are visible, although textiles and foams are separated here. It is clear that stimuli made from similar materials are indeed clustered together because they feel similar. However, in order to see which material parameters are responsible for this haptic similarity, a physical characterisation of these material parameters is necessary.

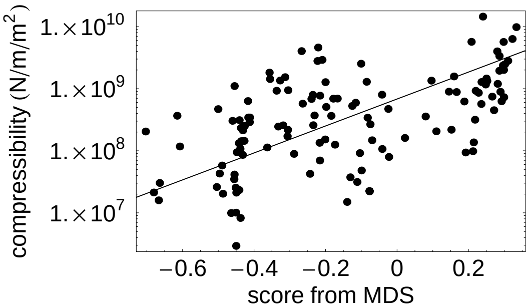


Fig. 8. Physical compressibility as a function of perceived compressibility for the 4-dimensional MDS space, with a fitted function (solid line).

3.3 Compressibility

The measured compressibility was fitted to the MDS space as described above. The resulting vector can be plotted with the stimulus locations in MDS space, as shown in Fig. 7 with the line labeled soft/hard. The measured compressibility as a function of the distance parallel to the vector in MDS space is shown in Fig. 8. The relation is not very clear, but there is an upward sloping trend visible in this logarithmic plot. Therefore, an exponential function has been fitted to the data with an exponent of 5.00. In order to assess the significance of this exponential relation, the Pearson product-moment correlation coefficient was calculated for the logarithm of the compressibility slopes versus the distance parallel to the vector. The coefficient was $r = 0.56$, which is not very high, but it corresponds to a significance level $p < 0.0005$. The data therefore indicate that on average, subjects employ a logarithmic 'mapping' of physical onto perceived compressibility.

3.4 Roughness

As stated before, physical roughness can be considered at many different spatial frequencies. To see which frequencies are important for the haptic perception of physical roughness, the average roughness in three 0.2 mm^{-1} wide frequency bands around 0.10, 1.0 and 10 mm^{-1} was calculated for each stimulus. For these three bands, vector orientations in the 4-dimensional MDS space were found in the same way as described above. In Fig. 9, the norms of these vectors are plotted for the three frequency bands. These vector norms indicate the relative importance of the material parameter for haptic perception of materials. We see that for the perception of physical roughness (middle three bars), the lowest spatial frequency (0.10 mm^{-1}) is the most important one. Therefore, when perceiving physical roughness, subjects pay the most attention to features with a length scale in the order of 10 mm. This material parameter is of comparable importance with compressibility (leftmost bar).

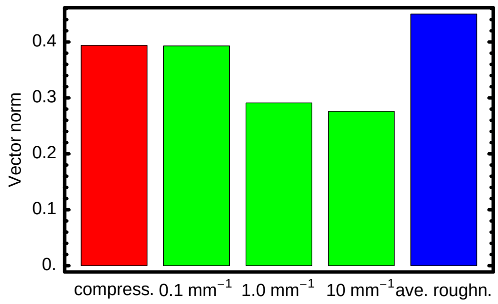


Fig. 9. MDS space vector norms for compressibility, the three spatial frequency bands for roughness and a weighted average of roughness over all spatial frequencies.

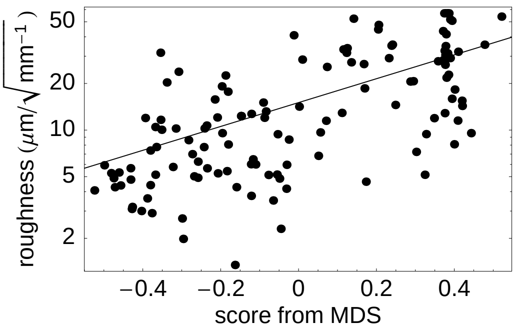


Fig. 10. Physical roughness as a function of perceived roughness for the 4-dimensional MDS space (dots), with a fitted function (solid line).

To assess the relation between perceived and physical roughness, we would like to express the physical roughness of every stimulus in a single number. To this end, principal component analysis (PCA) was applied to the power spectra, where every frequency bin was considered to be an independent dimension. All but the most important component were removed and the data were transformed back to the original units. This is equivalent to taking a weighted average of each spectrum. The weighing function that resulted from the PCA had roughly a $1/f$ shape (f being the spatial frequency) and favoured the lowest frequencies the most. The weighted average of the roughness for all stimuli is shown in table 1. These roughness numbers were correlated with the data from the MDS in the same way as the compressibility data, as described above. The vector that corresponds to this averaged roughness is plotted in Fig. 7, labeled rough/smooth. Its norm is shown in Fig. 9 (rightmost bar). From the plot, we see that the weighted average over all spatial frequencies is more important for the haptic perception of physical roughness than any of the three separate frequency bands. Physical roughness is also a more important material parameter than compressibility.

The physical roughness plotted against the perceived roughness is shown in Fig. 10. Again, an exponential relation is visible and an exponential function was fitted to the data with an exponent of 1.76. The Pearson test performed on the logarithm of the roughness and the distance in MDS space showed that the relation was significant ($p < 0.0005$) with a correlation coefficient of $r = 0.65$. This means that on average, subjects use a logarithmic mapping from physical roughness onto perceived roughness.

4 Discussion and conclusions

The first finding of this experiment is that based on the stress curve the haptic material space is most likely 4-dimensional. This number is higher than is found in some earlier MDS experiments (Hollins et al., 1993, 2000), but this is hardly suprising since the number of stimuli is about an order of magnitude higher. In experiments with a number of stimuli in the order of 20, the stimuli cannot be expected to 'fill up' a space of more than 3 dimensions. The high number of stimuli in the present experiment allows subjects to make very fine distinctions between groups, which in turn allows the less-important haptic differences to surface. Still, although our stimulus set is very broad, it did not include many organic materials (such as tree leaves or skin), sticky or moist materials, or (semi-)liquids. Therefore, we cannot exclude the existence of a higher number of dimensions. The fact that the number of dimensions is not very clear from the stress plot (Fig. 6) is probably due to differences between subjects. These were already observed by Hollins et al. (2000), but in the present study the differences might be even greater due to the higher number of stimuli. Unfortunately, the chosen method for acquiring the dissimilarity data does not allow for comparison between subjects.

As for the interpretation of the 4 dimensions, we can look at the norms of the vectors fitted in the space. A larger vector norm implies a better ordering of the stimuli in the direction of the physical parameter it represents, and therefore that physical parameter is a more important factor. From the vector norms, we can say that compressibility plays a role in haptic perception of materials, but it is not as important as the role played by physical roughness, although neither fits the MDS solution strikingly well. It can be seen from Fig. 7 that neither physical roughness nor compressibility can be identified with MDS dimension 1 (both are also a component of MDS dimensions 3 and 4). It is therefore likely that the subjects used some other parameter (or combination of parameters) as the main property for sorting the samples. When the perception of physical roughness is divided into spatial frequency bands, the roughness at the lowest spatial frequencies appears the most important. Although the tactile system becomes more accurate at smaller spatial scales (Louw et al., 2000), more attention is given to the larger-scale (lower spatial frequency) features. But of even more importance for the haptic perception of materials is the combination of roughness information from all spatial frequencies. The results reported here do not exclude the fact that 'rough' as a perception may have more components than just physical roughness. For instance, friction may also constitute an important factor. However, this is beyond the scope of the present paper, which deals with the physical parameters of roughness and compressibility.

In the plot of Fig. 7, the dimensions of roughness and compressibility are not completely orthogonal. This is probably not surprising because often, roughness and softness are correlated. Many stimuli, such as metals, are both smooth and hard, while others, such as textiles, are both rough and soft. It might be that in the first 2 dimensions of the MDS space, the dimensions of roughness and compressibility both follow the curved contour of the horseshoe shape in the plot. The horseshoe shape may be an artifact of the MDS procedure (Kruskal and Wish, 1978, appendix B). In the centre of this shape, we find the 'odd' materials that are both rough and hard, such as the structured glass and the ribbed aluminium block. It can therefore be suggested that, in contrast with the conclusions of Hollins et al. (1993) and Picard et al. (2003), the haptic material space cannot be respresented as a simple Euclidean space. In fact, when we try to do so, the dimensions of soft/hard and rough/smooth appear curved. The fact that this was not visible in earlier MDS experiments may be attributed to the low number or specificity of the stimuli used. Perhaps, a far more complicated model with curved spaces is necessary for the haptic material space.

For both compressibility and roughness, a logarithmic mapping from physical to perceived property is applicable. The exponent (slope in logarithmic plot) is 5.00 for compressibility and 1.76 for roughness. This exponential behaviour of roughness may not be incompatible with the power law found in the sandpaper experiments (Stevens and Harris, 1962; Ekman et al., 1965; Stone, 1967), when one keeps in mind that these experiments employed ratio scales, while the MDS score from the present experiment is a relative distance scale. When one interprets the distance between stimuli in MDS as the logarithm of the magnitude estimation on a ratio scale, the behaviour is compatible. The mapping that subjects used in the experiment by Stevens and Harris (1962) was described by the relation

$$\text{ratio scale score} \propto (\text{objective roughness})^{1.5}.$$

This can be expressed step-by-step thus:

objective roughness $\rightarrow \boxed{\log} \rightarrow \boxed{\times 1.5} \rightarrow \boxed{\exp} \rightarrow$ ratio scale

The mapping that took place in the present experiment is described by:

$$\text{MDS score} = 0.57 \log(\text{objective roughness}) + \text{some constant}.$$

(Note that the value of 0.57 is the reciprocal of the value 1.76 that was mentioned earlier.) The step-by-step procedure for this relation is:

objective roughness $\rightarrow \boxed{\text{log}} \rightarrow \boxed{\times 0.57} \rightarrow$ MDS score

In this perspective, one could say that the perception of roughness is a transformation that uses a logarithmic mapping to go from objective, physical roughness (i.e. pressure on the skin) to some kind of internal representation, and that there is another transformation that uses an exponential mapping to go from this internal representation to the ratio scale number. These two steps correspond to the 'log' and 'exp' steps in the first step-by-step procedure. In the case of the grouping task of the present experiment, the subject is not required to transform his or her sensation into a number. He or she can compare the sensations themselves. Therefore, the second step ('exp') is not needed, and is not present in the second step-by-step procedure. Because of the absence of this second step, the output (MDS score) may be closer to the internal representation of the sensation than a ratio scale number could be. To our minds, this sheds some interesting light on the way perceptions are represented internally and how they are transformed into external quantities.

Acknowledgements

This research was supported by a grant from the Netherlands Organisation for Scientific Research. The authors are very thankful to dr. Joop Wolke of the department of dentistry at Radboud University, Nijmegen, The Netherlands, for his permission for and help with using their Universal Surface Tester. We also thank mr. Hans Kolijn for his help with acquiring and characterising the stimuli and DRiem Papier for providing us with the paper for stimuli 67–71.

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